Learning among latecomer firms in low-carbon energy technology: the case of the Thai biogas industry

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Declaration

I, Tobias Reinauer, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signature *Date*

03/12/2018

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Abstract

The localisation of industries for low-carbon energy (LCE) technologies allows developing countries to align their economic development aspirations with efforts to reduce the amount of climate-damaging greenhouse gases that they emit into the atmosphere. This thesis aims to contribute to a better understanding of the localisation of such industries by analysing how firms accumulate technological capabilities, i.e. the resources needed to acquire, use, adapt, and change existing technology and/or to develop new technology. It focuses on the case of the Thai industry for medium and large-scale biogas plants and presents two research projects that are based on multiple-case study frameworks. The first of these analyses the documentation of a large sample of Thai biogas projects to determine the organisational arrangements that local and foreign firms have engaged in for the supply of technology in these projects. The second research project consists of a detailed comparative case study of technological learning at 10 Thai biogas engineering firms and is primarily based on interview data. The research presented in this thesis offers a number of micro-level insights about technological learning processes at so-called latecomer firms. This includes the extent of inter-firm heterogeneity in learning, the role of knowledge spillovers through informal learning mechanisms, differences in learning for technologies with particular kinds of characteristics, and the concomitant nature of changes in technological capabilities and learning mechanisms. These insights are helpful for decision makers in business, government, international donor agencies, and bi-/multilateral institutions involved in the design of targeted initiatives aiming to support the localisation of industries for the development and supply of LCE technology in the countries of the Global South.

Impact statement

The research presented in this thesis helps to further develop our understanding of how firms in low and middle-income countries accumulate technological capabilities. As will be explained in more detail below, this is particularly important for firms dealing with LCE technology due to the need to limit the amount of greenhouse gases emitted in the rapidly growing economies of the Global South. In addition to further developing our understanding of technological learning at such firms, the research presented in this thesis can also guide further research on this topic. The final chapter of the thesis contains a number of concrete suggestions for future research.

I have engaged in various activities to discuss and disseminate the results of the research presented here with peers in academia. For example, I have participated in multiple conferences and Ph.D. summer schools. I have also summarised the results of this research in the form of two papers, which I have submitted for publication to high-impact journals.

Furthermore, I have integrated some of the knowledge that I have acquired during my Ph.D. studies in my current work as a Teaching Fellow and Researcher at the Bartlett School of Environment, Energy, and Resources at University College London. In the future, I aim to continue to conduct research on the issue of low-carbon development in low and middle-income countries. As such, the knowledge acquired during this Ph.D. project forms an important basis for my career ambitions.

The research presented here also has a number of implications for decision makers involved in supporting the localisation of industries for the development and supply of LCE technology in low and middle-income countries. The final chapter of the thesis outlines a number of specific recommendations for firm management, national and sub-national governments, international donor agencies, and bi-/multilateral institutions. The main channel of knowledge dissemination to these stakeholders will be the previously mentioned journal paper publications.

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Abbreviations

AD	Anaerobic digestion
°C	Degrees Celsius
CDM	Clean Development Mechanism
CEO	Chief Executive Officer
FDI	Foreign direct investment
GDP	Gross domestic product
GNI	Gross national income
IPCC	Intergovernmental Panel on Climate Change
Kg	Kilogramme
Ktoe	Kilotonne of oil equivalent
LCE	Low-carbon energy
M.Sc.	Master of science
MW	Megawatt
N/A	Not available/applicable
pH	Potential hydrogen
Ph.D.	Doctor of Philosophy
PJ	Petajoule
PPP	Purchasing power parity
PV	Photovoltaic
R&D	Research and development
UCL	University College London
UNFCCC	United Nations Framework Convention on Climate Change
US	United States (of America)
USD	US Dollar

1. Introduction

In light of the risks and uncertainties associated with anthropogenic climate change, the world economy currently faces the dual challenge of promoting social and economic development while at the same time aiming to control the amount of climate-damaging greenhouse gases that become emitted into the atmosphere. This is particularly important for low and middle-income economies, for which structural change towards more and higher-value added industrial activity presents a way to increase per capita incomes and to address the persistent problem of poverty. Some of these economies have already achieved remarkable development over recent decades. This is reflected in substantial increases in the amount of greenhouse gases that they emit, despite simultaneous improvements in their carbon intensities of production (see Figure 1). The development of these economies is expected to continue over the coming decades, which likely leads to a further increase in their greenhouse gas emissions.

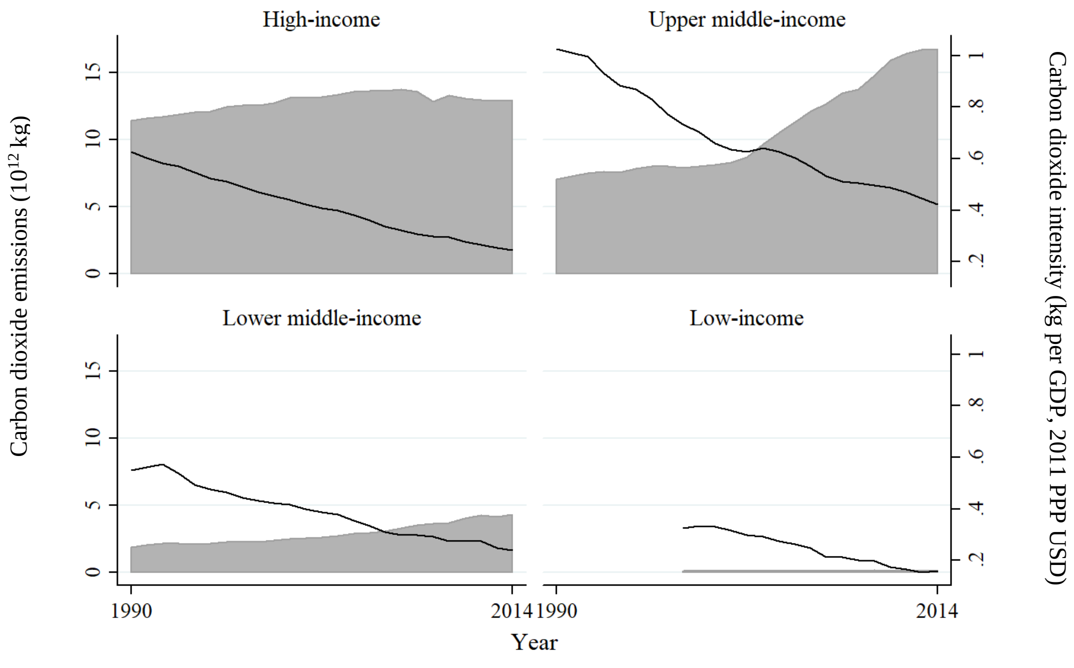

Figure 1: Carbon dioxide emissions (area) and carbon intensities of GDP (line) by country income group, 1990-2014. Data source: World Bank (2018).

Meanwhile, the Intergovernmental Panel on Climate Change (2018) estimates that the remaining carbon budget that would allow limiting global warming to 1.5°C compared to pre-industrial levels stands at about 420-770 $GtCO_2$. Given that the current estimated total annual emissions amount to between 39-45 $GtCO_2$, this means that approximately 10-20 years remain to entirely decarbonise the global economy. This is a formidable challenge that requires a rapid and radical transformation.

The need for decarbonisation highlights the importance of low-carbon development, particularly in the rapidly growing economies of the Global South. As illustrated above, development along a business-as-usual scenario will likely lead to substantial increases of greenhouse gas emissions in these economies. Furthermore, such development increases the risk of carbon lock-in, which will make transitions towards more sustainable forms of production and consumption even more difficult in the future (Unruh and Carrillo-Hermosilla, 2006). Focusing on the industrial sector in low and middle-income countries, Byrne et al. (2014) emphasise two opportunities for achieving low-carbon development: energy efficiency in carbon-intensive manufacturing and the localisation of industries for the development and supply of LCE technologies.

The present thesis focuses on the latter. In particular, it aims to contribute to a better understanding of how firms in low and middle-income countries accumulate the capabilities that allow them to develop and supply LCE technology. Following Van Dijk and Bell (2007, p.151), such capabilities are defined here as "a set of resources [including the] skills, experience, knowledge, and organisational arrangements needed to acquire, use, adapt, and change existing technologies and/or to create new technology." Hence, technology-supplying firms require capabilities to operate production equipment and to perform production processes efficiently. Importantly, in order to introduce technological change, firms also require capabilities for the adaptation of foreign technology to local circumstances, for changing and improving this technology, and/or for the development of new technology.

The accumulation of local technological capabilities has been highlighted as a key element of low-carbon development in low and middle-income economies (Berkhout, 2012; Ockwell and Mallett, 2012). Despite this, many support programmes at the national/sub-national and bi-/multilateral levels aiming to promote such development do not explicitly consider the role of capabilities. Usually, these programmes only include poorly defined provisions about the need to contribute to some form of local capacity building and/or international technology transfer. Often, they do not consider in detail what kinds of internal capability stocks firms require to operate successfully in competitive markets, nor are they based on a detailed understanding of how firms build their capability stocks through engagement in various kinds of learning activities. This thesis aims to contribute to a better understanding of how firms in developing countries build their capability stocks. In doing so, it hopes that it can contribute to the adoption of a more nuanced conceptualisation of technological capability building and learning processes among decision-makers involved in the promotion of low-carbon development in the countries of the Global South.

Before summarising the approach pursued here, it is useful to provide some more detail about the sorts of firms that this research focuses on. As the title of the thesis suggests, firms in low and middle-income countries are often referred to as latecomers. The concept of the latecomer has typically been discussed in the context of developing economies, although latecomers may also exist in more advanced economies, depending on how one defines them. Hobday (1995, p.1172) argues that latecomer firms are those which are dislocated from advanced markets and sources of technology. Bell and Figueiredo (2012a, p.17) argue that this does not need to be the case (anymore) as the spread of pervasive international networks has allowed firms in developing countries to gain at least some degree of access to advanced markets and technology. They contend that, instead, the defining characteristic of the latecomer firm is its initial inability to tap into existing networks to develop its production and innovation capabilities. Furthermore, its inability to innovate renders the latecomer initially imitative, meaning that it needs to emulate products or processes that were originally developed elsewhere to be able to compete, as opposed to developing them in-house (see also Kim, 1997). Mathews (2002, p.472) adds further defining characteristics of the latecomer, including a historically determined rather than a strategically chosen position of late entry, a strategic intent to catch up, and an initial competitive advantage such as low cost.

1.1. A multiple-case study of the Thai biogas sector

The objective of this thesis is to contribute to a better understanding of how firms in developing economies accumulate capabilities for the development and supply of LCE technology. Specifically, the thesis investigates how firms use various learning mechanisms to build their capability stocks. Two research projects are presented. The first focuses on the roles of different channels through which local firms obtain access to foreign sources of advanced technological knowledge. The second project consists of a micro-level study of how firms engage with firm-internal and external (domestic and foreign) sources of knowledge for learning. These issues are explored in the context of a case study of the Thai industry for medium and large-scale biogas plants. The thesis addresses the following overarching research question:

To what extent and how have Thai firms acquired expertise for the production and development of biogas technology?

Thailand's economy is an interesting case to investigate for this purpose. As illustrated in detail in Chapter 2 of this thesis, much of the literature on firm-level capability accumulation in developing countries has focused on a subset of large and rapidly industrialising countries - especially China and India - that host some of today's world-leading suppliers of LCE technology. These countries provide enabling environments that differ from those found in smaller developing countries, for instance, in terms of market size, local industrial structures, policy support, or macroeconomic conditions. These and other factors likely affect the ability of local firms to build their capability stocks. For example, this concerns the incentives that firms face to invest in their capabilities, their ability to redirect existing and related capabilities from one industrial sector to another, or the availability of opportunities to learn from foreign firms which have entered the domestic market.

By focusing on the case of biogas, the thesis also addresses another gap in the literature on firm capabilities in developing countries, namely the gap with regards to the variety of technology types that have been studied. As will be explained in detail below, technological characteristics affect the nature of the capabilities that are involved in technology development and supply. A review of the literature on firm capabilities in Chapter 2 shows that most existing studies have focused on the cases of solar photovoltaic (PV) panels and wind turbines. As will be argued below, the characteristics of these technologies differ from those of biogas systems in important ways. Over the past two decades, Thailand's biogas sector has experienced rapid development and has seen the emergence of several successful local technology suppliers. As such, this case is well suited for a detailed study of how latecomer firms in biogas develop their technological capabilities.

The research presented in this thesis is based on a multiple-case study framework in which the capability accumulation experiences of multiple Thai biogas technology-supplying firms are compared and contrasted. As will be argued below, this type of approach presents a middle ground between (i) in-depth case studies that focus on single firms and (ii) studies which focus on multiple national and/or technological contexts and which rely on more abstract, quantitative measures of technological capabilities and learning. While a multiple-case study can of course not go into the same level of detail as a single-case study, it allows for a comparison of several firms and, therefore, helps to identify common trends among and variation between capability development experiences. At the same time, the multiple-case study approach used here is based on in-depth qualitative data. This allows for a more fine-grained analysis of the relationship between learning and capability formation than those of large-N studies. Of course, this comes at the cost of a smaller sample size.

1.2. Summary of key findings

The approach pursued in this thesis allows for a number of insights about technological learning in the Thai biogas industry and about latecomer learning more generally. Firstly, the micro-level lens adopted here provides a comprehensive overview of the different kinds of learning mechanisms that Thai biogas engineering firms have engaged in. In line with previous research on the micro-level dynamics of latecomer learning (e.g., Bell and Figueiredo, 2012b; Figueiredo, 2003; Hansen and Ockwell, 2014), the thesis finds that learning is based on a multitude of activities involving both firm-internal and external sources of knowledge. The results suggest that informal learning mechanisms - i.e., those that are not based on contractual agreements between knowledge-providing and receiving organisations (e.g., learning based on observation, reverse engineering, or hiring skilled personnel) - are often key. This concerns both learning mechanisms based on domestic and foreign sources of knowledge. This finding contrasts with much of the literature on international technology transfer, which emphasises the importance of formal channels, such as foreign direct investment (FDI), licensing agreements, or joint research and development (R&D) programmes (e.g., Brewer, 2009; Hoekman et al., 2005; Popp, 2011; Saggi, 2002).

Secondly, the multiple-case study approach allows for insights about common trends among and variation between the technological learning experiences of different firms in the same industry. This concerns both the levels of technological expertise that they develop over time and the kinds of learning mechanisms they leverage for this purpose. The issue of inter-firm heterogeneity has also been highlighted in previous research based on multiple-case study approaches (e.g., Figueiredo, 2017, 2003; Hansen and Ockwell, 2014; Scott-Kemmis and Chitravas, 2007). However, country and sectoral-level research on latecomer learning usually glosses over this issue. As will be argued in Chapter 7, considering inter-firm differences is key when aiming to design policy support programmes which address the specific opportunities and challenges faced by firms that are at particular stages in their capability development.

Thirdly, the thesis presents a research project which investigates how the use of different learning mechanisms changes as firms develop increasingly sophisticated in-house capabilities. Specifically, it differentiates learning mechanisms by type (based on human resources, project experience, or R&D investments) and source (firm-internal, firm-external-domestic, firm-external-foreign) and describes in detail which kinds of learning mechanisms are most commonly observed at different levels of capability development. To my knowledge, this is the first systematic study at the level of the firm which analyses the co-evolution of technological capabilities and learning mechanisms (see Figueiredo et al., 2013; Hansen and Lema, 2019 for similar studies at the sectoral level).

Finally, the research presented here highlights the importance of considering the role of technological characteristics in latecomer capability accumulation. The micro-level study of multiple biogas engineering firms provides a detailed overview of the kinds of learning mechanisms that are most relevant in this case. Furthermore, the thesis includes a comparative analysis of learning based on foreign sources of knowledge for anaerobic digestion (AD) systems and biogas engines/engine-generator sets. The key insight here is that the supply of the former more commonly involves local firms as these systems rely heavily on experience accumulation in local project contexts. As the findings summarised above, this has important implications for the design of targeted programmes to support technological learning processes at latecomer firms.

1.3. Structure of the thesis

Chapter 2 reviews the literature that the present thesis is based on and aims to contribute to. It begins by reviewing how the firm-level accumulation of technological capabilities is conceptualised here. It then discusses the learning mechanisms which firms use to develop their capabilities. Next, it discusses other factors at the level of the firm, sector, and economy that likely influence latecomer learning. Based on these discussions, the chapter then reviews the literature on firm capabilities that has specifically focused on LCE technologies in low and middle-income country contexts. The chapter ends by introducing the research questions.

Chapter 3 discusses some general aspects regarding the research design that the thesis is based on. It does not provide detailed discussions of the data sources, sampling strategies, and methods used for data analysis - these are described in Chapters 5 and 6. Instead, the focus here is on some of the more general aspects of the research design, including the choice of a multiple-case study design, the use of a deductive approach based on qualitative data, and some issues related to data collection (language barriers and ethical concerns).

Chapter 4 introduces and justifies the choice for the case studied in this thesis. It begins by introducing the basic characteristics of industrial-scale biogas plants. It then provides a brief overview of the demand and supply side of the global market for biogas plants. Next, the focus turns to the case country studied in this thesis. A brief introduction to the Thai economy is followed by an overview of the country's energy sector and a summary of the history of the Thai biogas sector.

Chapter 5 presents the first project that has been conducted as part of this Ph.D. research. This project contributes to an understanding of how Thai biogas engineering firms have interacted with foreign organisations in the supply of biogas technology. This provides insights about their likely in-house capabilities and the types of equipment and knowledge flows that took place as part of these interactions. The analysis is primarily based on the publicly available documentation of a large sample of biogas projects that have applied for registration with the Clean Development Mechanism (CDM) under the United Nations Framework Convention on Climate Change (UNFCCC).[1] The chapter begins by discussing the analytical framework that the analysis is based on. This is followed by a description of the methods used for data collection and analysis. The chapter then presents the results and discusses what insights they provide in light of the literature on technological learning among firms in low and middle-income countries. Finally, the main points of this piece of analysis are summarised in a brief section at the end of the chapter.

Chapter 6 summarises the results of the second project conducted as part of this Ph.D. research. It presents a study that analyses the micro-level dynamics of how a sample of Thai biogas engineering firms have accumulated their technological capabilities. Primarily based on interview data, this analysis goes into detail about the kinds of learning mechanisms that these firms have engaged in. The chapter begins by discussing the analytical framework that the study is based on. Subsequently, it describes the strategies

[1] The CDM is a mechanism which was established under the Kyoto Protocol and which aims to bring down the costs associated with reducing global greenhouse gas emissions (UNFCCC, 1998). It allows emissions-saving projects in developing countries to generate so-called Certified Emission Reduction credits. Public and private institutions in industrialised countries can purchase these credits on international carbon markets and count them towards their emission reduction obligations.

that have been used for data collection and analysis. After presenting the results, the chapter discusses what insights they provide in light of the existing literature on firm-level technological capability building in developing countries. The chapter concludes with a brief summary.

Chapter 7 concludes the thesis. It begins by briefly outlining the approach pursued here. It then summarises the results presented in Chapters 5 and 6 and synthesises these into four key insights for the study of technological capability building at latecomer firms. The chapter then discusses what these insights imply for decision-makers in business, government, international donor agencies, and bi-/multilateral institutions. Finally, it highlights some limitations of the research presented in this thesis and discusses how future investigations could usefully address these.

2. Literature review and conceptual framework: technological learning among latecomer firms

This section discusses and synthesises different areas of literature that are relevant to understanding how firms in low and middle-income countries build the knowledge and skills they need to develop and supply industrial technology. The goal is to describe in some detail the elements that form part of the analytical framework which the empirical analyses presented in Chapters 5 and 6 are based on. Section 2.1 discusses the nature of technological capabilities that firms require to upgrade their production and innovation activities. Section 2.2 goes into detail about the ways in which these are acquired. Section 2.3 briefly outlines other relevant factors at the level of the firm, the sector, and the economy that may affect capability building and technological learning. Section 2.4 focuses specifically on the latecomer capability literature dealing with LCE technologies and uses the conceptual framework described in previous sections to highlight gaps in this literature. Finally, Section 2.5 presents the research questions.

2.1. Firm capabilities for technological catch-up

Much research has been conducted on the innovation-related activities and the associated knowledge management strategies of firms in high-income countries. The literature on strategic management has made important contributions to this field of knowledge. This includes the seminal works on core competencies (Prahalad and Hamel, 1990), on the importance of diversified competencies (Patel and Pavitt, 1994), and on dynamic capabilities (Teece et al., 1990). This literature typically focuses on firms whose competitiveness stems from technological advances and which operate at or close to the global technological frontier (see Dutrénit [2004] for a review). The core issue of interest in this literature is how firms manage and organise the knowledge resources that allow them to create, to sustain, and to renew their competitive advantage in a constantly changing business and technological environment (*ibid.*).

As illustrated by Dutrénit (2007, 2004) and Mathews (2002), this literature can be distinguished from another body of literature that looks specifically into how firms in low and middle-income economies accumulate technological capabilities. Here the focus is on how firms develop a minimum base of technological capabilities that allows them to carry out production and innovation activities. This contrasts with the study of technologically advanced firms in high-income countries, which have already accumulated high levels of such capabilities. The firms studied in the latecomer learning literature start from relatively low capability levels and through learning processes transition towards higher levels that allow them to creatively engage with increasingly more novel and complex technologies. Most of this literature focuses on technological capability accumulation at levels of technological mastery that is significantly below those of firms which operate at or close to the global technological frontier. Since the development of technological capabilities from a low starting point involves qualitatively different processes compared to managing knowledge resources at world-leading firms, the literature on strategic management and the latecomer capability literature mostly rely on different analytical frameworks (Dutrénit, 2007, 2004). The present thesis aims to contribute to the latecomer camp of literature.

To reiterate, this thesis follows Van Dijk and Bell (2007, p.151) in defining capabilities as "a set of resources [including the] skills, experience, knowledge, and organisational arrangements needed to acquire, use, adapt, and change existing technologies and/or to create new technology." Efforts to group capability types that are most relevant for latecomer firms in developing countries into different functional categories date back to the 1980s. Dahlman et al. (1987) proposed an early and influential framework. They group capabilities into different stages of the project life-cycle and argue that latecomers develop these in a sequence: from production, to investment, to innovation capabilities. First, latecomers develop production capabilities, which Dahlman et al. define as knowledge and skills in production management, production engineering, maintenance of equipment, and finding uses for production outputs (including marketing). They argue that latecomers initially rely more on production capabilities than innovation capabilities as they often purchase technology that had previously been developed elsewhere. Experience in production forms the basis for investment capabilities, i.e. the knowledge and skills necessary to decide on whether and how to expand existing plants and/or to develop new ones (including capabilities for procurement, project engineering, project management, project execution). Finally, Dahlman and colleagues argue that production and investment capabilities together allow firms to develop innovative capabilities, i.e. the ability to know what is needed and possible with regards to new products and processes. This framework has since been adopted by a multitude of studies, including two influential books on the subject of latecomer capabilities by Amsden (2001) and Kim (1997).

A major limitation of the approach to categorising capabilities as in Dahlman et al. (1987) is that it only differentiates between capability categories *across* technological functions. The approach fails to consider differences in capabilities *within* these functions. Lall (1992) was probably the first to explicitly address this problem. He developed a framework in the form of a two-dimensional matrix (illustrated in Table 1). The columns of the matrix differentiate between functions that fall under the investment and production capability categories. The rows represent activities of different levels of novelty and complexity. This is important because, as Lall (*ibid.*, p.168) put it, "(…) the very nature of technological learning (i.e. accumulated experience of problem solving, aided by external inputs or formal research efforts) would seem to dictate that mastery would proceed from simpler to more difficult activities (…)". In contrast to Dahlman and colleagues, Lall did not prescribe any particular order in which these capabilities are or should be developed, but emphasised that the sequence in which they need to be developed varies by firm and technology.

		Investment		**Production**			
		Pre-investment	Project execution	Process engineering	Product engineering	Industrial engineering	Linkages within the economy
Degree of novelty and complexity	Advanced	...	…	…	…	...	…
	Intermediate	...	…	…	…	…	...
	Basic	…	…	…	…	…	…

Table 1: Lall's (1992) framework to conceptualise firm capabilities across functions and complexity levels.

Bell and Pavitt (1995) added further conceptual clarity to Lall's (1992) framework by distinguishing between routine and innovation capabilities. Capabilities for routine activities were added as an additional, lowest level to Lall's matrix because the lowest level in his framework fails to differentiate between basic innovative activities and activities which do not involve any creative input from the firm. The latter concern only the execution of pre-defined processes such as the execution of externally developed and imported process specifications.[2]

[2] In the original work by Bell and Pavitt (1995) and in subsequent publications that have adopted their framework, the non-creative capability level is sometimes referred to as "production capabilities". To avoid

Capability category		Examples of activities falling under each capability level
Innovative	World leading	A large and diverse group of globally recognised research and development (R&D) experts and highly specialised engineers work on technology that is likely to push the global technological frontier. This is based on applied and basic research on radical, new-to-world product and process innovations. It involves the application of state-of-the-art research tools and methods and includes collaborations on technology development with other internationally leading firms and research institutes.
	Advanced	A varied group of specialised design and development engineers work on new-to-country product and process innovations that are close to the international technological frontier. The firm applies structured approaches to generate new knowledge and collaborates closely with nationally leading and other international organisations on technology development.
	Intermediate	A large number of specialised and well-trained engineers and technicians work on product and process innovations that are new-to-firm or that involve substantial modifications to existing technology. The firm effectively uses engineering design tools to produce new knowledge. It collaborates with other domestic firms and research institutes and interacts with other foreign-based organisations to improve technology.
	Basic	A small group of engineers and technicians work on minor improvements of existing technology designs based on simple and sometimes outdated design and engineering design tools. The firm mostly interacts with domestic organisations on achieving minor adaptations in existing technology.
		Fuzzy boundary
Routine	Extra basic	Highly skilled operators and technicians conduct regular monitoring, preventive maintenance, and product/process engineering tasks to ensure minimal down-time due to faults in the system. The firm has a high standard of organisational efficiency, including intra-firm communication between different teams to solve day-to-day problems in operation.
	Basic	Less skilled operators and technicians conduct monitoring and inspection in-house. Maintenance is partly done in-house, involving *ad hoc* fixes and sometimes requiring assistance from technology suppliers or specialised firms to address more complex problems.

Table 2: Differentiation of technological capability levels as suggested by Bell and Pavitt (1995). Examples of firm-internal resources are based on Amsden and Tschang (2003), Bell and Figueiredo (2012b), OECD (2005), and Radosevic and Yoruk (2018).

Table 2 illustrates the difference between capabilities for routine and innovative capabilities and provides some examples. The Bell and Pavitt framework has been popular among scholars of latecomer capabilities. It has been used and elaborated upon by a large number of single and comparative case studies (e.g., Dantas and Bell, 2011; Dutrénit, 1998; Figueiredo, 2017; Hansen and Ockwell, 2014; Kiamehr et al., 2014; Tacla and Figueiredo, 2006; Tsekouras, 2006) and also by studies based on statistical methods (e.g., Ariffin, 2010; Gammeltoft, 2004; Iammarino et al., 2008; Peerally and Cantwell, 2012; Yoruk, 2011). The present thesis adopts the framework by Bell and Pavitt (1995) and, thus, aims to build on this literature.

confusion with the functional capability category of production (e.g., as opposed to investment), this thesis uses the terms “non-creative” and “routine” capabilities to refer to this capability level.

In practice, the boundary between routine and innovative capabilities is fuzzy (as indicated in Table 2) (Bell and Figueiredo, 2012a). For instance, it is hard to imagine a scenario where a firm would develop innovation capabilities without learning how to perform at least some of the non-creative tasks involved in the operation of production equipment. Conversely, whenever a firm acquires knowledge and skills for routine activities, it likely also learns to some degree about the design principles of the technology and how these can be altered to improve performance. However, the amount of innovation capabilities accumulated when developing routine capabilities can be minimal, as the case of the Indonesian pulp and paper industry has shown (Van Dijk and Bell, 2007).

Furthermore, the distinction between routine and innovation capabilities implies two different kinds of technological catch-up (Bell and Figueiredo, 2012b). On the one hand, latecomers can develop the capabilities needed to perform routine tasks, which is based on replicating products and processes based on fixed, externally developed specifications. While Bell and Pavitt (1995) only include a single level for routine capabilities, subsequent work has differentiated between various levels to account for differences in the products and processes that non-innovative firms engage with (e.g., Figueiredo, 2003). Catching-up in terms of routine capabilities is usually associated with a narrow conceptualisation of the global technological frontier, i.e. one in which there is a single frontier, constituted by certain products and processes, that latecomers aim to approach (Bell and Figueiredo, 2012b, p.28). Adopting the terminology of Lee and Lim (2001), focusing on the development of routine capabilities leads to “path-following” or perhaps “path-skipping” catch-up along a pre-established technological trajectory. Studies assessing the productivity gap between advanced and latecomer firms seem to conceptualise catch-up in this way (e.g., Jung and Lee, 2010).

On the other hand, firms can catch up with regards to their ability to generate and manage technological change. For example, they can move from capability levels that only permit imitating technology which had previously been developed elsewhere to levels of capabilities that allow them to develop radically new products and processes which meet world-leading quality and performance standards. Furthermore, catching up with regards to innovative capabilities is important for technologies whose designs require substantial adaptation to local contexts. As will be argued in detail further below in the present thesis, this is particularly relevant in contexts where knowledge about locality-specific requirements is built through experience in local projects. Borrowing Lee's and Lim's (2001) terminology again, the development of innovative capabilities is associated with “path-creating” catch-up. This implies a view of the global technological frontier in which several distinct technological trajectories constitute global best practice.

Radosevic and Yoruk (2018, 2016) provide further detail on the kinds of capabilities that fall under the routine and innovative categories of capabilities. As will be explained further below, this is useful to develop operationalisations of the technological capability concept. Following Bell's and Pavitt's (1995) original work, Radosevic and Yoruk divide the routine capability category into capabilities required for operation and capabilities required for product and process engineering. While operation capabilities are reflected in the efficiency of production processes, product and process engineering capabilities allow the firm to perform incremental improvements in products and processes that do not involve changes in the design of the underlying technology. With regards to innovation capabilities, Radosevic and Yoruk build on a framework for the classification of R&D activities by Amsden and Tschang (2003). In particular, Radosevic and Yoruk divide innovation capabilities into capabilities required for technology development (advanced and exploratory) and capabilities for research (basic and applied). They add that, in practice, the boundary between these two capabilities types is often blurry. Nevertheless, it is useful to distinguish them since technology development and research involve qualitatively different tasks and likely require different types of capabilities.

As opposed to Bell and Pavitt (1995), Radosevic and Yoruk (2018, 2016) emphasise that their conceptualisation of capability types is not based on a strictly hierarchical structure. Transitioning from operation, to product and process engineering, to technology development, to research does not necessarily involve innovative activities on more novel and complex technologies. Similarly, it does not automatically involve a move towards higher value-added activities. Instead, Radosevic and Yoruk argue that there are certain thresholds which latecomers need to overcome to upgrade technologically. For example, focusing on the case of manufacturing, they argue that for latecomer firms there is an important threshold from advanced to exploratory development (Radosevic and Yoruk, 2018, p.58). The former involves prototypes for manufacture with a focus on reducing cost and uncertainties in production while the latter involves implementing own designs as fully engineered systems at the pilot-scale. While it is difficult to determine where exactly such a transition would be positioned on a Bell-and-Pavitt-type capability ladder, this would probably be at the intermediate or advanced levels.

The frameworks on latecomer capabilities by Bell and Pavitt (1995) and Radosevic and Yoruk (2016, 2018) can be combined as illustrated in Table 3. Routine capabilities involve capabilities for operation and product/process engineering. They are relevant for both the basic and extra basic levels of capabilities, although their relative importance and the precise kinds of activities that fall under these categories likely differ. Innovative capabilities involve capabilities for technology development and research. Again, the relative importance and precise nature of these probably changes as one moves from the basic innovative to the world-leading innovative levels.

Bell and Pavitt (1995)		**Radosevic and Yoruk (2018, 2016)**
Innovative	World-leading	- Research (basic, applied) - Technology development (advanced, exploratory)
	Advanced	
	Intermediate	
	Basic	
Routine	Extra basic	- Product/process engineering - Operation
	Basic	

Table 3: Integration of Bell's and Pavitt's (1995) and Radosevic's and Yoruk's (2018, 2016) frameworks on latecomer capabilities.

The relationship between the competitiveness of the firm and the accumulation of technological capabilities as conceptualised in Tables 2 and 3 is not straight-forward. While a move from the basic innovative to the world-leading innovative class of capabilities does allow the firm to engage creatively with products and processes of increasing novelty and complexity, this does not automatically imply higher competitiveness. Of course, competitiveness depends on factors other than just technological capabilities. However, there is compelling evidence that innovativeness is strongly and positively correlated with competitiveness. For example, Peltoniemi (2011) reviews 216 studies on industry life-cycles and finds that not a single one of these disputes the notion that innovativeness provides competitive advantages. The reader should note that the present thesis focuses on how firms develop their routine and innovation capabilities and not on how this contributes to their competitiveness or other indicators of business performance. This issue will be revisited in Section 2.5.

2.2. Learning mechanisms

Learning is conceptualised here as the various processes through which firms accumulate additional knowledge, skills, experience, and organisational arrangements which they require to carry out routine production and innovation activities (Bell, 1984; Malerba, 1992). As suggested by Figueiredo (2003), these can be broken down into knowledge acquisition (differentiated based on the source of new knowledge) and firm-internal knowledge conversion processes. While this research primarily focuses on knowledge acquisition, it is useful to briefly discuss knowledge conversion processes at this point. These processes concern the firm-internal management of knowledge and help to explain how the acquisition of new knowledge by individuals or groups of individuals within the firm results in the development of technological capabilities for the firm as a whole. An important concept here is the distinction between explicit and tacit knowledge (Polanyi, 1962). Explicit knowledge refers to knowledge that is codified, e.g., in the form of engineering-design drawings or patents. While such codifications contain detailed information, they are only useful when they are transformed into tacit knowledge. Tacit knowledge is people-embodied and is acquired through experience. It is what ultimately allows a firm to put a product or process into practice. In order to diffuse newly acquired knowledge throughout the firm, the knowledge needs to be converted: from tacit to tacit, explicit to explicit, tacit to explicit, and explicit to tacit (Nonaka, 1994). As will be discussed further below (Section 2.2.2), this has important implications for how different firm-internal and external learning mechanisms need to be combined to achieve learning.

Turning now to the ways in which firms acquire new knowledge, one can distinguish between two broad categories of processes (Bell, 1984). The first involves the accumulation of knowledge and skills as a by-product of experience in investment or production activities. This is a passive form of doing-based knowledge acquisition that can lead to minor improvements in the efficiency of processes and, thus, can contribute to a firm’s routine capabilities. It typically does not allow the firm to develop the capabilities required for innovation. The second category of learning is based on proactive efforts aimed at improving the firm’s capabilities. As opposed to passive forms of learning, this involves targeted investments that aim to leverage particular sources of knowledge, which is often costly and time-consuming. When pursued effectively and persistently, this kind of learning allows firms to achieve high levels of capabilities for routine and innovation capabilities (Figueiredo, 2003).

Several authors have developed lists of mechanisms through which firms acquire new knowledge and skills (including Bell, 1984; Bell and Figueiredo, 2012a; Figueiredo, 2003; Hansen and Ockwell, 2014; Kim, 1997; Malerba, 1992). These are typically divided into firm-internal learning mechanisms and mechanisms based on external sources of knowledge. Firm-internal learning mechanisms include the acquisition of experience by performing routine processes. More proactive forms of firm-internal learning are based on trial-and-error problem solving, firm-internal training programmes, or collecting and analysing operational data to inform improvements in product designs or production processes. Firms can also “learn by searching” by engaging in activities that specifically aim to generate new knowledge, e.g., in their R&D or design and engineering departments.

Learning can also be based on sources of knowledge that lie beyond the boundaries of the firm. For example, firms can hire employees who have acquired relevant knowledge and skills through their education or work experience. Firms can also channel publicly or otherwise available information into the firm in order to build capabilities - e.g., based on patents, engineering drawings, or textbooks. Frequently, learning based on external sources involves interactions with other organisations such as research institutes, industry associations, or other firms. This can be based on a wide variety of organisational arrangements, including arm’s length trade of equipment, obtaining licenses for particular pieces of equipment or designs, collaborations based on joint venture agreements, joint R&D programmes, and others. Organisational arrangements which allow latecomer firms to access foreign sources of knowledge are discussed in detail in Section 2.2.1 below.

Furthermore, the present thesis distinguishes learning mechanisms based on whether they involve domestic or foreign sources of knowledge. A large body of literature highlights the importance of linkages within the national innovation systems of developing countries (e.g., Chaminade et al., 2012; Mallett, 2015; Wong, 1999). However, evidence from case studies on latecomer firms suggests that these types of linkages are mostly associated with lower level capabilities (e.g. Hansen and Ockwell, 2014; Plechero, 2012). On the other hand, interactions with foreign organisations - particularly but not exclusively those located in high-income countries - frequently offer latecomers access to more advanced technological knowledge. If effectively incorporated into the firm, the knowledge that becomes available through interactions with these organisations can allow for the development of higher-level capabilities (Hansen and Ockwell, 2014; Kim, 1997; Lewis, 2007; Marigo et al., 2010; Plechero, 2012; Scott-Kemmis and Chitravas, 2007). This stems from the fact that, despite a growing number of world-leading technology suppliers in emerging economies, the majority of global innovative activities continues to take place in high-income economies (e.g., the World Intellectual Property Organisation [2017] reports that most patents continue to originate in these economies).

Building on the general conceptualisation of different mechanisms for technological learning summarised in Section 2.2 up to this point, the remainder of this section focuses in on two more specific issues in the literature on latecomer capability accumulation which the present thesis aims to contribute to. The goal here is to develop the conceptual frameworks that Chapters 5 and 6 will build on. On the one hand, this includes the issue of learning based on foreign sources of technological knowledge, which is often framed from the perspective of international technology transfer (discussed in Section 2.2.1). On the other hand, it includes a review of the literature on changes in the kinds of learning mechanisms which firms engage in as they develop increasingly deep stocks of technological capabilities (see Section 2.2.2).

2.2.1. Learning from foreign sources of knowledge

This subsection discusses the issue of learning from foreign sources of knowledge. It will first describe a general framework for the analysis of cross-border technology transfer and will then discuss what different kinds of interactions between local and foreign firms imply in terms of equipment and knowledge transfer. These issues will be elaborated upon in the analysis presented in Chapter 5.

Conceptual framework for cross-border equipment and knowledge flows

When thinking about firm-level processes of learning from foreign knowledge, it is useful to distinguish between the different kinds of flows involved. Figure 2 illustrates a simple conceptual framework based on a bilateral relationship in an organisational arrangement between a technology-supplier and recipient.

The framework includes three types of flows. Flow type A represents the technological artefacts - i.e. explicit knowledge in the form of machinery, design specifications, etc. - and the engineering and managerial services needed to deliver these. Flow type B represents the tacit and explicit knowledge necessary to put these artefacts into practice. Together, flow types A and B contribute to the capacity of the technology-receiving firm to perform routine tasks such as the operation and maintenance of imported equipment. To effectively make use of the learning opportunities that these flows represent, the firm needs to invest in firm-internal efforts (Figueiredo, 2003; Kim, 1997). Flow type C consists of a broad bundle of knowledge and skills for generating and managing technological change. As with flow type B, it is based on transfers of both tacit and explicit knowledge. If effectively combined with firm-internal efforts, this flow type leads to the development of innovation capabilities at the technology-importing firm.

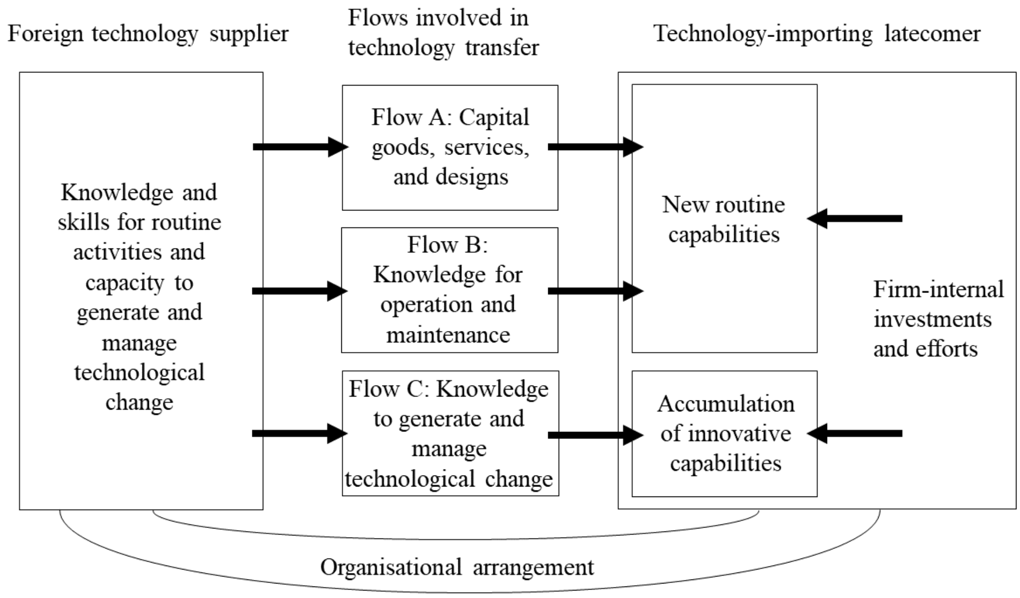

Figure 2: Conceptualisation of flows involved in international technology transfer between a technology supplier and importer. Adapted from Bell (1990, 2012), Ockwell et al. (2010), and Watson et al. (2015).

Having characterised the different types of flows involved in technology transfer processes, it is useful to think about the key factors that determine which flows occur in practice. It should be noted that the discussion in this section focuses exclusively on aspects that relate to the technology supplier and importer and the interactions between them. Other relevant factors at the level of the sector and economy are discussed in Section 2.3.

Starting on the left-hand side of Figure 2, two key factors determining which flows occur in practice are the capability levels of the technology supplier and its ability and willingness to transfer equipment and knowledge to foreign partners. The supplier's decision whether and how to transfer technology has mostly been studied in the context of the internationalisation strategies of multinational companies. For example, the literature based on the transaction cost approach analyses the costs involved in using different channels to transfer technology from one country to another (see Reddy and Zhao [1990] and Saggi [2002] for reviews). It usually pays little attention to what technology transfer implies in terms of capability transfer and learning (as also pointed out by Teece [2014, p.11]). Tsang (1997) is an exception in the literature which focuses on the technology supplier side in that he studies the capability-related implications of a multinational's internationalisation strategy. He argues that different channels require different amounts of investments to enable the transfer of tacit knowledge, on which flow types B and C in Figure 2 rely.

The literature on technological capabilities among latecomer firms mostly adopts the perspective of the technology-receiving firm (on the right-hand side of Figure 2). This literature usually focuses on the various learning mechanisms that firms engage in and combine to build their capability stocks. It primarily explains the types of knowledge and equipment flows that occur in technology transfer processes by referring to the latecomer firm's ability to internalise external knowledge. This is closely related to work by Cohen and Levinthal (1990), who argue that the firm's ability to absorb external knowledge depends on two factors: a broad and deep pre-existing knowledge base and investments in firm-internal efforts to make use of the learning opportunities that arise from having access to external knowledge. Empirical evidence suggests that this is particularly important for accessing advanced knowledge from foreign organisations (e.g., Li, 2011). Together, the pre-existing knowledge base and level of firm-internal efforts determine the novelty and complexity of new technology that firms can adopt.

Another key determinant of the types of flows involved in transfers of technology is the organisational arrangement in which the supplier and recipient find themselves (see bottom of Figure 2). The variety of existing arrangement types is large and includes imports of equipment, licensing agreements, relationships based on FDI, joint ventures, collaborative R&D programmes, foreign acquisitions and mergers, and others. Some have argued that the organisational arrangements which facilitate technology transfers are of secondary importance to the firm-internal efforts that the technology-receiving firm incurs in order to make use of external learning opportunities (Bell and Figueiredo, 2012b, p.75; Dahlman et al., 1987, p.768). However, many authors agree that organisational arrangements have a decisive impact on the amount of learning that takes place at latecomer firms. For instance, while acknowledging that the context of the technology recipient plays an important role, Wei (1995) states that "(…) the content of the technologies transferred varies widely in each of the methods [i.e., organisational arrangements types] used". Along these lines, some authors have recently analysed the kinds of organisational arrangement types that Chinese firms have leveraged to develop local industries for the production of solar PV panels, wind turbines, and electric vehicles (Fu and Zhang, 2011; Lema and Lema, 2016, 2012; Quitzow et al., 2017).

Following these studies, the analysis presented in Chapter 5 uses data on organisational arrangements for technology supply as a source of information about technological learning among latecomer firms. Specifically, information on organisational arrangements is used as an indicator for two aspects. First, organisational arrangements are used as an indicator for the likely amount of international knowledge transfer that takes place between a foreign and a local entity. The idea here is that different types of organisational arrangements imply different levels of cross-border interaction and, thus, are likely to involve different degrees of knowledge sharing. For example, arm's-length trade of production equipment - perhaps linked to services for the training of local workers in the operation and basic maintenance of machinery - is unlikely to allow the latecomer firm to develop capabilities much beyond those needed for routine production activities. Other arrangement types such as joint R&D programmes involve more frequent and intensive face-to-face contact, which is conducive for a lively exchange of knowledge between local and foreign personnel.

Second, organisational arrangements are used as an indicator for the likely level of absorptive capacity that the technology-receiving latecomer firm possesses. As argued previously, the absorptive capacity of a firm - i.e., its pre-existing knowledge base and firm-internal investments in learning - determines its ability to internalise technological knowledge from external sources. By extension, it also influences which kinds of organisational arrangements the firm is able to engage in with foreign organisations (Mowery and Oxley, 1995, p.70).

Review of organisational arrangement types for cross-border learning

This section offers a brief overview of the literature on technology transfer to latecomer firms that focuses on particular types of organisational arrangement. The review emphasises what this literature has to say about knowledge transfers to and absorptive capacity at the technology-receiving firm. The review is limited to a selection of arrangement types that have been found to be particularly relevant for the case of technological upgrading among latecomer firms. In this respect, Hoekman et al. (2005) highlight arrangements based on international trade, inward FDI, international joint ventures, and cross-border technology licensing agreements. Chen (2009) emphasises the role of cross-border learning through informal linkages. Some authors who focus on the diffusion of LCE technologies have also pointed to the importance of international, collaborative R&D programmes (Ockwell et al., 2015).[3]

As mentioned above, the specific nature of an organisational arrangement type for technology supply depends on the context within which it occurs, e.g., the particular

[3] Examples of arrangement types that have not been included here are strategic partnerships and alliances, foreign consultancy services, participation in bi-/multilateral development assistance programmes, outward FDI, and acquisitions of and mergers with foreign firms.

characteristics of the technology supplier and recipient. As such, in practice, one can distinguish between the technology transfer channel type and the kinds of knowledge flows that it facilitates (e.g., see Scott-Kemmis and Chitravas, 2007; Yoruk, 2009). However, rather than emphasising contextual detail, the review presented here focuses on what can be considered a typical case. In other words, the review discusses the different organisational arrangements types in situations where all other factors are assumed to be equal. In doing so, it follows Lema and Lema (2016, 2012) and Quitzow et al. (2017).

The remainder of this section compares arrangement types with respect to what they imply in terms of knowledge transfer to and absorptive capacity at the latecomer firm. This results in a ranking of arrangement types. Rather than viewing this ranking as a definitive hierarchy, it should be seen as an indication for approximately where one can place particular arrangement types on the spectrum of knowledge transfer and absorptive capacity.

Imports

Technology-supplying or using latecomer firms can gain access to foreign technology through imports of capital equipment and intermediary goods. If effectively combined with learning-by-using or other kinds of firm-internal efforts, and if perhaps combined with training programmes by technology suppliers, this type of organisational arrangement can lead to the development of capabilities for routine production activities involving the new equipment. A number of studies have investigated the extent to which technology imports contribute to the development of such capabilities at latecomer firms (e.g., Kumar et al., 1999; Madanmohan et al., 2004). The key issue of interest in these studies is how firms integrate external technology into their production activities.

While firms can develop routine production capabilities based on imports, they are less likely to accumulate innovative capabilities based on this organisational arrangement type. Van Dijk and Bell (2007) present a detailed case study of the Indonesian pulp and paper industry and show that firms have imported foreign machinery without developing significant amounts of capabilities for innovation. In cases where imports do lead to the development of innovation capabilities, this can be based on reverse-engineering, i.e. activities where local firms scrutinise imported products and production equipment with the goal to learn about their designs and to change or imitate them (Chen, 2009, p.529). However, this relies on the availability of high levels of absorptive capacity.

It should be noted that imports do not necessarily involve the transfer of technological artefacts but can also be based on imports of design and engineering services. To my knowledge, imports of services are less commonly studied with regards to their impact on the formation of local technological capabilities in low and middle-income countries.

Inward FDI

Inward FDI is an important organisational arrangement type through which capabilities can be transferred into a country (Dunning, 1994).[4] The focus here is on inward foreign direct investment where a foreign-based, tech-oriented multinational invests into a local subsidiary that it owns fully or partially.[5]

In principle, subsidiaries of foreign multinationals have easier access to advanced technological knowledge than local companies due to their connections to the networks and resources of their parent company. As such, both the transfer of capabilities required for routine production activities and for the generation and management of technological change should be easier to achieve in FDI constellations than in organisational arrangements based on imports. Similarly, one would expect that local subsidiaries have access to resources to build their absorptive capacity given that the technology-supplying parent company has a strong interest in an effective transfer. Hence, it is reasonable to assume that, all other things being equal, FDI-based arrangements involve more capability transfers and higher levels of local absorptive capacity than organisational arrangements based on imports.

However, it should be noted that the link between foreign ownership of a subsidiary and the development of technological capabilities at that subsidiary is not straight-forward. For example, Lall (1993, p.103) argues that multinationals sometimes choose to only transfer the outcomes of their R&D activities to subsidiaries as opposed to the capabilities required to perform R&D locally. This view seems to imply a

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[4] It should be noted that this research is not concerned with the often studied effects that FDI has on knowledge spillovers to other companies in the local economy. Keller (2010) and Saggi (2002) review research on this topic.

[5] Other types of FDI include equity-based investments by foreign institutional investors which themselves are not involved in the development and supply of technology. While such investments can include transfers of management capabilities (which can also include capabilities for technology management), these are not considered here.

technologically passive role of subsidiaries in which they merely adopt the technological assets that originate from the foreign corporate headquarters. On the other hand, empirical studies on Brazil and Argentina show that subsidiaries sometimes also take on active roles in technology development (Marin and Bell, 2006; Marin and Costa, 2009). However, Bell and Figueiredo (2012b, p.85) argue that this appears to be the case at a relatively small share of subsidiaries. Whether or not innovative subsidiaries are autonomous with regards to their innovative activities and strategy is a different question, which, to my knowledge, has not received any explicit attention in literature (see also Marin and Bell [2006, p.17]).

International joint ventures

Joint ventures are a special form of FDI in which a foreign-based multinational engages in a partnership with a local firm. This type of organisational arrangement has been studied in some detail in the Chinese context, where it has frequently been used as part of a strategy to gain access to advanced technological knowledge in exchange for granting foreign companies access to the country's large and rapidly growing domestic market (Dunne, 2011; Li and Cantwell, 2010; Nam, 2011). In principle, joint ventures have the potential to contribute to the development of technological capabilities at the latecomer firm as they are based on cooperation agreements with foreign companies in which both partners agree to exchange their mutually complementary assets. This likely involves intensive knowledge-sharing.

As with any type of organisational arrangement, the extent to which latecomers can learn from joint ventures depends on their ability to internalise the knowledge that becomes available through the partnership. Nam (2011) argues that while joint ventures usually do lead to the realisation of the contractually agreed upon production activities, the development of innovative capabilities at latecomer firms is less certain. Partnerships in which latecomers have substantially lower levels of capabilities than foreign partners can easily lead to situations where the latter control and aim to limit the amount of knowledge flows that take place. This is closely related to Lane's and Lubatkin's (1998) notion of relative absorptive capacity.[6]

[6] Lane and Lubatkin (1998) build on Cohen's and Levinthal's (1990) work and argue that a firm's ability to effectively absorb external knowledge depends on the absence of substantial differences between the technology supplier's and its own characteristics. Specifically, they highlight differences in the depth and quality of their respective knowledge bases, their organisational structures, and their institutional logics.

However, one can assume that, generally speaking, joint ventures are likely to involve some degree of knowledge transfer due to their collaborative nature. Similarly, a local company that is able to engage in a joint venture with a foreign partner likely possesses higher levels of absorptive capacity than one which imports equipment. The absorptive capacities of such firms might even be higher than those of foreign-owned subsidiaries who (in some cases) passively obtain technology from their foreign parent company.

Cross-border licensing

Licensing technology is another important organisational arrangement type through which firms in developing countries gain access to foreign technology (Correa, 2010). A few studies have focused on analysing the effect of cross-country in-licensing on technological learning among latecomers (e.g., Li-Ying et al., 2013; Wang et al., 2015). This organisational arrangement type is based on the purchase of the right to use a particular production process, to produce a product based on certain design specifications, or to distribute a product. Thus, cross-border licensing is similar to equipment imports in that it involves the purchase of embodied R&D from abroad, although the technology here is embodied in detailed design specifications and not in technological equipment. In contrast to equipment imports, licensing involves a more active role by the latecomer firm. Licensing production processes or product designs exposes the technology recipient to the detailed knowledge that underlies the technology. It requires the latecomer to engage creatively with the technology and to apply problem-solving skills in order to implement the process or design. Licensing for distribution involves less technological expertise on the side of the latecomer as distributors rely mainly on capabilities for marketing, installation, commissioning, and maintenance, which can be considered to be part of the routine production category of capabilities.

To make effective use of a license, a firm of course requires absorptive capacity. However, one can consider the fact that a firm holds a license to already be an indication for the presence of relatively high levels of absorptive capacity. Licensing is primarily based on transfers of codified knowledge, which means that the latecomer needs to be able to convert this knowledge into tacit knowledge for it to be of use. As such, licensing implies a higher level of absorptive capacity than joint ventures, as in the latter the foreign partners typically provide extensive training services to local firms (Hobday, 1995, p.1177; Mowery and Oxley, 1995, p.78). Furthermore, the ability to determine technology needs, to locate appropriate technology sources, and to agree on the contractual terms and conditions with the licensor also imply some degree of absorptive capacity.

Informal learning mechanisms

Perhaps with the exception of imports of final goods, the previously listed arrangement types all involve formal contractual agreements that set out the terms and conditions of the relationship between the local and the foreign firm. However, latecomer firms can also learn from foreign sources of knowledge through mechanisms that do not involve such agreements. These are defined here as informal learning mechanisms. The outcomes of engagement in such informal learning mechanisms are often referred to knowledge spillovers.

One such learning mechanism is labour turnover, i.e. the insourcing of tacit knowledge by hiring skilled individuals, e.g., staff who previously worked at competing firms which are based abroad (Luo et al., 2013). Furthermore, international trade shows have been identified as important temporary clusters that are conducive for knowledge exchange and learning with regards to market and technical information among local and foreign firms (Bathelt and Schuldt, 2010; Maskell et al., 2006). Informal learning about foreign technological systems can also stem from observation, e.g., during site visits or the operation and/or maintenance of technological systems that were developed by foreign-based organisations.

Early scholars of technological catch-up in low and middle-income countries argue that, while difficult to assess quantitatively, the importance of informal learning mechanisms for the development of technological capabilities at latecomer firms is likely to be high (Radosevic, 1999, p.147-148; Westphal et al., 1985, p.199). More recently, a small number of studies have tried to assess the relative importance of informal and formal learning and conclude that the former are key for latecomers (Chen, 2009; Egbetokun, 2015; Kesidou and Romijn, 2008).

Due to the breadth of learning mechanisms that can be included in an informal organisational arrangement category, it is challenging to make any general statements about what precisely this category implies in terms of knowledge transfer and absorptive capacity. For example, hiring foreign-trained experts involves high levels of knowledge transfer while it probably requires comparatively little absorptive capacity. On the other hand, reverse engineering requires very high absorptive capacity. In any case, learning based on informal mechanisms requires a high degree of autonomy by the local firm and has the potential to contribute to high knowledge transfer. Therefore, for the purposes of this study, the informal organisational arrangement type is considered to be approximately on par with the licensing category with respect to the amount of knowledge transfer and absorptive capacity that it implies.

International R&D collaborations

International R&D collaborations are another organisational arrangement type that allows latecomer firms to access advanced foreign knowledge. This can involve a variety of foreign organisation types, including private sector companies, universities, or public research laboratories. While the scope of capability transfers depends on the nature of any particular programme, R&D collaborations are typically associated with intensive interaction between foreign and local experts. The goal of such programmes is usually to combine mutually complementary knowledge assets and equipment to develop new technology. By collaborating with advanced foreign organisations, latecomer firms thus stand to benefit substantially in terms of increasing their capability stocks.

Again, the ability to benefit from these kinds of interactions depends on the latecomer's absorptive capacity. However, foreign organisations looking for local research collaborators are unlikely to engage with firms that do not possess a minimum standard of the capacity required to absorb new knowledge. In cases where the local firm initiates the collaboration, its ability to identify suitable foreign partners and to convince them to engage in a joint R&D programme already suggests a relatively high level of absorptive capacity. In cases where a latecomer firm manages to accumulate sufficient capabilities to outsource its R&D activities to other countries, the firm exhibits very high levels of absorptive capacities (Lema and Lema, 2012).

To my knowledge, there is no comprehensive study that has examined the role of international R&D collaborations for the development of technological capabilities at latecomer firms. There are only a number of studies that focus on the role of universities and public research institutes in economic catch-up in general, including their role in offering local firms linkages to foreign sources of technological knowledge (Chaves et al., 2016; Mathews and Hu, 2007; Mazzoleni and Nelson, 2007).

Summary of review of organisational arrangement types

Section 2.2.1 has outlined a conceptual framework for the analysis of technological learning from foreign sources of knowledge. This is based on a differentiation of channels for knowledge flows between technology suppliers and recipients. These channels are referred to here as organisational arrangements for technology transfer. The section has also reviewed the literature focusing on latecomer capability accumulation in particular kinds of organisational arrangements. Even though the evidence base for the different arrangement types is varied, the section has illustrated that they likely imply different levels of knowledge transfers to and absorptive capacity at the latecomer firms participating in them. Table 4 below presents a summary of this review. It ranks the discussed arrangement types based on what they imply in terms of knowledge transfer and absorptive capacity. As argued above, this ranking should be seen as an indication for *approximately* where the different arrangements are to be located on the spectrum of knowledge transfer and absorptive capacity in an other-things-equal context. The issue of organisational arrangements for technological learning based on foreign sources of knowledge will be the focus of Chapter 5 of this thesis.

Likely level of (i) knowledge transfer to and (ii) absorptive capacity at the latecomer firm	**Organisational arrangement type**
Low	Imports of equipment and services
↕	Inward FDI
	International joint ventures
	Cross-border licensing
	Informal learning mechanisms
High	International R&D collaborations

Table 4: *Ranking* of organisational arrangement types based on *implied knowledge* transfer and absorptive capacity at latecomer firms. Adapted from Lema and Lema (2016, 2012).

2.2.2. Co-evolution of technological capabilities and learning mechanisms

Based on the general introduction of technological capability and learning mechanism concepts in Section 2.1 and the beginning of Section 2.2, this section briefly reviews the literature on the ways in which learning mechanisms change as firms develop increasingly sophisticated levels of technological capabilities. This issue will be dealt with in detail in the analysis presented in Chapter 6.

As previously mentioned, learning mechanisms are a key determinant of the levels of technological capabilities that firms manage to accumulate. As Bell and Figueiredo (2012b, p.67) put it:

> *"The most proximate variables that contribute to explaining variation in the rate, depth, and continuity of innovative capability accumulation are concerned with the specific efforts firms make to create those capabilities – i.e. they are about the intensity, persistence, and effectiveness with which firms specifically manage and invest in acquiring and creating human resources, knowledge bases, and organisational capabilities they need to conceive and implement innovation. We refer to that investment as 'learning' (...)."*

Conversely, the levels of capabilities that firms accumulate likely also influence the kinds of knowledge sources that they can leverage for learning purposes. As firms deepen their capability stocks, the nature of the learning mechanisms through which they acquire new knowledge likely changes. This stems from the fact that higher levels of capabilities allow firms to become better at determining what further knowledge they need to acquire, where to access this knowledge, and how they can effectively acquire and incorporate the new knowledge into their existing knowledge stocks. In Cohen's and Levinthal's (1990) words, as firms develop higher level capabilities, they increase their absorptive capacity. Referring to learning based on firm-external sources of knowledge, Cohen and Levinthal argue that a firm's pre-existing knowledge base and its firm-internal learning efforts determine its ability to make use of available new knowledge. Kim (1998) develops this idea further and offers a model for the integration of firm-external and internal learning mechanisms (see Figure 3). He distinguishes between technology acquisition from external sources, firm-internal absorption and integration of this technology, creative engagement with the technology, and preparation of the firm's knowledge base for further acquisitions of external knowledge. Together, these steps allow for the integration of increasingly more novel and complex kinds of external knowledge into the firm.

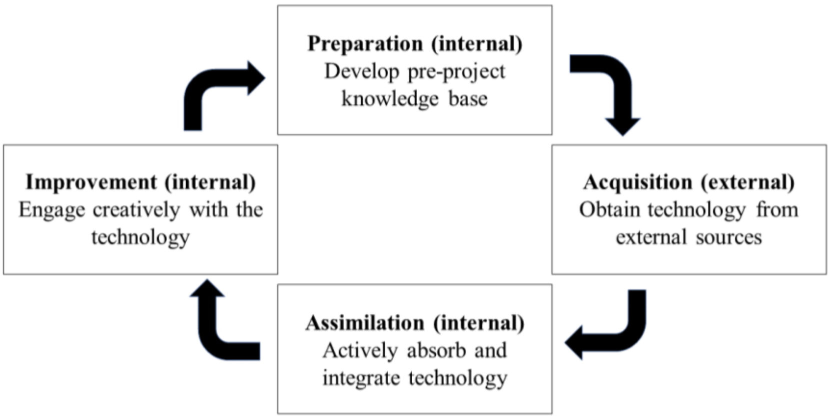

Figure 3: Model for the integration of internal and external firm-level learning mechanisms. Adapted from Kim (1998).

Hence, there appears to be a mutually reinforcing relationship between capability stocks and types of learning mechanisms; while learning mechanisms allow the firm to augment its capability stocks, higher-level capabilities - in combination with appropriate firm-internal learning efforts - enable the firm to engage in more knowledge-intensive mechanisms for knowledge acquisition. Interestingly, there seems to be very little research on this seemingly bi-directional relationship. With respect to this gap in the literature, Bell and Figueiredo, (2012b, p.69) state that:

> *"We know little about the relative importance of different learning mechanisms and even less about whether and how this varies as firms deepen their innovative capabilities. Without this understanding, the field lacks even a rudimentary basis for offering insights about the practicalities of managing learning in latecomer firms (...)."*

Most empirical studies on latecomer capabilities focus on the effects that learning mechanisms have on the accumulation of capability stocks (see Bell and Figueiredo [2012b] for a review). Only few studies specifically focus on the issue of concomitant changes in capabilities and learning mechanisms. While case studies offer scattered insights (e.g., Dantas and Bell, 2011; Figueiredo, 2003; Hansen and Ockwell, 2014; Yoruk, 2011), few studies address the issue explicitly and systematically. To my knowledge, there are only two studies that do this.

Figueiredo et al. (2013) examine how the frequency and types of learning mechanisms used by firms in the Brazilian natural resource-processing industry change as firms build higher levels of innovative capabilities. Their study presents two core findings. First, it shows that those firms which over time combine firm-internal and external learning mechanisms with increased intensity and variety have achieved the highest levels of capabilities. Furthermore, Figueiredo et al. (2013, p.38) state that firms which have achieved the highest capability levels over time have engaged in "*some* deliberate combinations of external and internal learning mechanisms" (emphasis added). Unfortunately, the paper provides little information about precisely what combinations of learning mechanisms are most relevant. Although their analysis is based on an impressive amount of data about the history of the investigated firms, there are some problems with the approach. Firstly, the study does not distinguish between external-domestic and external-foreign learning mechanisms and, as such, is unable to offer insights into how the relative importance of these shifts as firms develop deeper levels of capabilities. Secondly, the analysis focuses on differences in the learning mechanisms used across two long time periods (1950-1989 and 1990-2010). Thus, the paper only provides relatively coarse insights about changes in learning mechanisms as capability levels increase.

Hansen and Lema (2019) examine the co-evolution of capabilities and learning mechanisms in two industries for the supply of LCE technologies: wind turbines in China and biomass boilers in Malaysia. This paper contains a more fine-grained analysis with regards to the kinds of learning mechanisms and the time-scales over which they were used. While results are presented at the level of the sector and not at the level of individual firms, this study nevertheless presents detailed insights into the relationship between learning mechanisms and capability levels. On the one hand, this includes insights about the relative importance of firm-internal, external-domestic, and external-foreign sources of learning at different stages on the capability trajectory. In this regard, Hansen and Lema find that the latter have been particularly important for firms which managed to transition from routine production to innovation capabilities. Furthermore, Hansen's and Lema's comparative analysis offers insights into changes within these learning mechanism categories as firms increasingly deepen their capability stocks. Table 5 below presents a stylised summary of their core results in this regard. Given that there appears to be only a single study that provides such insights at a great level of detail, there is a clear need for more research on this topic.

Source of knowledge	Low capability levels	High capability levels
Firm-internal	- Trial-and-error - Gradual experimentation	- R&D in formalised in-house units
External-domestic	- Imitating local competitors	- Linkages to local universities and research institutes - Formalised user-producer cooperation
External-foreign	- Spillovers from foreign component suppliers - Licensing contracts - Joint ventures	- Cross-border collaborative R&D

Table 5: Summary of Hansen's and Lema's (2019) results regarding learning mechanisms observed at different stages in the technological capability accumulation process.

2.3. Other factors affecting firm capability accumulation

So far, Section 2.2 of this chapter has highlighted learning mechanisms as a key factor that helps to explain how latecomers develop their technological capabilities. Without aiming to be exhaustive, the present section briefly reviews other factors at the level of the firm, the sector, and the economy that directly or indirectly affect latecomer learning. To reduce the complexity of the analysis, these are not elaborated on in much detail in Chapters 5 and 6 of this thesis. Chapter 4 will revisit some of these factors when introducing the case of biogas technology and the Thai biogas sector.

Multiple factors at the level of the firm can affect technological learning. The most commonly mentioned ones are the age and the size of the firm. However, as Bell and Figueiredo (2012b, p.84) point out, these are unlikely to be key explanatory variables in their own right. Instead, they are more likely to be related to other mediating factors (e.g., experience). Another relevant variable is the ownership of the firm, particularly with regards to differences in technological learning between locally owned firms and local subsidiaries of foreign-based multinationals. A related and important aspect is whether and how firms participate in global value chains. Among other things, research on this topic has focused on technological upgrading under different kinds of power relationships between sellers and buyers (Gereffi et al., 2005; Humphrey and Schmitz, 2001). Other potentially relevant variables concern the market orientation and specialisation of the firm as well as differences in management and leadership (Bell and Figueiredo, 2012b). As mentioned above, the present thesis does not aim to establish exactly how these factors relate to the technological learning experiences of the firms analysed here. However, whenever relevant, important firm characteristics will be highlighted.

There are also some differences across sectors which influence technological learning at firms. A variety of analytical frameworks have been developed based on observable regularities in routine production and innovation activities. These include approaches based on technological regimes (Dosi, 1988; Malerba and Orsenigo, 1993; Nelson and Winter, 1982, 1977), Schumpeter Mark I&II (Breschi et al., 2000; Malerba and Orsenigo, 1996, 1995; Van Dijk, 2000), sectoral systems of innovation (Malerba, 2002), and the Pavitt taxonomy (Marsili and Verspagen, 2002; Pavitt, 1984). These frameworks focus on sectoral differences in some or all of the following dimensions: knowledge bases and learning mechanisms; basic technologies, demand structures, production/innovation inputs, and key linkages; types and structures of interactions between firms and other organisations; formal and informal institutions; and processes of variety and of selection (Malerba, 2002). While the present thesis does not extensively draw on any of these frameworks, it will occasionally highlight some of the insights they provide where useful.

Finally, there is a variety of factors at the level of the economy that affect firm learning. For example, Lall (1992) argues that economy-wide incentives and institutions affect whether firms invest in their in-house capabilities for routine production activities and innovation. With regards to economy-wide incentives, he highlights the importance of a stable political and economic environment. He also emphasises domestic and foreign competition, for instance, relating to the size of the local market, the diversification of demand, or the openness of the economy. Lall also mentions incentives from factor markets, which include the availability of financial institutions and markets and the presence of efficient labour markets. With respect to institutions, he highlights the importance of legal frameworks to support industrial activity by defining and enforcing the right to private property, including the protection of intellectual property. Institutions also include industrial associations that provide support services and facilitate linkages among different actors in the economy. Finally, Lall mentions institutions for training and the more basic research that firms are unwilling to invest in. As explained above, the role that these factors have played in the case of the Thai biogas industry will not be elaborated on in detail. Instead, the most important factors are summarised in Chapter 4 and will be highlighted in the analysis (Chapter 5 and 6) whenever relevant.

2.4. Reviewing the literature on latecomer learning for LCE technology

Up until this point, Chapter 2 has introduced the general analytical framework that the present thesis is based on. This included an introduction to the concepts of technological capabilities (Section 2.1) and mechanisms for technological learning (Section 2.2).

Section 2.3 discussed other factors at the level of the firm, sector, and economy which affect the technological learning experiences of firms.

Given that this thesis focuses on the diffusion of LCE technologies in low and middle-income countries, this section reviews the latecomer capability literature which focuses specifically on relevant technologies. Specifically, it focuses on the ways in which the concepts summarised in previous sections of the present chapter have been considered in this literature. Section 2.4.1 reviews the case study evidence focusing on the accumulation of capabilities for LCE technologies among latecomer firms. In light of how sectoral and national circumstances affect technological learning (see Section 2.3), this review pays particular attention to the national and technological contexts which this literature has predominantly focused on. Next, Section 2.4.2 reviews studies which have assessed international technology transfer to latecomer firms. The focus here is on whether and how the different approaches consider the elements of the conceptual framework on latecomer capabilities described above and, thus, to what extent they provide insights about the transfer of knowledge for the development of local capabilities.

2.4.1. Case studies

Table 6 provides an overview of the case study literature on technological capabilities and learning among LCE technology-supplying latecomer firms. It only includes studies that provide detailed qualitative insights - based on interviews and other sources of data - into the capability accumulation processes at these firms. A look at the second column of the table suggests that most of these studies focus on a subgroup of large and rapidly industrialising countries. This concerns China and India in particular, but also Brazil and South Africa. This is understandable considering that these countries host some of today's internationally leading LCE technology-supplying companies. Only a handful of studies have focused on countries that are not part of this group of countries, including Chile, Iran, Kenya, Malaysia, and Tanzania.

Authors	Country	Technology	Primary data source
Awate et al. (2015)	India	Wind turbines	Interviews, patents
Baker and Sovacool (2017)	South Africa	Solar PV panels, wind turbines	Interviews
Byrne (2011)	Kenya, Tanzania	Solar PV panels	Interviews, document analysis
de la Tour et al. (2011)	China	Solar PV panels	Interviews, patents
Figueiredo (2017)	Brazil	Sugarcane ethanol production	Interviews, company records
Fu and Zhang (2011)	China, India	Solar PV panels	Company resources, academic/grey literature, press news
Gallagher and Zhang (2013), Zhang and Gallagher (2016)	China	Solar PV panels	Interviews, academic/grey literature
Gallagher (2014)	China	Advanced batteries, gas turbines, solar PV panels, coal gasification	Interviews
Hansen and Ockwell (2014)	Malaysia	Biomass power equipment	Interviews
Hansen et al. (2016)	China	Biomass power equipment	Interviews
Hansen and Lema (2019)	China, Malaysia	Biomass power equipment, wind turbines	Interviews
Haum (2012)	India	Solar PV panels	Interviews, document analysis
Hayashi (2018)	India	Wind turbines	Interviews
Kiamehr (2017), Kiamehr et al. (2014)	Iran	Hydropower plants	Interviews
Kristinsson and Rao (2008)	India	Wind turbines	Academic/grey literature
Lema and Lema (2012)	China, India	Electric and hybrid vehicles, solar PV panels, wind turbines	Academic/grey literature, company resources
Lema et al. (2018)	Kenya	Solar PV panels, wind turbines	Various reports and databases
Lewis (2011, 2007)	China, India	Wind turbines	Interviews, other (N/A)
Luo et al. (2013)	China	Solar PV panels	Patents, biographical information of corporate leaders
Marigo et al. (2010)	China	Solar PV panels	Interviews and survey
Mizuno (2007)	India	Wind turbines	Interviews, various quantitative indicators
Ockwell et al. (2008)	India	Hybrid vehicles, coal gasification equipment	Interviews
Pueyo et al. (2011)	Chile	Wind turbine components	Interviews, company resources, interviews
Quitzow et al. (2017)	China	Solar PV panels, wind turbines	Interviews, academic/grey literature
Shen et al. (2016)	China	Electric vehicles	Interviews, company resources
Watson et al. (2015, 2011)	China	Energy efficiency in cement production, efficient coal-fired power generation, electric vehicles, offshore wind	Interviews, academic/grey literature

Table 6: Summary of qualitative case studies on firm-level capability accumulation for LCE technologies in developing countries.

A focus on the subset of large and rapidly industrialising countries is potentially problematic. The economy-wide incentives and institutions that affect firm-level learning (see Section 2.3) in these countries are likely to differ from those found in the larger and more rapidly industrialising countries. For example, this concerns the size of local demand, which affects both the incentives that firms face for investing in their capability stocks and the bargaining power that they have in negotiations with foreign firms regarding knowledge exchange in return for market access (Pueyo, 2013). Furthermore, the existing local industrial structures in these countries might be less diversified, thus, potentially reducing opportunities to build new industries based on capabilities that already exist in the country in similar or complementary industries. A thorough review of the elements of the enabling environments which affect latecomer learning and which differ between larger and smaller developing countries is beyond the scope of this thesis. However, given the differences highlighted above alone, it appears unlikely that smaller developing countries would be able to replicate the successes of the group of large and rapidly industrialising countries (Pueyo, 2013). Therefore, it is interesting and relevant to study the technological learning experiences of latecomer firms in the context of smaller developing countries.

The third column of the table suggests that this literature also appears to be limited with regards to its technological scope. Most of the existing literatures focuses on capabilities for the supply of solar PV panels and wind turbines and, to a lesser degree, hybrid and electric vehicles including advanced batteries. This is understandable given the remarkable development that these sectors have experienced in some of the rapidly industrialising countries of the Global South. However, the focus on this subset of technologies is also problematic because it only includes technologies that are comparatively modular in nature, that involve a high degree of standardisation, and that are produced in relatively large quantities (e.g., see Huenteler et al., 2016). For example, in addition to nationally specific conditions, these factors were found to be important for the rapid and initially export-led growth of the Chinese solar PV industry (e.g., de la Tour et al., 2011; Zhang and Gallagher, 2016). Only few studies investigate cases of catch-up for complex, project-based, plant-type technologies. This only includes studies on facilities for the production of sugarcane ethanol in Brazil (Figueiredo, 2017), biomass power equipment in Malaysia (Hansen and Ockwell, 2014) and China (Hansen et al., 2016), and hydropower plants in Iran (Kiamehr, 2017; Kiamehr et al., 2014). These types of technologies are deployed in much smaller quantities and require substantial adaptation to local contexts. They likely require different sets of capabilities than the more commonly studied group of technologies (e.g., see Binz et al., 2017; Malerba and Nelson, 2011; Schmidt and Huenteler, 2016). Thus, a detailed study of latecomer learning for biogas plants can provide new insights about processes of technological learning in such industries.

2.4.2. Studies focusing on learning based on foreign sources of knowledge

This section reviews the literature on international transfer of LCE technologies to firms in low and middle-income countries with a focus on whether and how it takes into consideration the concepts of technological capabilities and learning described in this Chapter. As previously discussed, international technology transfer offers latecomer firms the opportunity to access advanced technological knowledge for the development of their capabilities. The importance of international LCE technology transfer is widely acknowledged and has received much scholarly attention (e.g., Kirchherr and Urban, 2018; Lema and Lema, 2012; Ockwell and Mallett, 2012; Watson et al., 2015).

The empirical literature that focuses on international flows of LCE technology to latecomer firms in low and middle-income countries can be divided into two camps: in-depth case studies on firm-level capability accumulation and studies based on large-N approaches based on quantitative indicators. The former camp is summarised in Table 6 above. Most of these studies highlight the importance of foreign knowledge as a source for learning. They offer detailed insights about the kinds of organisational arrangement types through which local firms have accessed foreign knowledge. As they typically adopt the perspective of the latecomer firm, the studies offer detailed insights about the ways in which the latecomers integrate external knowledge and how this adds to their capability stocks.

The second camp of literature on flows of LCE technologies to latecomers is based on large-N approaches using quantitative indicators. This includes studies which use data on total inward trade or foreign direct investment (FDI) and estimate the effects that these have on aggregate carbon dioxide emissions or energy intensities at the level of the economy (e.g., Cole and Elliott, 2003; Hubler and Keller, 2010; Managi et al., 2009; Omri and Kahouli, 2014). Others collect data on trade (Glachant et al., 2013; Glachant and Dechezleprêtre, 2017) or FDI volumes (Glachant and Dechezleprêtre, 2017; UNCTAD, 2010) for specific LCE technologies and use this as a measure of technology transfer. All of these studies are limited because they focus on only a single or a limited number of indicators for international technology transfer. Moreover, they are based on relatively coarse scales. As such, they do not provide much useful insight into the dynamics of technological capability formation based on foreign sources of knowledge.

Another set of studies uses patents to construct indicators of technology flows. This includes indicators based on counts of patented international co-inventions (Hascic et al., 2012) and counts of so-called non-resident patent filings, where the home country of the inventor is used as the country of origin of the technology (Dechezleprêtre et al., 2015, 2011; Glachant and Dechezleprêtre, 2017; Hascic and Johnstone, 2011).[7] Using patent-based indicators as measures for innovation and technological diffusion has a number of well-documented limitations (e.g., see Arundel and Kemp, 2009; Hascic and Migotto, 2015). While a thorough discussion of these is beyond the scope of this thesis, it is worth mentioning that patents only capture a narrow aspect of the innovative activities that take place in practice. This is because propensities to patent differ across countries and are likely to be relatively low in countries that have poor intellectual property right enforcement measures in place. Moreover, patents only capture the output of R&D-based activities that result in inventions which meet patentability criteria. They do not capture the multitude of innovative activities that are critical for technological catch-up in latecomer firms, such as minor adaptations undertaken on externally accessed equipment or firm-internally achieved incremental innovation (Ariffin, 2010).

Yet another strand of literature uses statements pertaining to technology flows contained in the publicly available documentation of CDM projects to construct measures of international technology transfers. This includes a large number of studies that has been cited widely in the academic and grey literature (Ambec, 2017; De Coninck et al., 2007; Dechezleprêtre et al., 2009, 2008; Haites et al., 2012, 2006; Marconi, 2011; Murphy et al., 2015; Schmid, 2012; Seres et al., 2009; UNFCCC, 2010; Weitzel et al., 2015; Xie et al., 2013). This approach is limited because it only allows for the development of simplistic measures of technology transfers for individual projects (as also pointed out by Bell [2012, p.23-24]). These are mostly binary - technology transfer vs. no technology transfer - and sometimes distinguish between the poorly defined categories of equipment transfer, knowledge transfer, and equipment and knowledge transfer. Another problem with this approach is that the project developers' statements on technology transfer, which are contained in the project documentation, are not based on any agreed upon definitions.

[7] Dechezleprêtre et al. (2011) argue that non-resident patent filings can be used as a measure of international technology transfer because inventors are likely to only patent inventions in foreign markets if they expect there to be a market for the technology. This is because patents are costly to prepare and because they become published in the local language after they have been filed, which increases the risk of imitation. For these reasons, inventors are unlikely to file patents indiscriminately.

As such, the statements are inconsistent across projects, which raises serious doubts about their suitability as a basis for comparisons of technology transfers. Finally, this approach does not differentiate between transfers that occur for different types of technologies that are installed as part of a single CDM project.

A few studies have used social survey approaches to study how international LCE technology transfers have contributed to the formation of capability stocks at latecomer firms (Doranova et al., 2011; Gandenberger et al., 2016). While these studies can of course not go into the same level of detail about capabilities and learning mechanisms as the case study literature, they have perhaps the greatest potential to provide insights that are generalizable and that take into consideration at least some of the intricacies of the technological capability framework presented in this chapter. Unfortunately, these studies suffer from limitations with regards to their data collection procedures. In particular, they suffer from relatively low response rates and the associated risk of bias.

In conclusion, the existing literature on international transfers of LCE technology falls within one of two camps. On the one hand, there is the case study literature that provides detailed insights into capability formation dynamics among latecomers. While providing rich insights, the case study nature of this literature limits the generalizability of its conclusions. One the other hand, there are the studies that have used a variety of data sources to arrive at more generalizable results, but which either pay little attention to the issue of capability formation among latecomers or suffer from other data-related problems. There are a few exceptions that study both large numbers of firms and account for the capability framework. For example, Doranova, (2010) and Lema and Lema (2016, 2013) adopt the technological capability perspective and combine it with quantitative approaches at the firm and project-level to provide insights into the role of international technology transfer for capability formation among latecomers. In conclusion, there appears to be a need for more research which builds on the latecomer capability framework outlined in Section 2.1 and 2.2 of this chapter and which, at the same time, adopts a methodological approach which offers at least some degree of generalizability. This calls for an approach which provides micro-level insights into technological learning processes for a relatively large number of projects and/or firms. As the following section explains, this is the goal of Chapter 5.

2.5. Research questions

The present chapter has outlined the general analytical framework that the analysis presented in Chapters 5 and 6 are based on. It began by explaining how technological capabilities are defined in this thesis (Section 2.1). Next, it discussed processes of technological learning, which included more focused discussions of issues that will be elaborated upon in Chapters 5 and 6: channels for learning based on foreign sources of knowledge (Section 2.2.1) and the co-evolution of capability stocks and learning mechanisms (Section 2.2.2). Section 2.3 discussed some aspects of the wider context within which technological learning occurs. This involved highlighting some factors at the level of the firm, sector, and economy which can impact technological learning. Given the thesis's focus on LCE technologies, Section 2.4 reviewed studies pertaining to the previously discussed concepts which focus specifically on these kinds of technologies. Building on the conclusions of this literature review, the present section introduces the research questions that this thesis aims to address.

The core issue of interest here is how latecomer firms in developing countries accumulate technological capabilities. As illustrated above, there is a lack of research on firm-level capability accumulation among firms which supply complex, project-based, plant-type LCE technologies. Furthermore, there is a need for more research on technological learning in developing countries that are not part of the group of large and rapidly industrialising countries (China, India, Brazil, South Africa). To address this gap in the literature, this thesis focuses on the case of biogas technology in Thailand. The main research question addressed here is:

> *To what extent and how have Thai firms acquired expertise for the production and development of biogas technology?*

It should be noted that the main issue of interest in answering this question is the effect that learning mechanisms have had on the capability levels and types that firms accumulate in order to be able to engage in routine production and innovation activities (see Figure 4 below). The thesis does not focus extensively on the effect of capability accumulation on the performance of particular kinds of routine and innovative activities. As subsequent chapters will explain in detail, it is sometimes challenging to directly assess capability stocks (knowledge bases, skill sets, experience, organisational systems). Therefore, evidence on the performance of particular routine and innovative activities will sometimes be used as proxies for the capabilities that firms have accumulated. Figure

4 also illustrates that the thesis does not focus on the effect that the accumulation of capabilities has on business performance or on the wider economic, environmental, and social system. Furthermore, to reduce complexity, the thesis does not concern itself in much detail with other factors at the level of the firm, sector, and the economy.

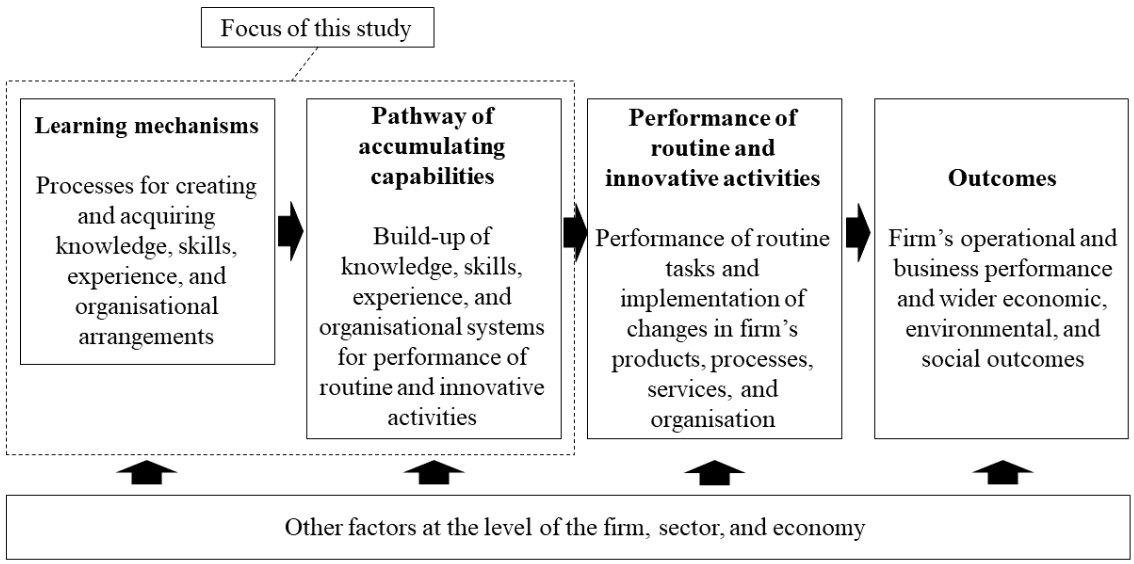

Figure 4: Analytical focus of this thesis. Adapted from Bell and Figueiredo (2012a).

The general research question stated above will be addressed by means of two research projects. These focus in on more specific issues about the ways in which Thai biogas system suppliers have accumulated their technological capabilities.

The first project (presented in Chapter 5) focuses on a subset of learning mechanisms: learning based on foreign sources of knowledge. As discussed above, learning based on foreign sources can provide access to advanced technological knowledge and is often associated with the development of high-level capabilities for routine activities and innovation. This project investigates the kinds of organisational arrangements through which Thai firms have accessed foreign technological expertise. Hence, the question addressed here is:

> *Through which organisational arrangements have Thai firms accessed foreign knowledge for the supply of biogas technology?*

The project also examines differences in the organisational arrangement types that have been used to source different kinds of technology that are part of biogas systems (AD systems and biogas engines/engine-generator sets). This will be explained in detail in Chapter 5. The corresponding additional research question reads:

How do organisational arrangements differ across technological components of biogas systems?

The goal of this project is to produce generalizable results through the study of a large number of projects and firms while at the same time considering elements of the latecomer capability framework outlined in the present chapter. As such, this question also addresses the lack of research that exists in this regard in the literature on international transfers of LCE technologies to developing countries.

The second project (presented in Chapter 6) addresses the issue of how firms have used certain kinds of learning mechanisms to develop their capability stocks. The goal here is to generate insights into the micro-level dynamics involved. The focus is on the particular modes of knowledge acquisition that firms have utilised to develop their capabilities. Given the lack of research on how learning mechanisms change as firms progressively deepen their capability stocks (noted in Section 2.2.2), this issue is also of interest here. The questions addressed in this part of the research are the following:

What types of knowledge and skills have Thai biogas system suppliers acquired through internal and external learning? How have they acquired these? How do learning mechanisms change as latecomers build higher levels of technological capabilities?

3. Research design

This chapter discusses the general research design pursued in the thesis. It does not provide detailed discussions of the operationalisations of key concepts, data sources, sampling strategies, and data analysis methods - these are presented in Chapters 5 and 6. Instead, the focus here is on some of the more general aspects of the research design, including the choice of a multiple-case study design (Section 3.1), the use of a deductive approach mainly based on qualitative data (Section 3.2), and some aspects related to data collection (Section 3.3). Section 3.4 concludes the chapter by briefly summarising its main points.

3.1. The case study design

The Thai biogas industry presents an interesting case for the study of latecomer capabilities for a number of reasons. First of all, Thailand's biogas sector is one of the largest in Southeast Asia and has experienced rapid growth over the past two decades (see Section 4.5). As such, it is interesting to see whether the growth in demand for biogas has been accompanied by the development of a local industry for the supply of biogas systems. Furthermore, focusing on the case of the Thai biogas industry helps address some of the gaps identified in the review of the LCE latecomer literature above. This concerns both the predominant focus of the literature on large and rapidly industrialising countries (in particular China and India) and on a subset of LCE technologies (mostly solar PV panels and wind turbines). As such, focusing on the case of biogas in Thailand has the potential to provide new insights about how the development of latecomer capabilities takes place in different contexts.

As with any research design, the choice for a case study approach focusing on a single country and technology has certain limitations. In particular, the approach pursued here calls into question the generalizability of the study's results (Yin, 2003). However, as opposed to research designs whose results are more generalizable, a case study approach allows for a detailed description of the case at hand (*ibid.*). This seems to be particularly useful in light of the gaps identified in the literature review above. Studying the Thai biogas sector in detail allows for the identification of the potential idiosyncrasies of this case. It also allows for the identification of new facets of firm-level catch-up that are potentially more generally relevant and that research designs which produce more generalizable results tend to overlook due to the relatively higher level of abstraction of the indicators on which they are based. Furthermore, the generalizability of such an in-depth case study can be assessed by comparison to those of other micro-level latecomer learning studies.[8] Here, of course, it is important to keep in mind that contextual differences - at the level of the firm, the sector, or the economy - might impact the key relationship of interest, i.e. the relationship between technological capabilities and learning mechanisms.

Within a given national and technological context, one can further distinguish between case studies that focus on a single firm and those that focus on multiple firms (Gustafsson, 2017; Yin, 2003). Single-case studies are typically explorative and provide information about issues that have not been addressed extensively in the literature. They are usually based on in-depth qualitative information and provide detailed insights which can be used to develop new or modify existing theory (e.g., Gustafsson, 2017). As such, they help to shape the conceptual frameworks that are used to think about the processes studied.

On the other hand, multiple-case studies allow for comparisons across different cases. Of course, such studies cannot go into the same level of detail as studies focusing on single cases, primarily due to the time and resource constraints that the researcher faces (Baxter and Jack, 2008). However, they provide other benefits. For example, they potentially allow controlling for potential biasing factors (related to national, regional, and sectoral contexts) and to single out the relationship between learning mechanisms and capability accumulation more clearly. Furthermore, multiple-case study approaches offer a basis for identifying lessons that are common across multiple cases and which might be valid more generally (Vannoni, 2015). Conversely, multiple-case studies can also provide insights about inter-case heterogeneity - e.g., with respect to the technological catch-up experiences of different firms within a given national and technological context (*ibid.*). As with large-N studies, the validity of the results of multiple-case studies of course depends on a variety of factors, including the number of cases investigated and the sampling strategy pursued.

3.2. A deductive approach based on qualitative data

Explorative studies of single cases are typically based on approaches to research that primarily rely on qualitative information and use an inductive approach to develop new

[8] Generating insights from comparative analysis is common practice in research on public policy (e.g., see Rose, 2005).

or to amend existing theory. On the other hand, large-N studies aiming to produce more generalizable results typically use deductive approaches in which quantitative data is used to test the propositions put forward by existing theory. This corresponds to the common differentiation in the social sciences between the positivist/deductive/quantitative and the interpretivist/inductive/qualitative camps of research. This section argues that the research presented in this thesis does not neatly fit into either of these categories.

As the above literature review has shown, latecomer capabilities and the learning mechanisms used for their accumulation are complex concepts. They are difficult to operationalise in ways that provide meaningful insights at the level of the firm when relying exclusively on quantitative measures. Instead, such analysis requires access to detailed qualitative information about the capability types that firms achieve and the learning mechanisms that they use for this purpose.

In this thesis, such information has been accessed through the documentation of biogas projects and through interviews that were conducted with biogas engineering firms during a research trip to Thailand from May to August 2017. Moreover, a variety of other sources have been used to collect additional data and to triangulate the information from the interviews and project documents. This includes company websites and brochures, news articles, blog entries, industry periodicals, the academic literature, and informal discussions with a variety of stakeholders in the Thai biogas sector held at a renewable energy trade show in Bangkok in June 2017.

In addition, the research is also based on some quantitative data that has been collected to supplement and test the conclusions drawn from the qualitative data. This mostly includes data on the capacity of biogas plants that were developed by the firms studied in this research. This data has been accessed during the interviews, from company materials, and from monitoring reports of biogas projects.

While the data used in this thesis is mostly qualitative, Chapters 5 and 6 follow a mainly deductive approach. The collected data is used to check whether the experiences of firms fit into certain conceptual categories that the theoretical literature has established. For example, this concerns the capability types and levels that firms have achieved and the learning mechanisms that they have engaged in. Hence, the approach used in this thesis mainly uses the collected data to verify or reject the propositions put forward by the theoretical literature. This approach is supported by Yin (2003), who argues that qualitative data can appropriately be used for theory testing when adequate quantitative measures are lacking. However, given the in-depth nature of the data from interviews and project documents, the research remains open to using the resulting insights to amend existing theory whenever considered appropriate.

3.3. A brief note on data collection

This section briefly highlights some general aspects that are relevant for the data collection processes which have been undertaken as part of this study. Chapters 5 and 6 provide more detail about the specific data collection methods that have been used for the empirical analyses.

One important aspect in this regard is the limiting role that language differences have played in the collection of data. As I do not speak Thai, it is possible that I was unable to access some relevant information. This applies both to the data which I retrieved from online resources and the interviews I conducted with stakeholders in the Thai biogas industry. Most interviews were conducted in English. Two were conducted in German. Around half of the interviews were conducted with people of Thai origin. Although all of them spoke English well, there were a few instances where language presented a barrier that prevented me from going into great levels of detail about some issues. As explained in more detail in Chapter 6, a Thai research colleague was present during some of the interviews and provided assistance with interpretation from English to Thai and vice versa.

Given that parts of the data collected for this thesis stem from interviews, I have given due consideration to issues related to ethics and data protection. Prior to conducting the interviews, the ethics of collecting and analysing data from experts in the Thai biogas industry were discussed with the Departmental Director of Ethics of the Bartlett School of Environment, Energy, and Resources at University College London. It was concluded that the potential to inflict harm onto participants in the study was low and that, therefore, no formal application to the UCL Research Ethics Committee was required. Interviewees were contacted with a standard interview request letter (see Appendix 6.6.4 in Chapter 6). The letter highlights that participation in the research was voluntary, that the interviewees could withdraw their consent to participate in the research at any time, and that any information that the participants provided was going to be handled confidentially. The letter also states that the data collected through the interviews was only going to be published in summarised and anonymised form so that neither the names of the firms nor any particular contribution by any of the interviewees can be identified. Lastly, the letter states that any data resulting from the interviews (audio recordings, transcripts, and any other data that could be used to identify the names of the firms included in the study) would be stored safely on password-protected computers and hard drives to which only I have access. I asked the interviewees to acknowledge the contents of the letter and to provide verbal, explicit consent to participate in this study.

3.4. Summary of main points

This chapter discussed some general aspects related to the research approach pursued this thesis. First, it briefly discussed the opportunities (in-depth study of learning dynamics) and caveats (limited generalisability) of an approach that focuses on a single country and technology. Given that the analyses presented in Chapters 5 and 6 are based on multiple-case study designs, the chapter also elaborated on some of the key differences between single and multiple-case studies. It was explained that a multiple-case study approach will be pursued here as it enables a detailed investigation of technological capabilities and learning activities while at the same allowing to generate insights about common trends among and differences between individual firms.

Furthermore, this chapter explained that information about capabilities and learning mechanisms will primarily be obtained through qualitative data collection methods. This is considered necessary given the complexity of these concepts and the difficulty to construct meaningful quantitative indicators which provide micro-level insights. Given that there is a rich tradition of theory on latecomer capabilities, the qualitative data will be combined with a (mostly) deductive approach to test whether the technological learning experiences of Thai biogas engineering firms correspond to the propositions put forward by this literature.

Finally, the chapter discussed some general aspects related to the data collection processes used in this Ph.D. project. This included a brief reflection on language barriers, ethical concerns, and strategies that were pursued to address these issues.

Before moving on the presentation of the two research projects that were conducted as part of this Ph.D. project, Chapter 4 provides some more information about the empirical background.

4. Introduction of case: biogas in Thailand

This section provides an introduction to the empirical context of the research presented in this thesis, which will set the stage for the analytical chapters that follow. It begins by introducing the reader to the basic design of biogas plants and the processes involved at such plants (Section 4.1). It then goes on to provide some information about the demand and supply side of the global market for industrial-scale biogas plants (Section 4.2). The focus then turns to the case country studied in this thesis. A brief overview of the development of the Thai economy (Section 4.3) is followed by an introduction to the country's energy sector (Section 4.4) and a summary of the history of the national biogas sector (Section 4.5).

4.1. Biogas plants for industry

Biogas is a flammable gas consisting of methane (50-75%), carbon dioxide (25-50%), and minor amounts of other components such as water, oxygen, sulphur, and hydrogen sulphide (da Costa Gomez, 2013). It is generated through a sequence of biochemical processes in which microorganisms break down biomass in oxygen-free environments - a process known as AD. The biomass feedstock types typically used for the generation of biogas can be grouped based on their origins and include energy crops (e.g., maize and elephant grass), agricultural wastes (animal manure and slurry and vegetable by-products and residues), industrial wastes (organic wastes from biofuel production, food industries, breweries, etc.) and municipal wastes (source-separated household waste, sewage sludge, the organic portion of municipal solid waste, and food waste) (Al Seadi et al., 2013).

The generation of biogas from organic waste products or purpose-grown crops helps to reduce the amount of greenhouse gases that become emitted during energy generation. It contributes both to the replacement of conventional, fossil-based fuels and the prevention of atmospheric methane emissions stemming from storing organic wastes in open spaces (see Vasco-Correa et al. [2018] for a review of studies estimating the greenhouse gas reduction potentials of different AD system types). The use of biogas systems also provides a number of additional benefits. For instance, they help avoid bad odour from openly stored wastes and reduce the biological and chemical oxygen demand of waste that re-enters the environment. The digestate, i.e., the material remaining after the AD process, can be used as fertilizer.

While the various microorganisms involved in the AD process and the environmental conditions under which they operate are generally understood, the different groups of organisms interact in complex ways with each other and their environment (Achinas et al., 2017; Murphy and Thamsiriroj, 2013). This makes it difficult to control the AD process with precision in industrial applications. In turn, this highlights the importance of design features that create optimal conditions for the microbial activity, that allow system operators to monitor system performance, and that allow operators to intervene in the environmental conditions whenever necessary.

The core of the biogas system is the AD unit where the organic input material becomes transformed into biogas and digestate. The variety of available AD reactor designs is large (e.g., see Mao et al., 2015). Typically, they comprise a substrate feeding system, agitation mechanisms to bring the microbes in contact with the substrate and to prevent sludge settlement at the bottom of the reactor, temperature control measures, and outlets for the generated biogas and digestate (Bachmann, 2013). Box 1 provides an overview of the most common medium to large-scale reactor types in Thailand, including brief descriptions of their key defining characteristics.

Common designs for industrial-scale AD reactors in Thailand and the wider Southeast Asian region

- **Anaerobic Filter Reactor**
  Tank-based reactor including a fixed medium inside to which microorganisms attach in order to prevent washout
- **Continuously Stirred Tank Reactor**
  Tank-based reactor including agitation equipment such as hydraulic or mechanical mixing
- **Modified Covered Lagoon Reactor**
  Covered lagoon involving some form of mixing mechanism such as baffles or bottom-feeding
- **Simple Covered Lagoon Reactor**
  Covered lagoon not involving any mixing mechanisms
- **Upflow Anaerobic Sludge Blanket Reactor**
  Reactor design allowing microorganisms to grow in aggregations to prevent washout despite rapid inflow of substrate through bottom-feeding

Box 1: Common designs for industrial-scale AD reactor units in Thailand and other countries in Southeast Asia. Sources: Rahayu et al. (2015) and data collected for this thesis.

In addition to the reactor unit, biogas plants also include a variety of other technological equipment (see Figure 5). Some plants include substrate pre-treatment processes to make the feedstock suitable for treatment in the digestion unit. This can include screening to remove large or non-biodegradable objects, mixing, pH neutralisation, and/or temperature adjustment (see Bochmann and Montgomery [2013] for a more complete overview of available pre-treatment options). The digestate is stored in a separate location and can subsequently be used as fertiliser due to its nutrient-rich composition. The generated biogas is either stored in the digester itself or in a separate container.

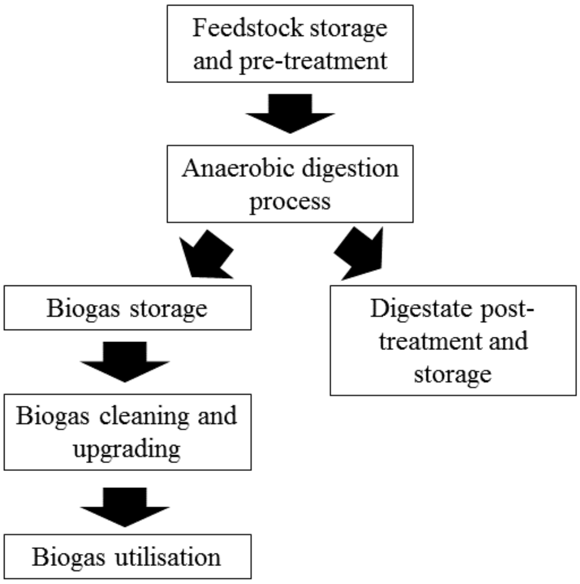

Figure 5: Typical processes involved at industrial biogas plants. Based on Rahayu et al. (2015).

The generated biogas can be used to heat boilers and/or to drive gas engines that are linked to generators for electricity production. It can also be used as fuel for gas vehicles or can be injected into gas grids. Some projects primarily invest in AD systems to prevent atmospheric methane emissions from waste storage in open spaces and use flares to burn off the biogas that they generate. For instance, some of the CDM projects analysed as part of the present thesis use this method to generate Carbon Emission Reduction credits by preventing atmospheric methane emissions from storing wastes in open lagoons.

Depending on the utilisation of the biogas, some plants also include biogas cleaning and upgrading equipment to condition the biogas for use in subsequent energy conversion equipment. This can involve dehumidification, compression, and/or hydrogen sulphide removal in scrubbers (Beil and Beyrich, 2013; Petersson, 2013).

Monitoring and control devices are used throughout all of these processes to ensure that temperature, pH values, liquid and gas flows, and gas pressures stay within ranges that allow for a stable and safe operation of the plant (Holm-Nielsen and Oleskowicz-Popiel, 2013).

The optimal design of a biogas plant is primarily determined by the composition and amount of feedstock that the plant will treat (Bachmann, 2013). While in principle any biodegradable matter can be used, the technical feasibilities and economic potentials of substrates differ, depending on the amount of feedstock available, its dry matter content, degradation rate, contaminant and inhibition risk, etc. (*ibid.*). Aside from the characteristics of inputs and the utilisation of outputs, the choice for a plant design also depends on a number of practical considerations, for example, the availability of space, funds, and infrastructure. In general, the goal of designing a plant is to make optimal use of the resources available for a particular project (Bachmann, 2013). The choice of equipment, dimensions, and layout needs to be tailored to the context of each plant, which means that no two biogas projects are exactly alike.

4.2. The demand for and supply of biogas plants

The global demand for biogas has increased rapidly in recent years, from approximately 300 PJ in 2000 to just about 1300 PJ in 2014 (see Figure 6). While Europe continues to host most of the world's biogas production, Asia has experienced the most rapid growth in recent years, with a nearly eight-fold increase from 2000 to 2014. The increase of biogas production in the Americas, which has mostly taken place in Canada and the USA, has been less rapid. Africa and Oceania host only a minimal fraction of global production. China, Germany, and the USA are the countries with the highest production figures (Figure 7). After China, Thailand has the largest biogas market in the group of low and middle-income countries. Its production levels even surpasses those of some economies in Europe which are generally considered to be advanced markets for biogas, such as the Czech Republic and France (Biogas Action, 2018).

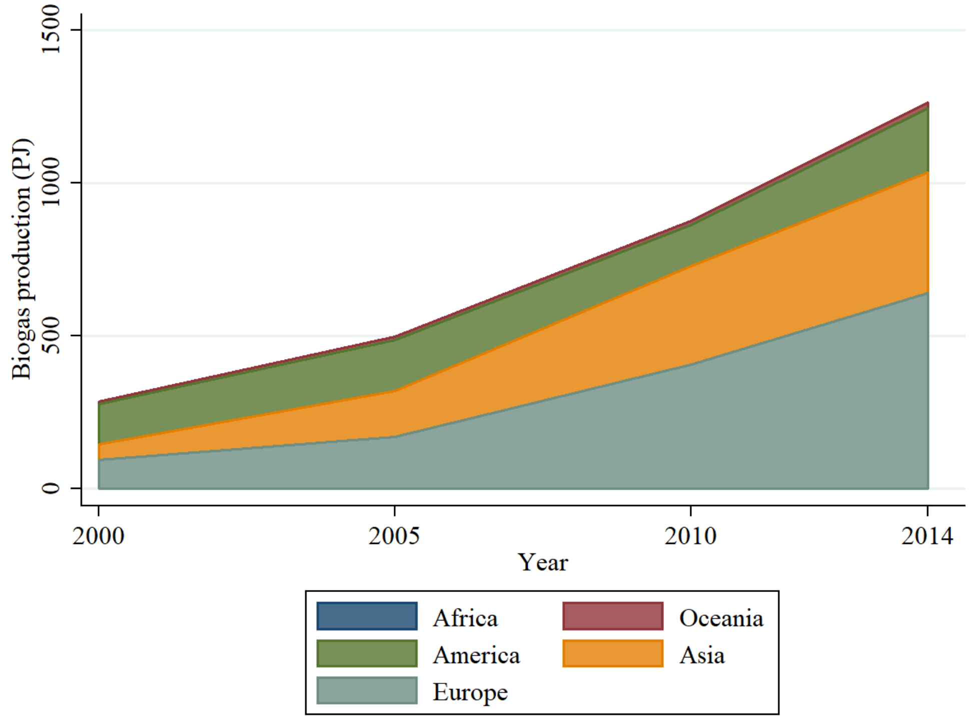

Figure 6: Biogas production per world region, 2000-2014. Source: World Bioenergy Association (2017). Conversion from biogas production in Nm^3 to PJ assuming average energy density factor of 21.6 MJ/NM^3 following World Bioenergy Association (2017).

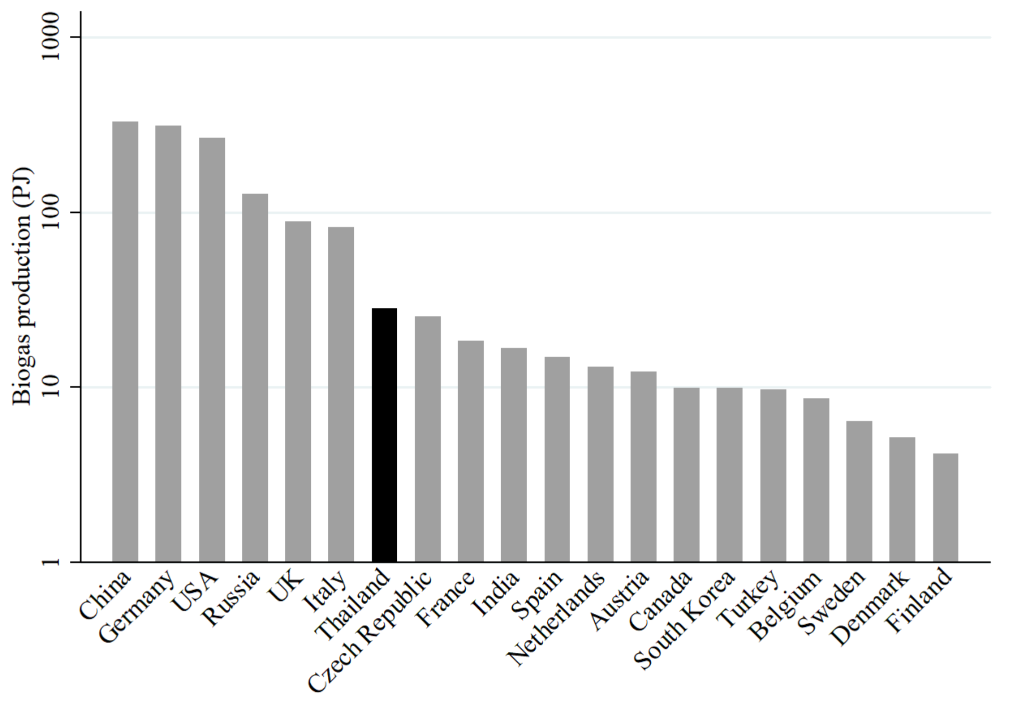

Figure 7: Biogas production of the 20 highest-producing countries. Logarithmic scale. The figure is based on 2013 or 2014 data depending on availability. Source: World Energy Council (2016).

Aside from producing different amounts of biogas, countries also differ in the ways in which they produce and use biogas. Such differences largely stem from feedstock availability, access to appropriate technology, and the existence of governmental regulations and incentives in energy, agriculture, and waste management. For example, Denmark is the world leader in terms of centralised plants that treat waste from several sources, Germany is at the forefront of farm-based systems, and the UK and USA most commonly use AD systems to treat waste at landfill sites or sewage treatment plants (International Gas Union, 2015; Vasco-Correa et al., 2018). An example of a difference in the way biogas is utilised is Sweden's focus on using biogas for transportation and Germany's focus on plants that are connected to heat and electricity networks (International Gas Union, 2015). Most low and middle-income economies have historically focused on household-scale biogas systems to generate fuel for cooking and lighting (Vasco-Correa et al., 2018). These are mostly based on low-cost solutions involving relatively simple designs that, among other things, do not include any measures for temperature control or substrate agitation inside the reactor. However, some developing countries have recently introduced larger biogas systems for the treatment of wastes from their agricultural and agro-processing industries (*ibid.*).

To my knowledge, there is no comprehensive and freely available report on the supply side of the global market for industry-scale biogas systems. A recent report by the Association of Southeast Asian Nations (2014) on biomass energy technologies suggests that Thailand - together with Singapore and Malaysia - hosts the most advanced industries for the supply of AD plants and biogas cleaning equipment in Southeast Asia. With regards to the global market, the research conducted for this thesis indicates that it is highly fragmented. Biogas engineering companies differ widely in terms of their size, orientation towards local and/or global markets, and the types and variety of substrates and reactor designs that they work with. In general, one can distinguish between three types of companies. Firstly, there is a group of large multinational companies with extensive networks of subsidiaries which have developed biogas plants for many different applications in various parts of the world. This includes companies like ADI Systems (based in Canada), Biothane (owned by Veolia, France), Global Water Engineering (Belgium), and Paques (Netherlands). These are mostly based in high-income countries. Secondly, there is a larger number of medium-sized companies that operate in particular countries or regions. These companies are typically specialised in the provision of particular designs of plants for the treatment of substrates that are common in the country or region in which they operate. Finally, there are many small companies that operate in a single country or province and that offer limited varieties of designs for an even smaller selection of substrates.

The supply of biogas systems involves a variety of organisations. The lead engineering company is the main organisation of interest in this thesis. It provides services in process engineering (choosing technological equipment, dimensions, and layout), mechanical, electrical, and instrument engineering (supplying, installing, and commissioning equipment), and civil engineering (site preparation, soil analysis, etc.) (Rahayu et al., 2015). The lead engineering company typically also sets up the contracts with all other companies involved in the project. This includes technology users, construction companies, specialised consultants, and suppliers of plant components such as tanks, membranes, mixing equipment, pipes and valves, electrical equipment, monitoring devices, etc. After commissioning, the lead engineering company hands over the project to the operation team or, in some cases, operates the project itself.

4.3. Thailand's economy and capacity to innovate

Turning now to the country studied in this thesis, this section provides a general overview of the Thai economy. Thailand is Southeast Asia's second largest economy (after Indonesia) with a total GNI of 388 trillion US dollars in 2016 (World Bank, 2018). It achieved its transition to upper-middle-income status in 2011 (World Bank, 2011a) after decades of sustained high growth, with the exception of the years of the Asian financial crisis and recent years following the 2014 coup d'état (see Figure 8). Since the 1970s, Thailand has pursued an export-focused growth strategy, which has led to substantial inflows of foreign direct investment and a restructuring of the economy away from agriculture and towards manufacturing and services (Asian Development Bank, 2015; Miroux et al., 2015). In 2016, industry made up approximately 36% of the country's economic output while services (including tourism) accounted for 56% (United Nations Conference on Trade and Development, 2018). Although agriculture constitutes only about 8% of economic output, Thailand continues to be a leading exporter of agricultural and agro-based products such as rice, sugar, cassava, and animal-based products (*ibid.*).

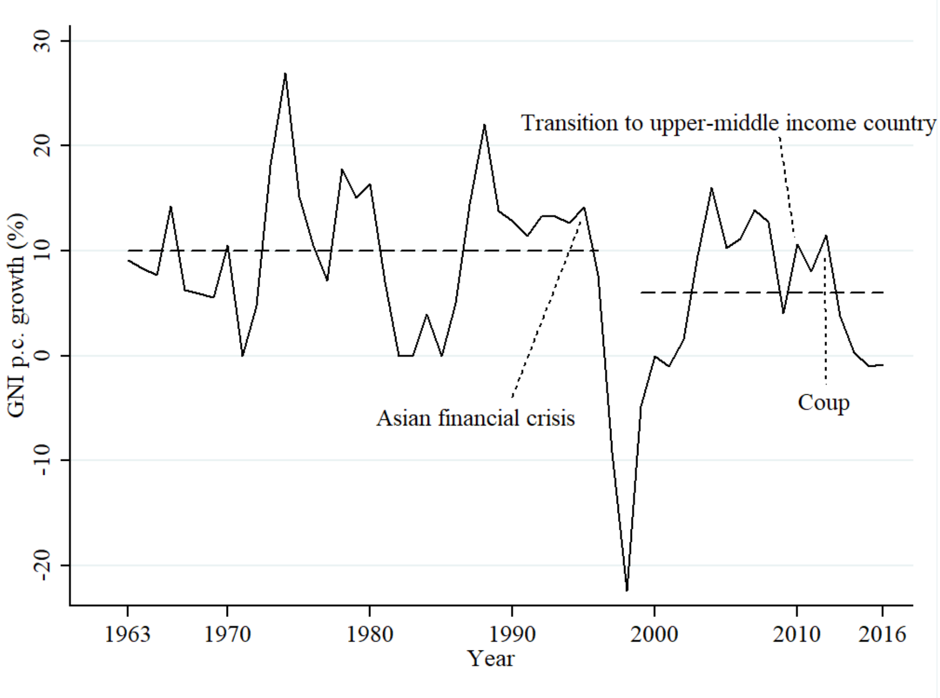

Figure 8: Economic growth in Thailand, 1963-2016. Source: World Bank (2018).

While Thailand has experienced rapid economic development in the past, it is currently at risk of falling into the so-called middle-income trap. On the one hand, rising wages mean that the country is losing previously held competitive advantages for low-skill activities based on low-cost labour to neighbouring countries such as Cambodia, Laos, and Vietnam. On the other hand, Thailand is struggling to develop the technological capabilities required to move to higher value-added activities and to compete with more advanced economies in the region such as Singapore and South Korea. Although foreign-based multinationals have transferred technology to their Thai subsidiaries and partners (particularly in the electronics, automotive, and natural-resource based industries), Miroux et al. (2015) argue that this has only had a limited effect on the development of domestic capabilities in general. This is evident in the fact that, between 1985 and 2005, most of Thailand's economic growth is explained by capital investments and employment reallocation towards manufacturing and services, while productivity gains only explain around one sixth of growth (World Bank, 2011b, cited in Miroux et al. 2015, p.4). The accumulation of local capabilities (or lack thereof) has also been studied at the micro-level in Thailand's electronics (Hobday and Rush, 2007) and automobile industries (Scott-Kemmis and Chitravas, 2007), the country's two largest manufacturing branches.

To overcome these problems, Thailand needs to invest into its capacity to innovate. At present, the country is outperformed in terms of innovation capacity by other countries in the region which are at comparable levels of development (Schwab and Sala-i-Martin, 2017). Data on the comparative performance of inputs and outputs for science, technology, and innovation corroborate this finding (Miroux et al., 2015). While Thailand's weak capacity to innovate likely has many reasons, recent research points to certain problems in the country's innovation system as key determinants. For example, Chaminade et al. (2012) highlight problems in institutions, networks, the local science and technology infrastructure, and support services. Miroux et al. (2015) emphasise the shortage of trained workers with suitable skills and the weak linkages among and between private sector firms, universities, and public research institutes. Furthermore, they argue that the piecemeal and uncoordinated nature of support schemes is unable to incentivise sufficient private sector financing for innovation.

4.4. The Thai energy sector

The combination of per capita income growth and an expanding population has led to a substantial increase in Thailand's demand for energy over recent decades. In 2015, total final energy consumption was at about 2.8 EJ, of which approximately 80% were used in the industrial and transport sectors (International Renewable Energy Agency, 2017). About three-quarters of the total demand is met through the use of fossil-based energy carriers, in particular petroleum products (49%) and natural gas (21%) (*ibid.*). While Thailand possesses fossil energy resources, these are unsuitable for consumption in the domestic market and are expected to deplete within a decade or so if current production rates persist (*ibid.*). As a result, the country relies heavily on imported energy. For example, between 2005 and 2015, Thailand spent an average of 7.4% of its yearly GDP on energy imports, with a peak of 12% in 2008 due to a sharp increase in the price of oil (Energy Policy Planning Office, 2018). Given the increasing demand for energy, an overreliance on fossil fuels, and depleting domestic resources of fossil-based energy carriers, Thailand's dependence on imported fuels is likely going to increase in the future unless drastic measures are taken to generate energy locally and to use energy more efficiently.

The plans of the Thai government to tackle these challenges are formulated in its Integrated Energy Blueprint, which contains five interconnected plans for oil, natural gas, electricity, energy efficiency, and alternative energy sources (International Renewable Energy Agency, 2017). The blueprint's primary goal is to increase energy security, while economic affordability and environmental sustainability are included as secondary objectives. However, a number of other developments indicate that the Thai government has ambitions to address the issue of energy security in ways that ensure environmental sustainability. For instance, the country's 12th National Economic and Social Development Plan (2017-2021) explicitly highlights the importance of green growth (Office of the National Economic and Social Development Board, 2017). Furthermore, the Thai government has signed and ratified the 2016 Paris Agreement under the UNFCCC and had previously already submitted its Intended Nationally Determined Contribution, pledging to limit greenhouse gas emissions by 20% by 2030 compared to a business-as-usual scenario (Office of Natural Resources and Environmental Policy and Planning, 2015).

The Alternative Energy Development Plan (2015-2036) contains Thailand's goals for the expansion of renewable energy (Department of Renewable Energy Development and Energy Efficiency, 2015). The plan is based on the objective to increase the overall share of renewables in final energy consumption to 30% by 2036. Table 7 outlines the targets for individual technologies in the electricity, heat, and biofuels categories. As it illustrates, biogas plays an important role in all three of these.

Type of energy	**September 2015 (MW)**	**2036 target (MW)**
Municipal waste	134.72	500.00
Industrial waste	-	50.00
Biomass	2,676.50	5,570.00
Biogas (wastewater/sewage)	365.10	600.00
Small hydropower	172.06	376.00
Biogas (energy crops)	-	680.00
Wind power	225.37	3,002.00
Solar power	1,313.65	6,000.00
Large hydropower	2,906.40	2,906.40

Electricity: increase of alternative energy ratio in electricity sector from 4.27% in 2015 to 20% by 2036

Type of energy	**September 2015 (PJ)**	**2036 target (PJ)**
Energy from waste	2.66	20.72
Biomass	182.92	925.28
Biogas	16.33	53.72
Solar power	0.23	50.24
Other alternative energy	-	0.42

Heat: increase of alternative energy ratio in heat sector from 19.15% in 2015 to 36% by 2036

Type of energy	**September 2015 (10^6 litre/day)**	**2036 target (10^6 litre/day)**
Ethanol	3.52	11.30
Biodiesel	3.17	14.00
Pyrolysis oil	-	0.53
Biomethane (tonne/day)	-	4,800.00
Other alternative energy (ktoe)	-	0.42

Biofuels: increase of alternative energy ratio in fuel sector from 6.6% to 25% by 2036

Table 7: Planned increases in capacity and production of renewable energy under Thailand's Alternative Energy Development Plan. Source: Energy Policy Planning Office (2016).

Over the past two decades, the Thai government has already introduced a number of measures to support the generation of renewable energy. One of the most important of these was the introduction of power purchase agreements in the early 1990s that enabled independent companies to generate and sell electricity to the public grid authorities. In addition, from 2007 onwards, certain technologies could apply for a so-called Adder, which allowed companies to receive a premium on top of the market electricity price.[9] Beginning in the 2000s, the Thai Board of Investment introduced corporate tax breaks for companies and reduced import duties for equipment in strategically important areas of technology. Another major initiative was the creation of the Energy Conservation Fund in 1992, which receives money from a tax on petroleum and which has since been used to fund a wide variety of initiatives, including investment subsidies and soft loan schemes for renewable energy projects. Renewable energy projects have also benefitted from Thailand's participation in the CDM under the UNFCCC and the associated sale of carbon credits. In addition to these, there have been a number of smaller initiatives such as technical assistance programmes and a stricter enforcement of environmental law, the latter of which constitutes a particularly important incentive for biomass and biogas projects using waste products as feedstock.

4.5. A brief history of biogas in Thailand

Prior to the late 1980s, efforts to diffuse biogas technology in Thailand were limited. In the 1960s, the Ministry of Health promoted the diffusion of small-scale (4-6 m^3) biogas systems for the generation of cooking fuel from animal manure (Siteur, 2012). In response to the 1973 oil crisis, the uptake of such small-scale systems intensified, so that by 1988 approximately 5,500 systems had become installed (*ibid.*). However, most of these projects were unsuccessful due to a lack of sufficient knowledge about system construction and operation (Suwansari et al., 2015). The first experiments with larger, high-rate systems began in 1984 when King Mongkut's University of Technology Thonburi developed a cassava wastewater treatment plant based on the Anaerobic Fixed Film design and, in the same year, 12 liquor facilities installed wastewater treatment facilities based on the Upflow Anaerobic Sludge Blanket design (*ibid.*). However, these

[9] The Adder scheme was replaced by a feed-in tariff at the end of 2014/beginning of 2015. The interviews conducted as part of this study (see Chapter 6) revealed that, by the time this research was conducted, only few projects had been awarded contracts on this basis (see Mehner et al. [2017] for a similar finding).

systems had problems too, particularly the latter, as they were not sufficiently adapted to the characteristics of the available feedstock (*ibid.*).

The first systematic effort to promote the use of larger biogas systems began in 1988 under the Thai-German Biogas Programme, which was jointly implemented by the Thai Department of Agricultural Extension, Chiang Mai University, and the German Corporation for International Cooperation on behalf of the German Government (Suwansari et al., 2015). The programme aimed to address the problem of increasing environmental stress from livestock farming. For this, it combined foreign and local expertise for the design, implementation, and operation of small to medium-scale ($<50m^3$) reactors for the treatment of animal manure. Upon conclusion of the programme in 1995, the National Energy Policy Office decided to continue to support the diffusion of biogas systems for livestock farms by offering investment subsidies to medium and large-sized plants, most of which were based on the Upflow Anaerobic Sludge Blanket design (Siteur, 2012). This led to the development of about 150 plants. The research conducted for this thesis has shown that this programme was critical for the cultivation of some of the technological capabilities that played an important role in the later development of the Thai biogas industry.

The 2000s and early 2010s were a period of rapid diffusion of biogas systems in Thailand, particularly in the cassava processing and palm oil milling industries. After several cassava wastewater treatment projects had been developed with the help of governmental investment subsidies, the year 2003 saw Thailand’s first fully commercial project that was wholly financed through equity: the Khorat Waste to Energy project. The project was a turning point for the industry and prompted an accelerated uptake of biogas systems in the cassava industry as well as some other agro-industries that produce wastes with similar characteristics (e.g., rice, sugar, and ethanol production). Around the year 2005, investors and plant developers gained interest in the palm oil milling sector. In contrast to cassava processing facilities, palm oil mills usually do not use biogas on-site as they burn solid waste products (palm kernel shells and mesocarp fibre) to generate energy for their operations. Hence, their main incentive to install biogas systems was not to save on energy bills but a combination of being able to sell electricity to grid operators, to sell carbon credits under the CDM, and to prevent odour problems stemming from the open storage of palm oil milling wastes (Siteur, 2012).

Today, Thailand hosts about 1,500 industrial biogas plants, of which the majority are small and medium-scale plants at livestock farms (see Table 8). The market for plants at livestock farms, cassava processing facilities, palm oil mills, and some other agro-industrial facilities is nearly saturated (Mehner et al., 2017), although there are still opportunities to develop projects at smaller facilities and to improve the performance of existing plants. Consequently, biogas engineering companies increasingly focus on alternative substrates, particularly agro-industrial wastes with higher dry matter content (cassava pulp, empty fruit bunches from oil palm, etc.). The government has recently announced plans to increase the use of compressed biogas for transportation (Department of Renewable Energy Development and Energy Efficiency, 2015), which has led to some R&D activity in this field. R&D efforts have also been focused on the digestion of Napier grass, an energy crop. In fact, while the Alternative Energy Development Plan of the Thai government stipulates that biogas production from waste products should be increased from currently about 412MW to 600MW by 2036, its targeted increase of biogas production from energy crops is much more ambitious: from currently 0MW to 680MW by 2036 (see Table 7 in Section 4.4 above).

Host facility type	Number of biogas plants	Biogas production (PJ/year)
Livestock farms	1,250	4.69
Palm oil mills	72	3.82
Starch processing facilities	56	7.85
Ethanol production facilities	19	5.25
Other	80	2.73

Table 8: Estimated number of biogas plants and biogas production per host facility type in Thailand. Source: Energy Research and Development Institute Nakornping and Chiang Mai University (2017), cited in Mehner et al. (2017, p.65). Conversion from biogas production in Nm^3 to PJ assuming an average energy density factor of 21.6 MJ/Nm^3 following the World Bioenergy Association (2017).

In summary, Thailand is one of the world's largest biogas producers (see Figure 7 in Section 4.2) and hosts one of the most advanced industries for the supply of biogas systems in Southeast Asia (Association of Southeast Asian Nations, 2014). While early attempts in the 1980s to develop industrial biogas systems only involved small-scale systems, the country has become host to some of the largest biogas systems in the world in recent decades. Initially, the focus was primarily on the treatment of liquid wastes from agriculture and agro-industries. However, as these market segments have become increasingly saturated, local and foreign firms have begun to focus on the treatment of more solid substrates, including both solid wastes and energy crops. During the post-2000 period of rapid growth, some local firms with advanced technological capabilities have emerged, which, for example, is evident in the fact that these firms now export technology to neighbouring countries in Southeast Asia (Siteur, 2012).

Against this background, the following two chapters present two projects that have been conducted as part of this Ph.D. research. These investigate in detail to what extent and how local biogas engineering firms have developed the technological capabilities which have allowed them to develop and produce biogas systems.

5. Organisational arrangements for cross-border technology transfer

5.1. Introduction to the chapter

This chapter presents the first study that has been conducted as part of the Ph.D. project summarised in this thesis. Section 2.4.2 reviewed the literature on international transfers of LCE technology to developing countries and argued that existing methodological approaches aiming to produce generalizable results mostly rely on simplistic indicators. These approaches usually do not provide detailed insight into the issue of knowledge transfer for local capability formation. The present chapter aims to fill this gap in the literature. As explained in Section 2.5, the core aim of this chapter is to produce generalizable insights about the kinds of learning mechanisms involving foreign sources of knowledge that Thai biogas technology-supplying firms have used to build their capability stocks. This is done by means of examining the organisational arrangement types (imports, FDI, international joint ventures, cross-border R&D collaborations, etc.) that they have engaged for the supply of technology to a large sample of biogas projects in Thailand, i.e. all biogas projects which have applied for registration with the CDM.

The chapter addresses the following research question:

Through which organisational arrangements have Thai firms accessed foreign knowledge for the supply of biogas technology?

The project also examines differences in the organisational arrangement types that have been used to source (i) AD systems and (ii) biogas engines/engine-generator sets. The corresponding supplementary research question is:

How do organisational arrangements differ across technological components of biogas systems?

The chapter is structured as follows. Section 5.2 discusses the methodology. It introduces the rationale of the analysis, discusses some caveats of the approach, describes how the organisational arrangement types were determined, and describes the data sources that have been used. Section 5.3 presents the results. Section 5.4 discusses the insights that they provide about technological learning among Thai biogas engineering firms and latecomer learning more generally. Section 5.5 concludes the chapter by briefly summarising its main points.

5.2. Methodology

5.2.1. Rationale

The analysis presented here draws on the literature review presented in Section 2.2.1. There, it was argued that identifying the types of organisational arrangements which local firms engage in with foreign organisations provides insights about two related aspects: (i) the likely amount of knowledge transfer that took place as part of the arrangement; (ii) the likely amount of absorptive capacity that the latecomer firm possesses and that allowed it to engage with the foreign partner in a certain manner. By reviewing the latecomer capability literature which focuses on international technology transfer in specific organisational arrangement types, Section 2.2.1 has ranked arrangement types based on these two dimensions (see Table 9 below, reproduced from Section 2.2.1).

Likely level of (i) knowledge transfer to and (ii) absorptive capacity at the latecomer firm	**Organisational arrangement type**
Low	Imports of equipment and services
↕	Inward FDI
	International joint ventures
	Cross-border licensing
	Informal learning mechanisms
High	International R&D collaborations

Table 9: Ranking of organisational arrangement types based on implied knowledge transfer and absorptive capacity at latecomer firms.

The analysis of organisational arrangements that were used to supply biogas technology in the Thai biogas sector is based on an examination of a large sample of CDM projects. The method is inspired by research on CDM projects involving wind turbines and solar PV panels by Lema and Lema (2013, 2016). They have pioneered an approach which allows for a structured classification of the organisational arrangements through which technology has been supplied in individual projects. The present research adapts and applies this approach to the case of Thai CDM projects involving biogas technology.

While the key focus of this thesis is on suppliers of AD systems, the approach used in this chapter also lends itself to a comparative analysis of the organisational arrangements used for AD systems and biogas utilisation technology. With regards to latter, the study focuses exclusively on biogas engines/engine-generator sets. Other technologies - burners, burner-boiler sets, flares, or biogas upgrading equipment - are excluded for a number of reasons. Firstly, comparing organisational arrangements across projects is most meaningful if the projects involve similar kinds of technologies, because these require similar types of capabilities for their development and supply. Secondly, biogas engines/engine-generator sets are the most commonly installed type of biogas utilisation technology in Thai CDM projects - they are used in around 78% of the projects.

5.2.2. Caveats

Before introducing how the firms' engagement in different organisational arrangement types has been determined based on the available data, it is necessary to discuss some caveats of the approach pursued in this chapter. Firstly, as highlighted in Section 2.2.1, knowledge flows to and levels of absorptive capacity at local latecomer firms can vary across different instances of the same organisational arrangement type (e.g., Yoruk, 2009). However, following Lema and Lema (2016, 2012) and Quitzow et al. (2017), this research does not emphasise contextual detail. Instead, it assesses organisational arrangements in an all-other-things-equal context. Based on the literature on capability building through individual organisational arrangements types (presented in Section 2.2.1), it appears that differences in knowledge transfer to and absorptive capacity at latecomer firms are larger *across* than *within* different organisational arrangement types.

Secondly, the reader should note that the intention here is not to suggest that technology transfer takes place through any particular type of organisational arrangement in single instances of knowledge transfer. Instead, effective technology transfer frequently takes place over extended periods of time and through repeated and various kinds of interactions (e.g., see Hansen and Ockwell, 2014, p.627). The goal of the present analysis is not to determine all relevant learning mechanisms. Instead, it aims to highlight the learning mechanisms/organisational arrangement types that have played a dominant role in the case of each case.

Thirdly and relatedly, it should be noted that the individual organisational arrangements types are not always mutually exclusive. For example, a joint venture might entail a joint R&D project, imports can involve or lead to informal learning (e.g., through reverse engineering), joint R&D programmes can involve licensing agreements, etc. The objective of the analysis presented here is to determine the organisational arrangements type that have been most important for the firms included in this study.

Finally, the list of organisational arrangements considered here is not exhaustive. There are other arrangement types that have not been included because they have not been found to be of major importance in the projects analysed. This mostly includes organisational arrangement types that involve very high levels of knowledge transfer to and absorptive capacity at the latecomer firm, such as strategic partnerships and alliances, acquisitions of and mergers with foreign firms, outward FDI, and outward R&D.

5.2.3. Determining organisational arrangements for technology transfer

Four factors are used to categorise the organisational arrangements that local and foreign organisations have engaged in for the supply of AD systems and biogas engines/engine-generator sets in the sample of Thai biogas CDM projects. Table 10 below illustrates how the organisational arrangements are determined for individual projects. Four variables are used for this purpose. This includes the location of the technology-supplying firm, the location of the ownership of this firm, the location of technology ownership, and the origin of the technology. The first column of the table illustrates the arrangement types considered in this study.

The first factor is the location of the technology supplier. In the case of AD systems, the study focuses on the location of the design and engineering company. In the case of biogas engines/engine-generator sets the focus is on technology manufacturers of the final product. Based on the framework presented in Table 10, these can be either located inside or outside the case country.

The second factor is the location of the ownership of the technology supplier. This is either internal or external to the country. In cases where technology is supplied through an international joint venture, ownership is considered to be shared.

The third factor is the ownership of the technology. Local ownership implies that the technology has been invented by a local firm. Alternatively, ownership of a technology can be local if it has been conferred from a foreign to a local firm as part of a licensing agreement. Technology ownership is defined as intellectual property ownership. This includes the ownership of technological components that are key for the design of the systems. A firm is considered to own a technology if it holds a patent or a license for a particular AD system or engine/engine-generator set design in Thailand at the time of the start date of the CDM project in question. Patents and licenses can be held by firms inside or outside the case country or can be jointly owned by domestic and foreign firms. Technology ownership is considered to be undefined if no information about patents or licenses is available or if relevant patents or licenses expired prior to the start of a particular project.

Organisational arrangement type	**AD system design and engineering company/ biogas engine manufacturer**	**Ownership of AD system design and engineering company/ biogas engine manufacturer**	**Ownership of technology**	**Origin of technology**
Imports of equipment and services (*Foreign-based design and engineering company/manufacturer provides technology design/technological equipment*)	External	External	External or N/A	External
Inward FDI (*Local subsidiary of foreign multinational supplies technology*)	Internal	External	External or N/A	External, shared, or internal
International joint ventures (*Design and engineering company/manufacturer is jointly owned by foreign multinational and local company)*	Internal	Shared	External, shared, internal, or N/A	External, shared, or internal
Cross-border licensing (*Local design and engineering firm/manufacturer holds product license for foreign technology*)	Internal	Internal	External-conferred	External
Informal learning mechanisms (*Local design and engineering firm/manufacturer acquired foreign technology informally*)	Internal	Internal	N/A	External
International R&D collaborations (*Technology was jointly developed by foreign and local firms*)	Internal	Internal	External, shared, internal, or N/A	Shared
Local innovation (*No involvement of foreign firms)*	Internal	Internal	Internal or N/A	Internal

Table 10: Categorisation of organisational arrangements. Internal and external refer to the case country. Shared means that the factor is shared between a local and a foreign organisation.

The last factor is the origin of the technology. To determine the origin of a certain type of AD system or engine/engine-generator set, one first needs to find out where the core technological process was invented on which the technology is based. In cases where technology has developed incrementally, determining the origin of the AD system or engine/engine-generator type involves finding out where substantial innovative steps have taken place. This can refer to significant changes in the overall system designs or key system components. As explained below, this was based on a review of a variety of data sources and the understanding of the different AD system designs that I have developed over the course of this Ph.D. research project.[10]

Based on these four factors, I used the available information to develop brief biographies of the firms involved in the supply of AD systems and biogas engines/engine-generators sets in the sample of Thai biogas CDM projects. As explained below, this was based on a variety of data sources.

5.2.4. Data

Data on the four factors outlined in Table 10 was collected as follows:

(1) The CDM database of the Institute for Global Environmental Strategies (2018a, 2018b) was used as a starting point to identify all Thai biogas CDM projects. The study uses data on all projects that have submitted project design documents to the CDM Executive Board by May 2018.

(2) The project documentation was used to determine the names and locations of (i) the AD system-suppliers and (ii) the manufacturers of the biogas engines/engine-generator sets. This documentation includes project design documents, validation reports, and monitoring reports, all of which are available from the website of the UNFCCC (2018a, 2018b). In a limited number of cases, the project documentation does not contain the names of technology suppliers, such that I had to use other means to determine these (e.g., by directly contacting project participants or consulting project reports by organisations other than the UNFCCC).

(3) The ownership of the technology supplier, the ownership of the technology design, and the origin of the technology were determined using a variety of sources containing publicly available information. This involved a detailed online search for data available on each project, technology-supplying firm, and technology type. Data sources include the CDM project documentation, company

[10] Section 2.2.1 highlighted that subsidiaries of foreign-based multinationals differ in the extent to which they are involved in technology R&D. To reflect this, the right-most column of Table 10 specifies that the origin of technology in the FDI arrangement type can be either foreign, shared, or local.

websites, reports on individual projects by organisations other than the UNFCCC, news articles, industry periodicals, the patent literature, and the academic literature. Where necessary, project participants were contacted directly.

The chapter appendix (Section 5.6.2) includes the datasets that were compiled for this analysis. They contain detailed information about the data sources that have been used to determine the four variables described in Table 10 in each case.

The names of the technology-suppliers are almost always mentioned in the CDM project documentation. Only in a few cases did I have to consult alternative data sources. The ownership of firms could be identified through online searches. Determining technology ownership required a more in-depth search. As it turns out, this variable is undefined in most cases. The finding that patents are not frequently used as a means to protect intellectual property for AD systems is also supported by the interview data collected for the analysis presented in Chapter 6. However, there is still a chance that I was unable to locate all relevant information, especially in cases where this information was only available in the Thai language. Information on the origin of technology and the extent to which local firms have added substantive innovative steps to originally foreign technology was sometimes available in the CDM project documentation. In most cases, I also had to consult other data sources (company websites, brochures, etc.). For some of the smaller local firms, it was sometimes difficult to find detailed information about whether and how they have introduced changes to basic AD system designs that had previously been developed abroad (see Box 1 in Section 4.1 for an overview of the most relevant examples). Where such information was unavailable and the underlying basic reactor design was developed abroad, I assumed that technology origin is external. This introduces some uncertainty about whether some of these organisational arrangements should be included under the "informal" or the "local innovation" category. However, this does not significantly change the overall findings of the analysis presented in this chapter.

A total of 103 applications for Thai biogas CDM projects have been filed with the UNFCCC Executive Board by May 2018 (see Figure 9).[11] These include 99 regular CDM

[11] From around 2010 onwards, the number of new CDM project applications decreased significantly. The main reason for this is the drastic reduction in global demand for Certified Emission Reduction credits from around this time onwards (UNFCCC, 2014).

projects, two bundled projects, and two Programme of Activities applications.[12] These applications include biogas projects at a total of 118 sites. Several of these sites include multiple types of AD systems. As the organisational arrangements are determined individually for each AD system at each site, this results in an analysis of a total of 131 arrangements.

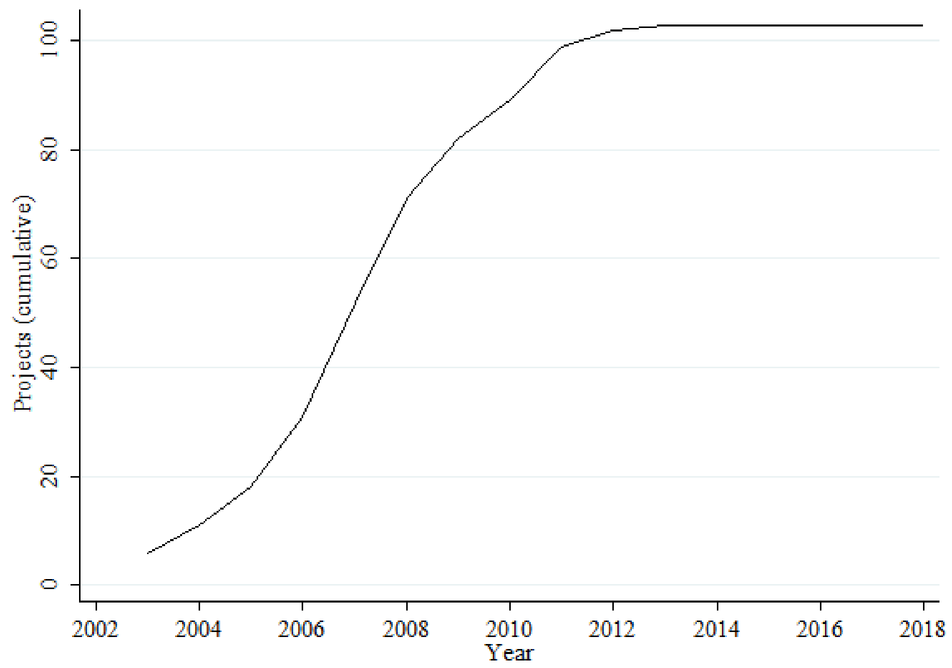

Figure 9: Cumulative number of Thai biogas projects that have applied for registration with the CDM, 2002-2018.

Out of the total of 103 CDM projects, 80 indicated that they involved installations of biogas engines/engine-generators (78%). This includes bundled projects and Programmes of Activities. The total number of project sites at which engines/engine-generator sets have been installed is 95. For five out of these 95 projects, I was unable to determine the biogas engine/engine generator set model. Two further projects had not decided on a particular biogas engine/engine generator set model by the time the project documentation was written. In these cases, I was also unable to determine the model type via direct contact to project participants. Therefore, the organisational arrangements for

[12] Some CDM projects "bundle" multiple biogas projects into a single application. Figure 9 counts bundled projects and Programmes of Activities as single CDM projects. Bundling and Programmes of Activities have been introduced by the CDM Executive Board to reduce the cost and administrative burden associated with project registration, especially for projects of smaller sizes.

the supply of biogas engines/engine-generator sets has been determined for 88 CDM projects.

Table 11 divides the CDM projects by feedstock type and compares them to estimates for the total number of biogas projects in Thailand. The data shows that CDM projects based on livestock and the "other" waste category only make up a small share of the total of all projects. On the other hand, projects for the remaining categories - including waste from palm oil milling, cassava processing, and ethanol production - were registered with the CDM in comparatively many cases. This is likely to do with the larger size of these projects and their potential to generate large numbers of carbon credits. It also has to do with the fact that many of these projects were developed during the time that the CDM was active. Thus, in line with the thesis's overall focus on medium and large-scale biogas plants, the analysis presented here focuses primarily on the organisational arrangements that have been used for the supply of biogas technology to comparatively large projects.

Host facility type	**Biogas projects**	**CDM biogas projects**	**Share (%)**
Livestock farms	1,250	22	2
Palm oil mills	72	33	46
Starch processing facilities	56	43	77
Ethanol production facilities	19	17	89
Other	80	3	4

Table 11: Comparison of estimated number of biogas projects and projects that have applied for registration with the CDM by substrate type. Source of data for estimates of total number of projects: Energy Research and Development Institute Nakornping and Chiang Mai University (2017), cited in Mehner et al. (2017, p.65).

The AD systems deployed in these projects were supplied by 25 firms. Biogas engine/engine-generator sets were supplied by 8 manufacturers.

5.3. Results

This section presents the patterns in the organisational arrangements types that have been used to source AD systems and biogas engines/engine-generator sets in the sample of Thai biogas CDM projects. As explained above, these are discussed with respect to the likely amount of knowledge transfer to and absorptive capacity at Thai biogas technology-supplying firms that they imply.

Figure 10 below shows the results for AD systems. The black bars represent how often each organisational arrangement type has been used to supply technology in the sample of projects. The grey-shaded bars indicate how many design and engineering firms were involved under each arrangement type. The data shows that, overall, there appears to be a concentration of arrangements and firms on the right-hand side of the figure. This suggests that many local AD system suppliers have relatively high levels of absorptive capacity and that they have been able to access advanced knowledge from foreign sources.

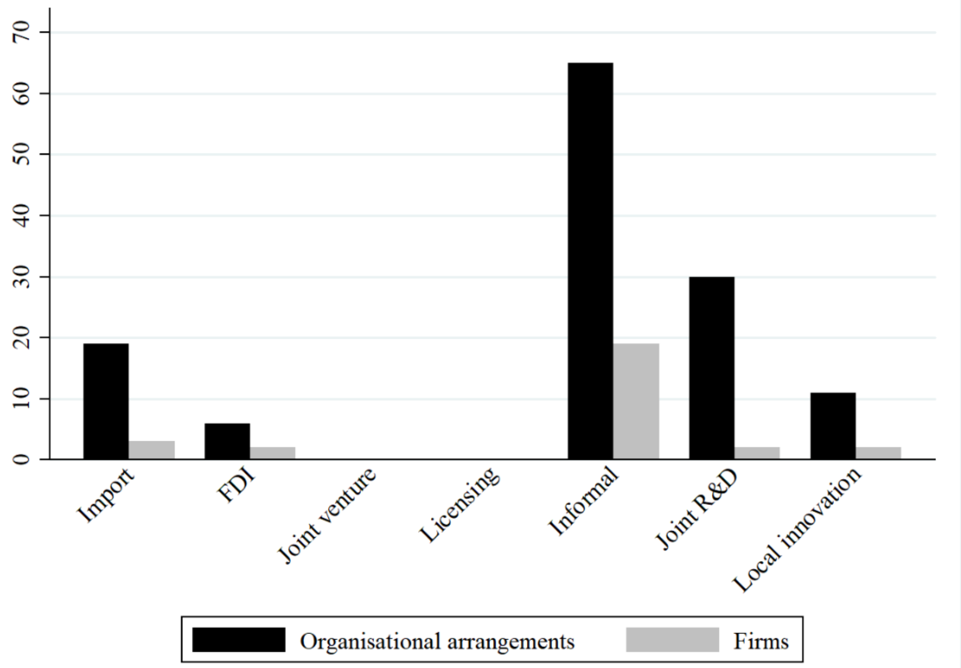

Figure 10: Number of organisational arrangements used to supply AD systems in Thai biogas CDM projects and number of firms involved by arrangement type.

Imports make up a relatively small share of the observed arrangements. These projects have been purchased from three companies which are based in Canada, New Zealand, and India respectively. All three of these are comparatively large firms that have developed projects across many different countries. As discussed in previous sections of this chapter, the import arrangement type implies transfers of equipment and services into the country and likely only contributes to the development capabilities for the operation of the imported equipment. This organisational arrangement type usually does not contribute much to the accumulation of the capabilities required to change existing or to develop new technology. One potential reason for why imports play such a minor role here is that there are locally based competitors that can offer AD systems at similar levels of cost and/or quality. This can be considered an indication that there are local firms which possess the required technological capabilities to develop and supply these. Other potential reasons for why clients tend to opt for local AD system suppliers are explored below.

Organisational arrangements based on FDI are used even less frequently in the sample of projects than arrangements based on imports. Only two local subsidiaries of foreign-based multinational companies have been involved here. One of these is based in Hong Kong and Belgium, the other is based in Germany. Both are global corporations with offices and projects spread across multiple countries and continents. As discussed in Section 2.2.1, the mere presence of a subsidiary does not provide much insight about the extent to which technological capabilities have been accumulated locally. While some subsidiaries predominantly rely on routine capabilities and offer technology that has been developed abroad, others engage actively in technology R&D based on their own stocks of innovative capabilities. However, one can assume that, at a minimum, parent companies ensure that local subsidiaries possess levels of routine capabilities that allow them to supply AD systems which are up to the multinationals' standards. The study presented in Chapter 6 provides more detailed, micro-level insights about the capability accumulation and learning experiences of a smaller sample of biogas engineering firms in Thailand. As one of the firms analysed in Chapter 6 is a subsidiary of a foreign-based multinational, the chapter will offer some insight into how learning occurs in this type of firm.

There are no projects which have sourced AD systems via the joint venture arrangement type. Given the concentration of organisational arrangements and firms on the right-hand side of Figure 10, it is unlikely that the absence of joint ventures stems from a lack of local absorptive capacity. Instead, it seems more likely that this stems from other reasons, for instance, the Thai government's decision not to pursue an exchange-market-for-technology strategy or fears of foreign firms to lose their intellectual property during such collaborations.[13] The approach pursued in this study does not allow for an analysis of knowledge spillovers to local firms based on foreign investments. However, one can assume that the low number of arrangements based on inward FDI and joint ventures has had a limiting effect on the amount of spillover that has taken place in the Thai biogas industry.[14]

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[13] The Chinese government has pursued an exchange-market-for-technology-strategy in a number of industries. In the case of the local automotive industry, for example, this has had a substantial impact on the ability of local firms to develop their technological capabilities (e.g., see Dunne, 2011; Li and Cantwell, 2010; Nam, 2011).

[14] The micro-level study of capability accumulation and learning presented in Chapter 6 provides some insight about instances where local firms were able to learn from projects that had previously been developed in Thailand by foreign-owned subsidiaries.

There are also no recorded organisational arrangements that are based on technology licensing. In general, few firms seem to file patents for whole AD system designs or system components at intellectual property right offices. Hence, technology ownership is undefined for the majority of the projects analysed here. There are several potential explanations for this finding. For example, firms might prefer non-patent-related strategies to protect their system designs. This could include secrecy. Some firms might also rely on complementary capabilities (e.g., project commissioning or operation capabilities), the absence of which would make it challenging for competitors to copy their designs and to offer them in the market. Low patenting activity in Thailand might also be related to a lack of trust in the local intellectual property right protection system, which only performs moderately on international scoreboards (International Property Right Index, 2017). Furthermore, some relevant patents may have already expired. Lastly, I might have been unable to access all relevant information, especially for cases where information about patents is not available in English. However, as will be explained in more detail below, the interviews conducted for Chapter 6 corroborate the finding presented here that patents are not a commonly used way to protect intellectual property among Thai biogas engineering firms.

It appears that many Thai biogas engineering firms have learnt from foreign sources of knowledge through informal channels. As described in Section 2.2.1, informal learning is defined in this thesis as learning from firm-external sources of knowledge which does not involve contractual agreements between knowledge providers and recipients. The effects of learning through such channels are often referred to as knowledge spillovers. In fact, the data suggests that a large share of projects have sourced technology via the informal category of organisational arrangements. This arrangement category also involves the largest number of firms (19) out of all arrangement types considered in this study. Table 12 below illustrates that this includes a variety of firm types, including local private sector firms, university-based organisations, local agro-industrial producers (i.e., the organisations which usually are buyers of AD systems), and a government-funded association which provides support to the domestic biogas sector. These findings suggest that learning based on informal channels is common in the Thai biogas industry.

Organisational arrangement type	Firm type	Number of firms
Informal	Government foundation	1
	Agro-industrial producer	3
	Private sector	13
	University-based organisation	2
Joint R&D	Private sector	1
	University-based organisation	1
Local innovation	Private sector	1
	University-based organisation	1

Table 12: Types of firms involved in the informal, joint R&D, and local innovation types of organisational arrangements. Note: Three of the firms are included under two different organisational arrangements types because they have used different arrangement types to supply different kinds of reactor designs.

As discussed in Section 2.2.1, examples of informal learning include hiring employees who previously acquired relevant knowledge by working at other firms, learning through informal interactions with other companies (e.g., in industrial clusters or at trade shows), learning by observing projects that were developed by competitors, and learning from suppliers and buyers. Thus, the informal category of organisational arrangements as defined in this chapter actually groups together a variety of mechanisms for knowledge transfer. Given the importance of this arrangement type and given that the methodology used in this chapter does not allow for a more disaggregated analysis of the underlying learning mechanisms, informal learning will be discussed in detail in Chapter 6 of this thesis.

Joint R&D initiatives between local and foreign organisations are the second most frequently observed organisational arrangement type. This involves two R&D-based partnerships between (i) a local firm and a Dutch university and (ii) a local university-based organisation and a German development agency (see Table 12 above). This arrangement type usually involves close interaction and intensive knowledge sharing between foreign and local partners. Furthermore, the ability to engage in research collaborations with organisations from high-income countries can be considered an indicator for relatively high levels of absorptive capacity and local innovative capabilities. Hence, the fact that two local firms have engaged in this kind of learning mechanism and that they have supplied technology to a comparatively large number of projects illustrates that there are some locally owned firms in the Thai biogas industry which possess the ability to absorb and learn from advanced foreign knowledge. The micro-level analysis presented in Chapter 6 will elaborate on the two R&D collaborations mentioned above and will show how these have played critical roles in the technological capability accumulation experiences of the two local biogas engineering firms involved.

Some of CDM projects are based on locally developed AD system designs. This involves two local organisations: a private sector company and a university-based organisation (see Table 12). Local innovation does not involve any foreign sources of knowledge and, as such, does not provide information about these firms' ability to engage with foreign organisations. Instead, this organisational arrangement type suggests that there are some Thai firms which have managed to accumulate technological capabilities that allow them to develop and supply their own reactor designs.

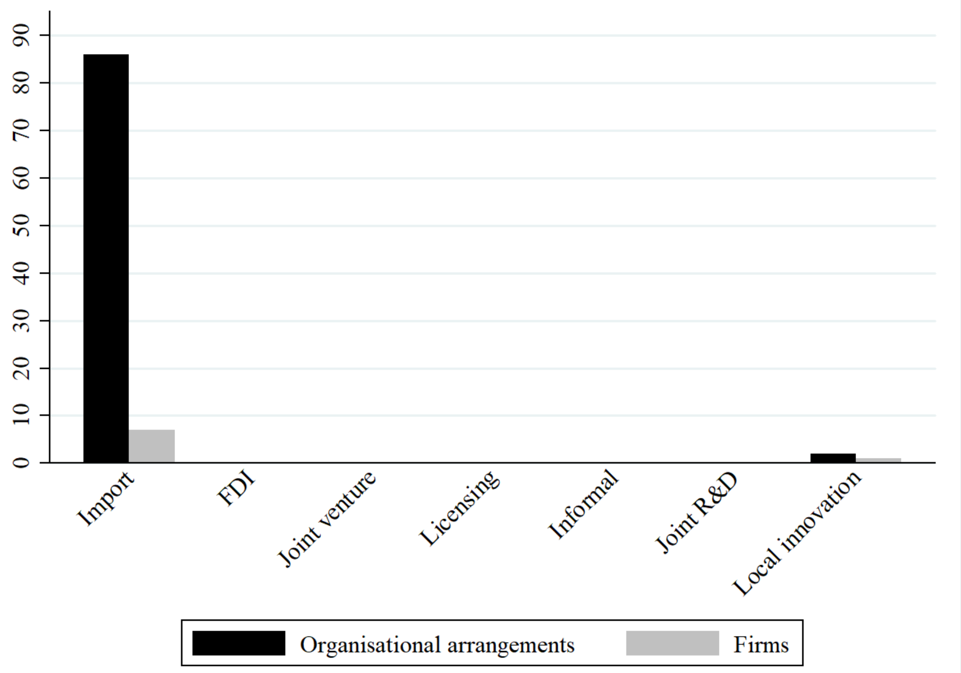

Figure 11: Number of organisational arrangements used to supply biogas engines/engine-generator sets in Thai biogas CDM projects and number of firms involved by arrangement type.

Figure 11 shows the organisational arrangement types that were used to source biogas engines/engine-generator sets in the sample of Thai biogas CDM projects. Technology has been sourced via equipment imports in virtually all of these projects. The figure also shows the number of manufacturers involved in each arrangement type. These are located in Austria (for 33% of all projects), Spain (29%), Germany (21%), South Korea (6%), the United States of America (4%), and China (4%). With the exception of China, these are all high-income countries. Two projects use technology supplied by a local company (2%). These were truck engines originally manufactured by a Japanese company which had subsequently become converted by a Thai company to run on biogas (source: personal communication with project participant). Modifying truck engines in this way involves a number of steps that require significant design capabilities (e.g., see Siripornakarachai and Sucharitakul, 2008). Therefore, these two projects can be considered to involve local innovation. However, in at least one of these projects, the modified engine performed poorly and was eventually replaced with an imported engine from Canada (source: personal communication with project participant). Hence, given the predominance of foreign technology and the failure of an engine that was based on local innovation, the data collected for this study suggests that Thailand does not possess significant capabilities for the production and development of biogas engines/engine-generator sets. Given the limited involvement by local firms, one can also assume that international technology transfer has predominantly consisted of cross-border flows of equipment, perhaps linked to the provision of training services on how to operate and maintain the machinery. The data presented here suggests that flows of the knowledge required to produce or further develop technology have likely not taken place to a significant degree.

5.4. Discussion

The analysis presented in this chapter determines what kinds of organisational arrangements Thai biogas engineering firms and foreign partners engaged in to supply AD systems and biogas engines/engine-generator sets. By focusing on a large sample of biogas projects, the chapter provides a representative overview of the kinds of cross-border learning mechanisms that local firms used. This offers some insights about latecomer learning processes in this particular context. On the one hand, the data suggests that Thai AD system-supplying firms have learnt from a wide variety of foreign sources of knowledge. This result is discussed in Section 5.4.1. Furthermore, the results indicate that there are differences in the patterns of organisational arrangements that have been used to supply AD systems and biogas engines/engine-generator sets to Thai biogas projects. Section 5.4.2 discusses some of the characteristics of these technologies that can help explain this finding. Finally, Section 5.4.3 discusses the finding that the informal category of organisational arrangements has been found to be particularly important in the case of the AD systems.

5.4.1. Variety in observed organisational arrangement types

The patterns of organisational arrangements used to supply technology in the sample of biogas projects suggests that Thailand does not host a significant industry for the development and production of biogas engines/engine-generator sets. In contrast, the available evidence corroborates the conclusions of previous studies which find that the country hosts a sizeable industry for the supply of medium and large-scale AD systems (Siteur, 2012; Suwansari et al., 2015). Given that some local firms have accumulated the capabilities needed to develop and supply AD systems, this sub-section focuses exclusively on this type of technology. Specifically, it discusses how the findings with respect to AD systems compare to the limited body of literature that analyses organisational arrangements for cross-border learning and catch-up for other LCE technologies in other national contexts.

Lema and Lema (2016, 2013) study the organisational arrangement types that firms in a variety of low and middle-income countries have relied on to supply solar PV panels and wind turbines. Like the findings of the present analysis on AD systems, Lema's and Lema's results suggest that latecomer firms engage in a substantial variety of organisational arrangement types with foreign partners. This mostly concerns firms in China and India, i.e. firms located in countries that host comparatively advanced industries for the supply of solar PV panels and wind turbines. Projects in other countries mainly source technology via international trade. With respect to Chinese and Indian wind turbine projects, Lema and Lema (2013) find that technology is sourced through imports, inward FDI, international joint ventures, cross-border licensing agreements, and locally developed technology (see also Hayashi, 2018; Quitzow et al., 2017). For Chinese and Indian solar PV projects, they find that technology has been sourced via imports, inward FDI, joint ventures, licensing, joint R&D projects, strategic acquisitions and alliances, and local innovation (Lema and Lema, 2016; see also Quitzow et al., 2017).

Thus, these studies support the finding of the present chapter that technology is sourced via a variety of organisational arrangement types. Numerous analyses on the global diffusion of LCE technology have argued that imports and inward FDI are the main channels for their international transfer (e.g., Glachant and Dechezleprêtre, 2017; Popp, 2011; Schneider et al., 2008). Echoing Lema and Lema (2016, 2013), the findings presented in this chapter suggest that technology transfer does not only, and perhaps not even primarily, take place through these channels. Instead, technology frequently seems to be transferred through channels that involve more active roles of local firms, such as collaborative R&D or learning through informal mechanisms. This highlights the importance of viewing international technology transfer not merely as cross-border flows of equipment and financial resources, but as processes which involve learning on the part of the technology-receiving firm (Lema and Lema, 2012; Ockwell and Mallett, 2012). This has important implications for the design of appropriate support mechanisms to accelerate the global diffusion of LCE technology, which will be discussed in Chapter 7 of this thesis.

While the present study and previous research both find that a variety of cross-border organisational arrangements have been used to source technology, it should be noted that the precise mixes of organisational arrangements seem to differ across technologies and national contexts. For example, the informal organisational arrangement category, which has been found to be the most important learning mechanism category in the case of the Thai industry for AD systems, is not considered in Lema's and Lema's (2016, 2013) studies on solar PV panels and wind turbines. In turn, Lema's and Lema's studies both find that some Chinese and Indian firms have accessed technological knowledge by engaging in joint ventures and licensing agreements with foreign partners (see also Fu and Zhang, 2011; Gallagher, 2014; Lema and Lema, 2012; Lewis, 2007). This has not been observed in the case of Thai AD system suppliers. Furthermore, the same studies also find that Chinese and Indian solar PV and wind turbine manufacturers have used organisational arrangement types which have not been considered in the present analysis. This includes foreign acquisitions, overseas R&D, and strategic alliances (*ibid.*). In another paper, Lema and Lema (2012) argue that these “unconventional” learning mechanisms have been particularly important for Chinese and Indian national champion firms in wind and solar for accessing advanced foreign knowledge, particularly in the later stages of these industries’ development.

Thus, there are some significant differences in the observed patterns of organisational arrangements across sectoral and national contexts. This is likely related to some of the factors outlined in Section 2.3. For example, with respect to differences across sectors, Malerba (2002) highlights that, among other things, differences in knowledge bases, basic technologies, and demand structures are key to understanding innovation dynamics. With regards to national contexts, Lall (1992) discusses how the firm’s incentives to invest in technological capabilities are influenced by economy-wide incentives (from macroeconomic stability, competition, and factor markets) and institutions (legal frameworks for industrial activity, institutions facilitating linkages in the innovation system, and training and research institutions). More research is needed to understand exactly how these and other factors influence cross-border learning and latecomer catch-up more generally. As explained in Section 2.5, a thorough analysis of how sectoral and national-level factors have influenced technological learning in the Thai biogas industry is beyond the scope of this thesis. However, Section 5.4.2 below will briefly discuss some factors related to the characteristics of AD systems and biogas engines/engine-generator sets that help to explain the differences in observed patterns of organisational arrangements.

5.4.2. Organisational arrangements and technological characteristics

The results presented above illustrate that there are marked differences in the ways that AD systems and biogas engines/engine-generator sets have been supplied in the sample of Thai biogas CDM projects. AD systems have been sourced through a variety of organisational arrangements. In contrast, biogas engines/engine-generator sets have almost exclusively been sourced via imports of foreign equipment. These differences are likely related to some of the sectoral differences mentioned in Section 2.3, including differences in basic technologies, knowledge bases, and production and innovation inputs.

As explained in Section 4.1 of the present thesis, AD systems are complex technological systems. The key determining factors of their designs are the characteristics of feedstocks. These characteristics can differ from project to project, even for the same type of feedstock (e.g., in terms of volume of available waste, continuity of waste supply, or the waste's precise chemical composition). This means that each AD system design needs to be tailored to the project context at hand. Solutions which have been developed elsewhere cannot simply be transferred without modification across projects and geographies. This helps to explain why the import category of organisational arrangements has been observed relatively infrequently in the data presented above.

Furthermore, the need to adapt AD systems implies that the development of projects depends heavily on the availability of local engineers who possess good design capabilities and who are familiar with local project contexts (e.g., see Chen [2009] for a similar argument). Given the complexity of AD systems and the uncertainties involved, it is difficult to codify the knowledge required for their development. Hence, much of this knowledge is tacit and needs to be built through experience. This helps to explain why the organisational arrangement types which involve firms that are based in Thailand dominate in the results presented above. Furthermore, the nature of this knowledge helps to explain why arrangement types that involve foreign organisations predominantly include arrangement types that can relatively easily facilitate the transfer of tacit knowledge (FDI and joint R&D programmes). This potentially also includes some informal learning mechanisms that can facilitate the transfer of tacit knowledge (e.g., hiring experts with experience from abroad or knowledge exchange through close collaboration with suppliers and buyers). Hence, the findings presented here support Stock and Tatikonda (2000) and Tsang (1997), who argue that international transfers of technology which involve high levels of complexity and tacit knowledge usually occurs through channels that are based on close interaction between knowledge providers and recipients.

The need to adapt systems to project contexts also means that producer-user relationships and, thus, geographical proximity between these two parties is important (see Harirchi and Chaminade [2014] for a recent review of the literature on user-producer relationships in innovation processes). Due to the large size and complexity of AD systems, it is costly and time-consuming for technology suppliers to test how changes in system designs affect performance before projects are developed (e.g., by developing pilot plants). As such, suppliers often experiment with changes in system designs at full-scale, commercial projects (source: communication with project participant). Furthermore, the precise impacts of changes in system designs often only manifest themselves after relatively long periods of operation (*ibid.*). This means that AD system users frequently rely on ongoing support by technology suppliers during the operational phases of projects to successfully maintain the biological processes inside the reactor and to avoid long and costly down-times. The need for producer-user relationships is yet another reason that helps to explain the limited relevance of imports. Furthermore, as close producer-user relationships require trust and good communication, the need for such relationships might also help explain the predominance of organisational arrangement types involving locally owned firms (informal arrangement types, international R&D collaborations, and local innovation). Multiple of the interviews conducted for the analysis presented in Chapter 6 of this thesis revealed that, in the Thai context, communication and trust is often more easily established among locals as compared to between foreign-born biogas experts and local clients.

Biogas engines/engine-generator sets rely on different kinds of learning mechanisms compared to AD systems. They rely less on adaptation to local project contexts and involve higher degrees of standardisation. In fact, biogas engines are very similar to natural gas engines (source: communication with project participant). Furthermore, engines/engine-generator sets can relatively easily be shipped across large distances due to their comparatively small size. As such, technology producers do not need to be located in close proximity to users. This means that engines/engine-generator sets can be produced centrally at large manufacturing plants which benefit from economies scale. This combination of factors implies that developing countries face substantial barriers to market entry for engines/engine-generator sets and similar kinds of technologies (Schmidt and Huenteler, 2016). This is reflected in the distribution of the organisational arrangement types that have been used to source biogas engines/engine-generator sets in the sample of Thai CDM projects.

Hence, it appears that the characteristics of technologies influence (i) the kinds of channels that are best suited for their international transfer and (ii) the potential for the localisation of industries for their development and supply (see also Quitzow et al., 2017; Schmidt and Huenteler, 2016). The degree of standardisation, the reliance on tacit knowledge, and the size/transportability of the technology seem to be key aspects in the case analysed here. The analysis presented in Chapter 6 of this thesis will provide more micro-level insights about how technological learning takes place at AD system-supplying firms. Generating a detailed understanding of how firms dealing with particular technologies build their capabilities provides insights that can inform targeted policy support mechanisms. This will be discussed in detail in Chapter 7.

5.4.3. Informal learning mechanisms

The results presented above illustrate that the informal category of organisational arrangements has been particularly important for the supply of AD systems in the sample of Thai biogas CDM projects. Moreover, they show that a large share of the firms involved in the supply of AD systems has made use of this arrangement type as a learning mechanism (19 as compared to three for imports and two for FDI, joint R&D, and local innovation respectively). This supports the claims by early scholars on latecomer learning (Radosevic, 1999, p.147-148; Westphal et al., 1985, p.199) and more recent empirical studies (Chen, 2009; Egbetokun, 2015; Kesidou and Romijn, 2008) with regards to the relative importance of informal learning compared to learning based on formal channels. It also highlights the need to conduct more research to generate a better understanding of the scope and impacts of informal learning. Technology transfer through informal mechanisms is more difficult to quantify than, for example, transfers via trade, FDI, or licensing. However, given the predominance of this learning mechanism type in the Thai industry for AD systems, it would be worth investigating whether it plays a similarly important role for the diffusion of other kinds of LCE technologies.

The relative importance of the informal arrangement category begs the question which micro-level learning mechanisms are involved here. As indicated above, the informal arrangement category combines a variety of micro-level learning mechanisms through which local firms access knowledge from foreign sources. The methodology used in this chapter is unable to offer more detailed information about precisely which of these mechanisms are most important in the case of the Thai industry for AD system. The following chapter of this thesis presents a more detailed analysis of capability accumulation and technological learning at a smaller sample of Thai biogas engineering firms. This will provide more detailed insights about the precise kinds of learning mechanisms that they have engaged in with foreign partners, with domestic organisations, and firm-internally.

5.5. Summary of main points

The goal of this chapter is to determine what kinds of organisational arrangement types Thai biogas technology-supplying firms have engaged in with foreign partners for the purposes of technological learning. The chapter presents a comparative study of the organisational arrangement types which have been used to source AD systems and biogas engines/engine-generators. This is based on an analysis of a large sample of Thai biogas CDM projects.

The study yields some insights about latecomer learning processes. It shows that Thai AD system-supplying firms have engaged in a wider variety of cross-border learning mechanisms than is commonly argued in the literature on international technology transfer. Informal mechanisms and cross-border R&D collaborations are found to be more important than the more commonly studied arrangement types based on international trade or inward FDI. Furthermore, the analysis illustrates that the patterns of organisational arrangements used to supply AD systems and biogas engines/engine-generator sets differ substantially. It is argued that the particular characteristics of these technologies are likely key determinants of these differences.

An additional finding concerns the frequent use of organisational arrangements based on informal learning mechanisms among Thai AD system suppliers. As explained above, the methodology applied in this chapter is not suited to provide further details about the precise kinds of learning mechanisms that this type of organisational arrangement type involves. This issue will be addressed in Chapter 6 of the thesis.

5.6. Chapter appendix

5.6.1. Follow-up analysis: Comparison of results with technology transfer indicators based on information from CDM Project Design Documents

In Section 2.4.2 it was argued that the existing literature on technology transfers under the CDM has a number of limitations. This sub-section briefly compares the organisational arrangement-based results presented above to a set of results obtained by replicating the approach that is exclusively based on the information contained in the CDM project design documents.

The approach to measuring technology transfer in CDM projects solely based on the information available in the project design documents has been developed by Haites et al. (2006) and Dechezleprêtre et al. (2009, 2008). These studies have been widely cited and their method has been adopted in many subsequent studies (e.g., Haites et al., 2012; Marconi, 2011; Murphy et al., 2015; Schmid, 2012; Seres et al., 2009; UNFCCC, 2010; Weitzel et al., 2015; Xie et al., 2013). In fact, a recent special issue in the Energy Policy journal on technology transfer and cooperation for LCE technology finds that Dechezleprêtre et al.'s (2008) study is the second most widely cited study in this field of research, with a total of 121 citations (Kirchherr and Urban, 2018, p.603).

The weaknesses of this approach have been discussed in Section 2.4.2. To recap, these concern the simplistic and ill-defined categories of the technology transfer measures, the inconsistency of the project developers' statements about transfers contained in the design documents, and the focus on a single measure for transfers despite the fact that projects often involve multiple types of technology.

The design document approach is replicated here by following the description contained in Dechezleprêtre et al. (2008). This involves checking all project design documents of Thai biogas CDM projects for explicit claims about technology transfers. As in Dechezleprêtre et al. (2008), the documents were first scanned for the following keywords: transfer, technology, equipment, import, training, supplier, provider, and manufacturer. For projects for which no information about technology transfers could be found in this way, I read the project documents in their entirety. For reasons of comparability with the organisational arrangement-based data, I focused only on claims about transfers of AD system technology and ignored claims related to biogas engines/engine-generator sets. Based on this approach, the CDM projects were then allocated to one of the following categories: no information about technology transfers available, no transfer, equipment transfer, or combined transfer of equipment and knowledge. The resulting dataset is included in Appendix 5.6.2.

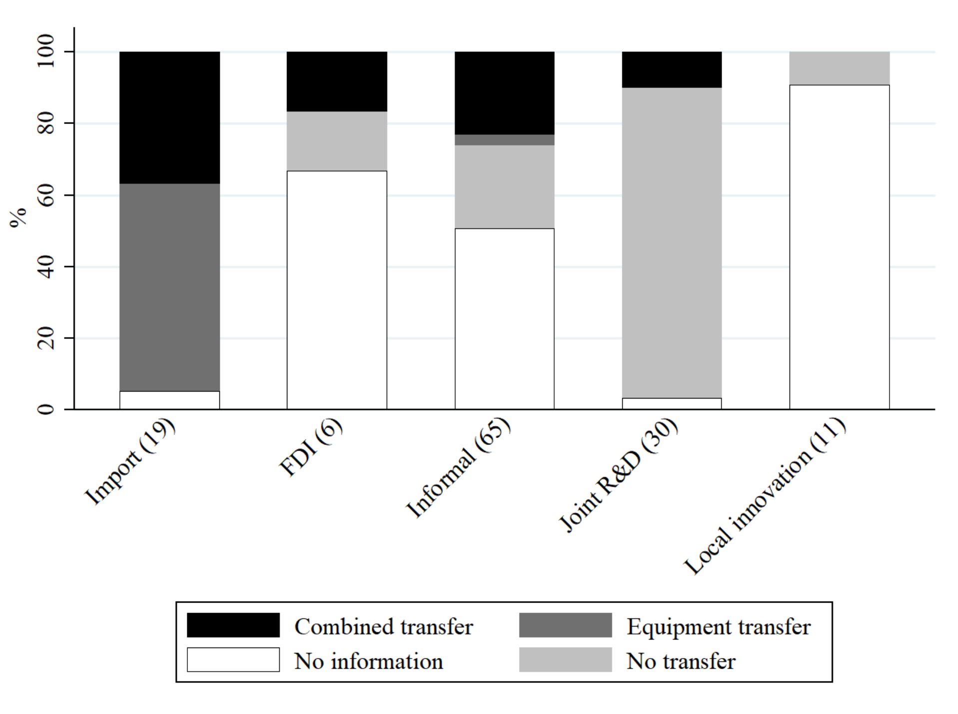

Figure 12: Comparison of technology transfer indicators. In brackets: the number of organisational arrangements that have been analysed for each arrangement category.

Figure 12 summarises the results. It shows that there is no information available for a large share of the projects. Furthermore, the organisational arrangement and design document categories only overlap sensibly in two categories. First, the local innovation category only contains projects categorised as no information or no transfer, which appropriately suggests that foreign companies were not involved in the supply of technology in these projects. The import category contains a comparatively large share of equipment transfer, which corresponds to the idea that imports of turnkey facilities mainly lead to transfer of equipment and that they contribute little to the transfer of tacit knowledge that could lead to the development of routine and/or innovative capabilities at local firms. The developers of the projects falling under the joint R&D category predominantly claim that no technology transfer has taken place. This directly contradicts the idea that close interactions between local and foreign firms contribute to knowledge transfer. The FDI and informal organisational arrangement types contain mixes of different design document-based transfer categories, including “no information” in many cases, making it difficult to determine the precise relationship between the two indicators.

Overall, there does not appear to be an obvious relationship between the results of the organisational arrangement-based and the project-design-document approaches.

This means that the limitations of the design document approach summarised above are reflected in the results presented here. This finding is supported by a survey of the UNFCCC (2010) which aims to validate the design-document-based approach and concludes that results obtained through this approach should be viewed with caution.

Also, the results illustrate that the design document approach does not provide much useful information about technological learning and innovation at latecomer firms in developing countries (see also Lema and Lema, 2016, p.224). While the approach does consider transfers of knowledge, this mostly seems to concern the knowledge required to operate imported machinery. As such, the project design document-based approach does not offer much insight about the kind of latecomer learning that the present thesis focuses on, i.e. learning at technology-supplying firms related to routine production activities and the creative engagement with technology. While capabilities for technology use are clearly important, they represent only a narrow aspect of the range of capabilities that firms in low and middle-income countries can develop. Such a restricted view of technology transfer fails to account for the wider implications that such transfer can have for the development of local industries and for low-carbon development more generally (Byrne et al., 2011).

5.6.2. Complementary information

The following files can be found on the CD ROM appended to the thesis:

- Appendix Chapter 5a_CDM project database_AD reactors.xlsx
- Appendix Chapter 5b_CDM project database_biogas utilisation.xlsx
- Appendix Chapter 5c_CDM project database_simple TT indicators.xlsx

6. Micro-level dynamics of technological learning

6.1. Introduction to the chapter

This chapter presents the second project that has been conducted as part of the Ph.D. research summarised in this thesis. As explained in Section 2.5, the chapter aims to provide micro-level insights into the kinds of learning mechanisms that Thai biogas engineering firms have used to develop their stocks of technological capabilities. This is done by means of a multiple-case study approach to identify common trends among firms and to highlight potential inter-firm heterogeneity. Furthermore, the chapter seeks to address the knowledge gap with regards to how learning mechanisms change as firms develop increasingly higher levels of capabilities. As explained in Section 2.5, the chapter addresses the following research questions:

> *What types of knowledge and skills have Thai biogas system suppliers acquired through internal and external learning? How have they acquired these? How do learning mechanisms change as latecomers build higher levels of technological capabilities?*

I have collaborated with two senior researchers on this project. In the interest of transparency and to provide evidence that the work presented here can principally be accredited to me, Section 6.2 outlines the contributions of the collaborators. Section 6.3 presents the sampling strategy and method used for data collection. It also discusses how technological capabilities and learning mechanisms have been operationalised. Section 6.4 presents and discusses the results. Section 6.5 provides a brief summary of the chapter.

6.2. Statement on research collaborations

I have collaborated with two senior researchers in the completion of the research project summarised in this chapter. This includes Dr. Ulrich Elmer Hansen, a Senior Researcher at the Department of Management Engineering at the Danish Technical University. Dr. Hansen offered advice in the data analysis and write-up stages of the project. A key contribution was his suggestion to summarise the data on concomitant changes in technological capabilities and learning mechanisms in the form of Table 21 in Section 6.4.3.1. I am currently collaborating with Dr. Hansen on a summary of parts of the research presented here in the format of a journal paper publication. The preparation of this publication has involved discussions about various aspects relating to how the materials are presented to the reader, particularly with regards to the method used and the results.

Furthermore, I collaborated with Dr. Rathanit Sukthanapirat, a Senior Researcher at the Department of Civil and Environmental Engineering at Kasetsart University in Thailand. The Department of Environmental Engineering kindly offered to host me during a field research trip from May to August 2017. Dr. Sukthanapirat organised two of the 13 interviews conducted for this research and was present during four of these. During the interviews, she occasionally asked follow-up questions based on her expertise in AD. In a few instances, she also helped to overcome language barriers by translating from English to Thai and vice versa.

I confirm that the statement above is accurate and complete.

Supervisor signature *Date*

03/12/2018

Ilkka Keppo

6.3. Methodology

6.3.1. Sampling and data collection

Sampling strategy and sample

The goal of the sampling strategy used in this research project was to include as large a number of firms as possible while at the same time keeping the number small enough so that a detailed analysis of their technological learning experiences remained feasible under the given time and resource constraints. Since the project is concerned with the accumulation of technological capabilities in Thailand, the sampling process focused on firms with a local presence, i.e. firms which have a team that is permanently located in Thailand. This means that foreign-based importers of turnkey biogas systems were excluded from the sampling frame. Another aim was to obtain a sample that includes a variety of firms, including small and large, old and young, domestic and foreign-owned, and private and public-sector firms. Finally, I aimed to include the firms which have historically held the largest market shares in the Thai biogas sector. As no detailed information on market shares appears to be available, the selection of firms contacted for interviews was primarily based on the dataset that was developed for the study on Thai biogas CDM projects presented in Chapter 5. This is discussed in more detail below.

I am aware of a total of 31 biogas technology-supplying firms operating in Thailand. Although there might of course be more firms, this number is based on the detailed knowledge of the Thai biogas sector that I have developed over the course of the research conducted for this Ph.D. project. In order to check for information about additional firms, I reviewed reports about the Thai biogas industry (Mehner et al., 2017; Siteur, 2012; Suwansari et al., 2015). Furthermore, almost all of the individuals interviewed for this study mentioned the names of some of their competitors. This was used as further confirmation that all relevant firms had been identified.

At the beginning of this research project, I managed to get in touch with a number of professionals in the Thai biogas industry through my academic network. This allowed me to get access to an initial group of Thai biogas firms. Once the first set of interviews was conducted, some of the interviewees assisted me in getting in touch with further companies. In two cases, a local research colleague established contact with firms directly. Hence, the sampling strategy is based on snowball sampling with elements of purposive sampling to ensure heterogeneity in the characteristics of the sampled firms (Saunders et al., 2007).

In total, I conducted interviews with 13 biogas technology-supplying firms in Thailand. Appendix 6.6.1 provides some background information about the interviews. Three of these firms were deemed unsuitable for inclusion in the comparative analysis presented in this chapter. One of these firms was only founded in the beginning of 2017 and had not been involved in the development of any biogas projects by the time the interviews were conducted. The remaining two firms offer services that differ from those of the other 11 firms. One primarily offers systems for biogas extraction from landfills, which is based on technology with substantially different characteristics from those used for biogas generation from agro-industrial wastes and energy crops. The other focuses on the sale of biogas systems and engineering activities related to biogas utilisation systems. Hence, the final sample used for analysis consists of 10 firms. Key characteristics of these firms have been anonymised due to confidentiality concerns.

I did not conduct interviews with 18 out of the 31 biogas technology-supplying firms operating in Thailand.[15] While some of these declined requests for interviews,

[15] This includes the following: seven relatively small, locally owned, private sector firms (one of which had gone out of business before the fieldwork for this research was conducted); a relatively large local company

others could not be contacted because no up-to-date contact information was available. Assuming that all relevant firms have been identified, the final sample of 10 firms makes up approximately 32% of the total of firms that have been involved in the industry. This represents a relatively large share for a detailed comparative case study.

Table 13 contains some background information about the 10 firms that ultimately became included in this study. The second column of the table illustrates that they vary in size. However, the reader should note that this data provides a somewhat distorted picture since some of the firms also operate biogas projects and employ staff for this purpose. Representatives of some of the firms (Epsilon and Zeta) mentioned that project operation staff made up large shares of their employees. Table 13 also shows that the ages of the firms included in the sample vary. While the oldest firm was founded in the late 1980s (Alpha), the youngest was founded in the 2010s (Kappa). One firm is a subsidiary of a foreign-based multinational (Epsilon). Note that for this firm, the entry under the "Year of foundation" column refers to the starting year of its involvement in the Thai biogas sector. All other firms are local. Two of the local firms are university-based organisations (Alpha and Beta).

Firm	**Number of employees**	**Year of foundation**	**Ownership**	**Type**	**Percentage of Thai biogas CDM projects for which the firm supplied biogas systems**
Alpha	11-50	1985-1990	Domestic	University-based	2.5
Beta	51-100	1990-1994	Domestic	University-based	21.2
Gamma	51-100	1990-1994	Domestic	Private sector	17.8
Delta	101-200	1995-1999	Domestic	Private sector	4.2
Epsilon	101-200	2000-2004	Foreign	Private sector	4.2
Zeta	101-200	2000-2004	Domestic	Private sector	1.7
Eta	11-50	2000-2004	Domestic	Private sector	4.2
Theta	1-10	2000-2004	Domestic	Private sector	8.5
Iota	11-50	2005-2009	Domestic	Private sector	0.0
Kappa	1-10	2010-2014	Domestic	Private sector	0.9
Sum	-	-	-	-	62.7

Table 13: Summary statistics of firms included in the final sample. Sources: interview data and data on Thai biogas CDM projects collected for analysis presented in Chapter 6.

that primarily provides a key system component but also provides design and engineering services; two subsidiaries of foreign multinationals, one of which had terminated its biogas business before the fieldwork for this research was conducted; three local producers of agro-industrial products whose engineering units had begun to develop their own biogas systems; one university-based organisation; a government-supported foundation providing support services for the Thai biogas sector; four foreign-based multinationals that do not have local subsidiaries in the Thai market, one of which was acquired by another before the fieldwork for this research was conducted.

In the absence of detailed information about market shares, data on Thai biogas CDM projects was used to get a sense for these firms' importance in the Thai biogas market. This information is taken from the dataset developed for the analysis presented in Chapter 5. The right-most column of Table 13 shows the percentage of Thai biogas CDM projects for which the firms supplied biogas systems (total: 118). The data shows that the sample includes firms with high shares - in particular Beta and Gamma - and firms with smaller shares. Iota has not been involved in any CDM biogas projects. 13 other firms that have not been interviewed as part of this study have supplied biogas technology to CDM projects in Thailand. However, none of these was involved in more than 2.6% of the total number of Thai biogas CDM projects. This suggests that the sample of this study likely includes the most relevant firms that have been involved in the Thai biogas sector, at least during the time that the CDM has been active.

Hence, the comparative case study presented below is based on a relatively large sample of 10 firms. The variety in their size, age, ownership, type, and market shares provides reassurance that they encapsulate some of the heterogeneity that exists in the Thai biogas industry.

Data collection and potential risks

The field research for this project was conducted in Thailand from May to August 2017. This involved interviewing leading personnel of the sampled firms' management and technical units. Each interview lasted between one and two hours. The interviews followed a semi-structured design. This offered the benefit of being guided by a set of questions while at the same time being flexible to discuss issues that had not originally been included in the interview guide (Saunders et al., 2007). Each interview began with a number of questions about the historical background and business profile of the firm. The interviewees were then asked to identify the most relevant technological milestones and breakthroughs that their firms had achieved throughout their lifetimes. In the final and longest stage of the interviews, these milestones were discussed one after another. This included questions about what they imply in terms of the technological capabilities that the firms had accumulated and the different learning mechanisms that they had used to achieve these milestones. Appendix 6.6.2 contains the complete interview guide.

This method of data collection bears a number of risks. Section 3.3 has already discussed the issue of language barriers that applies equally to the analysis presented here and in Chapter 5. Given that the analysis presented here is based on interviews, a number of further issues need to be discussed.

For instance, there are some issues that relate specifically to interviews conducted with experts. All of the interviews included in the analysis below have been conducted with leading personnel of Thai biogas engineering firms. As such, they can be considered expert interviews.[16] Interviewing experts has a number of benefits. For example, it allows the researcher to gain access to specific and detailed knowledge that would be difficult to obtain otherwise (Van Audenhove, 2007). This is clearly important in the context of the present study as it involves collecting detailed information about the technological learning experiences of firms. Another benefit of interviewing experts is that the researcher might be able to tap into the experts' personal networks to identify potential candidates for further interviews (*ibid.*). As explained above, I made use of the snowballing method, which was greatly facilitated by the fact that many professionals in the Thai biogas sector appear to be well connected with each other.

However, expert interviews also present certain challenges, particularly relating to the characteristics of the researcher. As such, it is critical to reflect on the impact that I have had on the research process and outputs. Interviewing experts puts researchers - particularly junior researchers - into inferior positions in which they ask experts to share their time and knowledge without having much concrete benefits to offer in return. Also, the researcher's status and knowledge of the issues discussed influence the information that the interviewee is willing to provide (Van Audenhove, 2007). Therefore, the success of the interviews in the case of the present study depended decisively on the my technical knowledge of biogas systems. I acquired such knowledge by extensively reviewing the technical literature and by completing the research project based on publicly available information (presented in Chapter 5) prior to conducting the interviews. Before embarking on the research trip to Thailand, I also conducted a pilot interview with a large British biogas engineering company to test the interview guide and to see whether my knowledge of key processes at biogas plants was adequate to hold a detailed discussion about the technical aspects involved in the development and supply of biogas projects.

Another potential problem with the data collection method used here is that interviewees might give inaccurate accounts of their firms' histories. Some might

[16] Meuser and Nagel (1991, p.433) define an expert as somebody who is in charge of planning, executing, and controlling solutions or strategies and who has special access to information about processes, groups, or behaviours.

overstate achievements due to social desirability bias. Other interviews might suffer from recall bias as subjects might find it challenging to remember details of events that occurred far in the past. As Eisenhardt and Graebner (2007, p.28) put it, interviews of this type bear the risk of "retrospective sensemaking by image-conscious informants." Ideally, this problem would be addressed by interviewing multiple individuals working in the same organisation to obtain information from a variety of perspectives. However, this was considered infeasible given the time and resource constraints of the research project and the relatively small sizes of some of the firms included in the study. Instead, I collected data from alternative sources to triangulate the information obtained through the interviews. This included company brochures and webpages, the database of Thai biogas CDM projects that I developed for the analysis presented in Chapter 5, project documentation by other organisations, the technical and academic literature, patents, news articles, and industry periodicals. In a few instances, interviewees were contacted via email after the interviews had been conducted to request clarification or additional information. Finally, I also collected quantitative data from the monitoring reports of CDM projects (See Appendix 6.6.3 for more information).[17]

6.3.2. Operationalisation of key concepts

Operationalising capabilities

Assessing the technological capabilities of firms is not a straight-forward task. There is no single indicator that encompasses all relevant dimensions and assessing individual components directly - such as human resources, experience, skills, knowledge bases, and organisational systems - is challenging in practice. For these reasons, many authors use what has been referred to as the revealed capabilities approach (Bell and Figueiredo, 2012a, p.20). This involves collecting data on certain characteristics of a firm's innovative activities, including innovation inputs (e.g., human and financial resources), processes (e.g., the use of particular technical and organisational methods), and outputs (e.g., relating to the novelty and complexity of innovations). Based on the firm's involvement with these, the researcher then infers the kinds of capabilities it likely possesses. This is typically based on scales distinguishing between different levels and types of capabilities

[17] This information has been used as additional information about differences in the sizes of projects that the firms included in this study have developed. As explained in detail in the following section, project size is used as one of several indicators that provide information about the capability levels that a firm possesses.

(basic routine, extra basic routine, basic innovative, intermediate innovative, etc.) along the lines of Table 2 presented in Section 2.1.

The list of indicators used in this study to determine the capabilities that Thai biogas technology-supplying firms have developed over time are presented in Table 14 below. All of these indicators relate to the technical capabilities that latecomer firms accumulate. To remind the reader, this is based on Dutrénit (2007, 2004), who argues that these kinds of capabilities are particularly important for capability accumulation below and up to the advanced level of innovative capabilities. Other kinds of capability types, e.g. relating to marketing, project management, or financing, are not considered in much depth here.

Aspect of routine production and innovation processes	**Indicator**	**Description**
Inputs	Qualifications of staff	The qualifications of staff are used as a measure for the knowledge, skill, and experience that a firm possesses. Qualifications are determined based on two dimensions: the type of degree/training that staff have completed and the levels of experience in biogas or related sectors that they have accumulated.
	Collaborations with external partners	Following Lall (1992), information on collaborations with external partners is used as an indicator for the firm's linkage capabilities, i.e. its ability to establish connections to other organisations that allow for the transmission of information, skills, and equipment. Collaborations are distinguished by type, intensity, and continuity.
Performance	Methods and tools	Methods and tools refer to the particular kinds of activities that firms engage in during innovation processes - e.g., the use of particular methods to test substrates, to experiment with new designs, etc.. These are distinguished based on the complexity of the required knowledge bases and the amount of required experience. Amsden and Tschang (2003) use a similar indicator in their study on R&D in the Singaporean electronics and biotech sectors.
	R&D and design and engineering activities	Following Amsden and Tschang (2003) and Radosevic and Yoruk (2018, 2016), the innovative activities of firms are distinguished based on what kinds of activities along the innovation chain they involve (basic or applied research, exploratory or advanced development, or product engineering). It is important to note that there is not necessarily a linear relationship between different levels of capabilities and the activities along the innovation chain (as discussed in Section 2.1).
Outputs	Awards	Awards are used as indicators for the firm's ability to develop novel and complex technology. They are distinguished based on whether they involve national or international prizes.
	Exports	Exports are interpreted as an indication for the firm's ability to participate in competitive international markets (e.g., see Ernst et al., 1998). Furthermore, they are seen as an indicator for the ability of the firm to develop systems that are suitably adapted to circumstances that differ from those found in Thailand. Exports are distinguished based on the number of projects and the regions where they take place (neighbouring countries in Southeast Asia, other low/middle-income regions, high-income regions).
	Patents	Patents are understood to be an indication of the ability of the firm to develop technology that meets the novelty criteria for patentability. They are differentiated based on whether they are national patents or EPO/USPTO patents, assuming that

	the latter involve more substantial novelty, complexity, and potential economic impact.
Performance standards	Following Radosevic and Yoruk (2018), ISO 9001 certificates are used as an indicator for high operational efficiency and, thus, for the presence of high-level routine production capabilities. In addition, the study also considers ISO 17025 certificates as indicators for routine capabilities. These concern quality standards at testing and calibration laboratories (International Organisation for Standardization, 2018) and, therefore, are relevant for biogas technology-supplying firms.
Product innovations	This indicator ranks innovations according to their novelty and scope of change. With regards to the former, the study follows the Oslo Manual and distinguishes between the following categories: new-to-firm, new-to-market, and new-to-world (OECD, 2005). The scope of change is determined by comparing the different kinds of innovations that the firms included in this study have engaged in.
Reactors - size	The size of the reactor is interpreted as an indicator for the complexity of the systems that a firm can handle. While Ariffin and Figueiredo (2004, p.580) point out that one ought to differentiate between a firm's ability to (i) creatively engage with technology and (ii) to handle technological complexity, I maintain that handling complex technological systems requires an element of creative engagement (e.g., with respect to the need to adapt technological designs to project contexts). Reactors are allocated to one of three categories: small and medium, large, very large.
Reactors - variety	The variety of reactors that firms offer is seen as an indicator for the breadth of the firm's knowledge base. A broad knowledge base allows firms to offer various system designs that are appropriate for different project contexts. Firms are categorised based on the number of different reactor types that they have developed.
Scientific publications	Scientific publications are seen as an indicator for the firm's capability to undertake basic and applied research. Data for this indicator is distinguished based on the frequency of research outputs and the quality of the outlets in which they are published.
Substrates	Similar to the indicator based on the variety of reactors that a firm offers, information on the variety of substrate types that a firm has worked with provides insights about the breadth of its knowledge base. In addition, the amount of dry matter content of substrates is seen as an indicator of the firm's ability to handle technological systems that require sophisticated technological know-how (source: multiple interviews conducted for this study).
System performance	System performance is used as an indicator for routine capabilities, i.e. the ability of the firm to supply well-functioning technological systems. A simple distinction is made between systems that operate well and those that do not.
Trademarks	Following Mendonça et al. (2004), trademarks are used as an indicator for the firm's ability to offer differentiated products and, thus, are seen as an indicator for high-level routine production capabilities.
Types of service	Finally, the types of services that firms engage in are considered to reveal further information about their capability levels. In particular, firms that are hired to fix underperforming biogas systems which were previously developed by competitors are considered to enjoy a good reputation for their technical capabilities among clients. As such, companies that have offered such revamping services are considered to exhibit high levels of routine capabilities.

Table 14: Summary of indicators used to determine the capability levels of firms.

The list of indicators shown in Table 14 was developed based on an iterative process of consulting the academic literature and the data collected as part of this research. Prior to the start of the data collection process, I compiled a comprehensive list of potential indicators based on the literature on latecomer capability accumulation (including Amsden and Tschang, 2003; Bell and Figueiredo, 2012b; Figueiredo, 2003;

Hansen and Ockwell, 2014; Radosevic and Yoruk, 2016). When conducting interviews with Thai biogas engineering firms, this list was continuously updated to reflect the indicators that were identified as most relevant for the present case. This also involved going back to the literature to gain a better understanding of the capability indicators that had been mentioned during the interviews, i.e. to determine what exactly they imply in terms of capabilities and to see if and how other studies have used them. As such, the list of capability indicators in Table 14 has been developed specifically with the empirical case of the present study in mind. Similar approaches focusing on other sectors would likely result in different sets of indicators. The right-hand column of the table briefly summarises how each indicator relates to the technical capabilities of firms. More detailed information on the capability indicators is included in Appendix 6.6.3.

Having introduced the different indicators, the next step is to think about what ranges of capability levels they represent. While the description of the indicators in Table 14 already contains some information on types and levels of capabilities, Table 15 below provides a more detailed overview of these. The columns of the table illustrate the distinction between routine production (basic and extra basic) and innovation capability types (basic, intermediate, advanced, and world-leading). This reflects the distinction between capability categories and levels introduced in Table 2 of Section 2.1. The grey shading illustrates the ranges of the capability categories and levels which each individual indicator covers. These ranges were determined based on the latecomer capabilities literature, the technical literature on biogas systems, and cross-firm comparisons of the information available from the interviews and supplementary data sources. Appendix 6.6.3 provides additional information on how these ranges have been determined for each indicator.

<table>
<tr><th rowspan="2">Aspect of innovation process</th><th rowspan="2">Indicator</th><th colspan="2">Routine</th><th colspan="4">Innovative</th></tr>
<tr><td>Basic</td><td>Extra basic</td><td>Basic</td><td>Inter-mediate</td><td>Advanced</td><td>World-leading</td></tr>
<tr><td rowspan="2">Inputs</td><td>Qualifications of staff</td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td></tr>
<tr><td>Collaborations with external partners</td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td></td></tr>
<tr><td rowspan="2">Performance</td><td>Methods and tools</td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td></td></tr>
<tr><td>R&D and design and engineering activities</td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td></td><td></td></tr>
<tr><td rowspan="12">Outputs</td><td>Awards</td><td></td><td></td><td></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td></td></tr>
<tr><td>Exports</td><td></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td></tr>
<tr><td>Patents</td><td></td><td></td><td></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td></tr>
<tr><td>Performance standards</td><td></td><td style="background:#a6a6a6"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Product innovations</td><td></td><td></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td></tr>
<tr><td>Reactors - size</td><td></td><td></td><td></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td></tr>
<tr><td>Reactors - variety</td><td></td><td></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td></tr>
<tr><td>Scientific publications</td><td></td><td></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td></td></tr>
<tr><td>Substrates</td><td></td><td></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td></tr>
<tr><td>System performance</td><td style="background:#a6a6a6"></td><td style="background:#a6a6a6"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Trademarks</td><td></td><td style="background:#a6a6a6"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Types of service</td><td></td><td style="background:#a6a6a6"></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 15: Capability ranges covered by different indicators. The grey-shaded areas indicate the variety of capability levels that data on each indicator reflects.

As explained above, data on these indicators has been collected using interviews and supplementary data sources. To provide the reader with a sense for the scale of the resulting dataset, Table 16 provides an overview of the number of individual pieces of information that were categorised under each indicator and for each of the 10 firms included in this study. These pieces of information are mostly statements by the interviewees and occasionally refer to information from supplementary data sources. The reader should note that the numbers are not always consistent across firms and indicators. For instance, in some cases one entry for awards refers to a single prize that a firm was awarded while in other cases an entry might refer to a range of similar prizes that the firm has won over a defined time period. As such, the purpose of the table is not to provide a comparative overview of data availability across firms and indicators but to provide the reader with a sense for the amount of data that has been used to develop the aggregated capability levels. These are discussed next.

Aspect of innovation process	**Indicator**	**Firm**									
		Alpha	Beta	Gamma	Delta	Epsilon	Zeta	Eta	Theta	Iota	Kappa
Inputs	Qualifications of staff	3	3	4	8	9	5	4	5	2	10
	Collaborations with external partners	3	9	3	6	4	4	3	2	7	4
Performance	Methods and tools	5	7	7	5	4	3	1	4	5	5
	R&D and design and engineering activities	8	9	4	5	5	2	4	2	5	7
Outputs	Awards	3		4	3	2	4	2			2
	Exports	1	2	1	3	3	1	2	1		4
	Patents		3						1		
	Performance standards		1	1	1	1	3				
	Product innovations	1	4	3	6	4	3	4	2	6	5
	Reactors - size	1	5	1	3	2	1	1	1		2
	Reactors - variety	2	9	2	3	2	1	4	2	5	1
	Scientific publications	1	1						1		1
	Substrates	7	5	1	6	2	1	4	2	8	6
	System performance	5	4	2	2	2	4	2	1		1
	Trademarks				1	1					1
	Types of service	1			1	1					1

Table 16: Overview of data entries falling under each capability indicator for the firms included in the study.

The aggregation of the individual capability indicators into an overall capability level for each firm involved a number of steps. First, each piece of information was ranked according to the ranges illustrated in Table 15 (see Appendix 6.6.3 for more details). For this purpose, I adopted Miles et al.'s (2014, p.214) approach of case-ordered descriptive matrices to analyse and categorise the data on individual capability indicators.

Subsequently, each piece of information was assigned a year, which allowed for temporal ordering. In the words of Miles et al. (2014, p.194), this led to the development of event-listing matrices for each firm. These matrices served as capability biographies that provide detailed information about the capability development pathways that the firms included in this study have undertaken. Next, using these biographies, I divided each firm's lifetime into different stages. The stages were determined based on marked changes in the types of activities that firms engage in with regards to the routine production and innovation inputs, performance, and outputs. The number of different lifetime stages for each firm range from one to four.

Finally, I determined a single, overall capability level for each lifetime stage of each firm. Given the amount of information available on the capability indicators, I considered assigning overall capability levels to lifetime stages more practical than attempting to assign an individual level to every year of a firm's lifetime.

The use of a quantitative weighting system to aggregate individual indicators into an overall capability level was considered impractical for two reasons. On the one hand, the amount of information that is available for the lifetime stages of the firms is inconsistent. As such, some overall capability levels had to be based on three pieces of information while others were based on eight or more. On the other hand, there is no theoretical basis to determine the weights for individual indicators. As such, it is unclear whether, for example, an entry about the award of a national prize for a particular biogas project should be considered to contribute to the overall capability score to an equal extent as a collaboration with a foreign-based research centre.

For these reasons, I decided that combining the information on the individual indicators for a particular firm and lifetime stage needed to be based on my personal understanding of the firms' histories. Of course, this involved an element of subjective judgement. However, given the qualitative nature of this research and the fact that I have developed a detailed understanding of the firms' capability development pathways, this is considered appropriate.

I am unaware of any existing studies which focus on firm-level latecomer learning and analyse capabilities in a similarly structured and transparent way. While some have developed capability indices at the level of the economy (Archibugi and Coco, 2004; Fagerberg and Srholec, 2008; Radosevic and Yoruk, 2018), there appear to be no studies that assess capabilities in a similar way at the level of the firm. Most other firm-level studies tend to provide comparatively little information about the capability indicators that they rely on and the ways in which they aggregate these into overall capability levels.

Operationalising learning mechanisms

The final list of learning mechanisms was developed in a similar way to the list of capability indicators. Before going into the field, I compiled a comprehensive list of learning mechanisms based on the literature on latecomer capabilities. During the data collection process, I checked which of these were most relevant in the case of Thai biogas technology-supplying firms. This included the occasional use of prompts and probes to find out in more detail which learning mechanisms were most relevant. The list of learning mechanisms was adapted over the course of the data collection procedure.

Type	Internal	External-domestic	External-foreign
Human resources	- Education and experience of founding members	- Learning by hiring staff educated at local university and/or with experience from local organisation	- Learning by hiring staff educated at foreign university and/or with experience from foreign organisation
Project -based	- Learning by doing on a project-to-project basis - Learning by using through operation of projects - Learning through systematic collection and analysis of operational data	- Learning through observation of project developed by local company - Learning through operation of project developed by local company - Learning by acquisition of project developed by local company - Learning through collaboration with local component supplier - Learning through collaboration with local engineering and construction company - Learning through collaboration with local biogas expert - Learning from user feedback	- Learning through observation of project developed by foreign company - Learning through operation of project developed by foreign company - Learning through acquisition of project developed by foreign company - Learning through collaboration with foreign component supplier - Learning through collaboration with foreign engineering and construction company - Learning by collaborating with foreign biogas system designer
R&D	- Learning through testing at pilot-scale plant - Learning through testing in laboratory - Learning through on-site testing - Learning through trial and error experimentation	- Learning through collaboration with local testing facility - Learning through research collaboration with local organisation	- Learning through collaboration with foreign testing facility - Learning through research collaboration with foreign organisation - Learning through consultation of the academic and technical literature

Table 17: List of learning mechanisms used in the analysis.

Table 17 illustrates the final list of learning mechanisms that has been adopted for the study. The learning mechanisms have been divided by the origin of the knowledge that they are based on. Following Hansen and Lema (2019) and Hansen and Ockwell (2014), the study distinguishes between learning based on firm-internal learning activities, learning based on external knowledge from domestic sources, and learning based on external knowledge from foreign sources. In addition to differentiating learning mechanisms by source, they are also distinguished by type (see first column of Table 17). This includes learning mechanisms related to human resources, technological learning that takes place as part of project-related activities, and learning based on R&D activities.

Table 18 provides an overview of the number of pieces of coded information that fall into each category for the 10 firms analysed here. As was the case for the capability indicators above, it should be noted that the numbers presented here are not necessarily consistent across firms and indicators. The purpose of the table is to give the reader a sense for the amount of information available.

Source	**Type of learning mechanisms**	**Firm**									
		Alpha	Beta	Gamma	Delta	Epsilon	Zeta	Eta	Theta	Iota	Kappa
Firm-internal	Human resources	1		3	1	3	3	2	5	2	3
	Project -based	1	7	1	10		3	2	1	3	
	R&D	1	3	1	4	1			2	1	2
External-domestic	Human resources	2		1	1		2			2	2
	Project -based	4	5	1	1	1				1	2
	R&D	2		2					1	1	
External-foreign	Human resources	1			3	2					
	Project -based		5	1	5	1	3	3	1	5	5
	R&D	1	3	2		2				1	3

Table 18: Overview of data entries falling under each learning mechanism type for the firms included in the study.

As with the capability indicators, each of these pieces of information about learning mechanisms was assigned a year. This allowed me to develop learning mechanism biographies for the firms. Based on the year that individual pieces of information were assigned, the learning mechanisms were allocated to one of the firms' lifetime stages as explained above. The learning biographies and capability biographies formed the basis for the analysis presented in the following section of this chapter.

6.4. Results and discussion

The presentation and discussion of the results proceeds in three stages. Section 6.4.1 presents the results for the overall capability levels of the 10 firms included in this study. Based on similarities in the trajectories of their capability development, the firms are then allocated to one of four groups. Section 6.4.2 presents and discusses the data on learning mechanisms and analyses differences in the kinds of mechanisms that are most prevalent across these four groups. Section 6.4.3 presents and discusses the results with respect to concomitant changes in capability levels and learning mechanisms.

6.4.1. Capability development pathways

This section presents and discusses the data on capability levels. For this, it also discusses some of the micro-level data that the overall capability levels are based on. To reiterate, the research question addressed here is:

> *What types of knowledge and skills have Thai biogas system suppliers acquired through internal and external learning?*

6.4.1.1. Results

As mentioned in the summary of the history of the Thai biogas industry (Section 4.5), the market for medium and large-scale biogas systems in Thailand was comparatively small before the turn of the millennium. The data collected for this study reflects this. Figure 13 shows that only few of the firms included in the sample analysed here existed in the 1980s and 90s (only Alpha, Beta, and Gamma). Two of these are university-based organisations (Alpha and Beta) which have developed many of their initial projects with the support of the Thai government and/or foreign development agencies. This included the early and scattered efforts to introduce AD systems at cassava processing and liquor facilities in the 1980s as well as the projects developed under the 1988-1995 Thai-German Biogas Programme highlighted in Section 4.5.

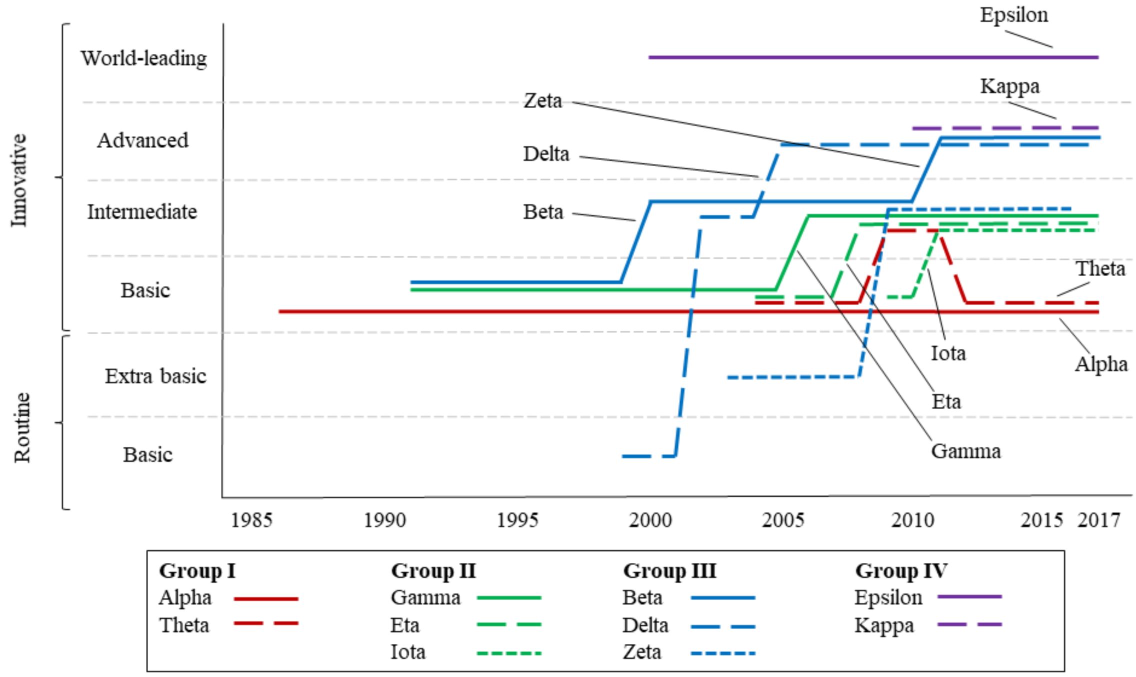

Figure 13: Development of technological capabilities at the firms included in the present study, 1985-2017.

Overall, the technological capability levels of the firms in the Thai biogas industry were relatively low before the year 2000. Alpha, Gamma, and Beta all fall under the basic innovative category for this period. This is likely related to the limited incentives that firms faced to invest in their capability stocks at the time due to the low demand for biogas systems and unfamiliarity of potential clients with the technology. Reflecting on the state of the market in the mid-1990s, a representative of Gamma remembered:

> *"[It was] very hard to make the customer/the factory know what the biogas system is. Because in Thailand, [at] that time, there was no biogas technology. Even the name [of the technology] ... [clients did] not know anything."*

Also, there was only limited policy support for the development of the sector at the time. Relevant policies mostly had an agricultural waste management focus and did not aim to promote the use of biogas to generate heat, electricity, or fuels for transport. In fact, most anaerobic digesters at the time were installed with a primary focus on reducing the discharge of polluted water into rivers and to protect nearby communities from odour from openly stored wastes (source: multiple interviews conducted for this study). As such, the potential to generate biogas from the waste of the country's large agricultural and agro-industrial sectors remained largely untapped during this time.

Around the year 2000, there was a marked change in the sector's development. As described in Section 4.5, the market rapidly expanded during the 2000s and 2010s. Key determinants for this were the Thai economy's dependence on energy imports and the increasing price of oil (source: multiple interviews conducted for this study). To reduce dependence on energy imports, the Thai government introduced a variety of measures to promote the domestic generation of energy around this time (International Renewable Energy Agency, 2017). This included allowing biogas producers and other renewable energy generators to sell electricity to the grid authorities via power purchase agreements and, additionally, to pay them an Adder on top of the price for each unit of electricity sold. As illustrated in Chapter 5 (Figure 9, Section 5.2.4), the market for biogas was further supported through Thailand's participation in the CDM, which experienced rapid growth throughout the 2000s and early 2010s. In addition, the Thai government introduced a variety of other support measures, including investment subsidies, soft loan schemes, tax relief, and technical assistance programmes (as highlighted in Section 4.5). While the representative of Gamma mentioned the difficulty of selling biogas systems prior to the year 2000 (see quote above), s/he described the post-2000 period as the "honeymoon period for renewable energy".

The rapid growth of the Thai biogas sector is reflected in the data presented in Figure 13 above. Many of the firms included in the present study entered the market in the period from 2000-2010 (Delta, Epsilon, Zeta, Eta, Theta, Iota, and Kappa). Aside from Epsilon and Kappa, all these firms started out at relatively low levels of capabilities, ranging from the basic routine to basic innovative categories. However, many of them appear to have invested in technological learning during this period, as suggested by their relatively rapid transitions towards higher positions on the capability ladder. Furthermore, the rate of change in technological capabilities levels after the year 2000 is notably faster compared to the pre-2000 period: three to six years as opposed to nine to 15 years for the former. While this thesis does not go into detail about how individual policy support mechanisms have affected firm-level capability accumulation, the interviews made clear that the market support schemes summarised above have had a decisive impact on the firms' decisions to invest in their capability stocks.

Figure 13 also allocates the firms into four groups based on the capability trajectories that they have undergone. Group I consists of firms that have experienced little or no change in their capability stocks throughout their lifetimes (Alpha and Theta). While Alpha remained at the same capability level throughout, Theta has actually reverted back to its original basic innovative level after temporarily having exhibited capabilities of the intermediate innovative class. The firms in Group II have all experienced moderate increases from the basic innovative to the intermediate innovative capability category, although at different speeds (Gamma, Eta, and Iota). Group III consists of firms that have managed to upgrade their technological capability stocks more substantially (Beta, Delta, and Zeta). While Zeta has transitioned once from the extra basic routine to the intermediate innovative class of capabilities, Beta and Delta have transitioned to higher levels twice and have managed to reach the advanced innovative level. Finally, the firms included in Group IV have exhibited high levels of capabilities at the advanced and world-leading levels since they were founded (Kappa) or became involved in the Thai biogas market (Epsilon).

Table 19 below provides further detail on the differences across the four groups of firms. Following Table 15 (presented in the methodology section of this chapter, see Section 6.3.2), it lists all capability indicators considered here and uses grey shading to illustrate which capability levels these can take. As explained above, this is based on a review of the literature on latecomer technological capabilities (also, see Appendix 6.6.3 for more details). The black shading in the table illustrates the ranges of capability levels which the different groups exhibit based on the data available for the various indicators.[18] The table shows that the firms which have achieved higher levels of *overall* capability levels score higher on nearly all individual capability indicators too. There are only few exceptions, including the indicators for patents and scientific publications.[19] This demonstrates the usefulness of basing estimates of overall capability levels on a multitude of different capability indicators. While focusing on a single or smaller number of indicators - e.g., patenting - could lead to bias with respect to certain kinds of activities that firms perform, assessing a wide range of indicators allows for the development of a

[18] The reader should note that, to reduce complexity, the table does not include a temporal dimension. As such, the table does not demonstrate how the different firms' and groups' performance on the individual capability indicators has developed across the various stages of their lifetimes.

[19] The fact that firms with high capability levels do not produce many scientific publications is not surprising. In fact, many of the firms interviewed for this research mentioned that they take active measures to prevent knowledge spillovers to competitors. As such, they are unlikely to make the results of their R&D available to the public by publishing them in academic papers. Potential reasons for why patents are not commonly used in the Thai biogas industry are discussed in Section 5.3 and include preferences for other intellectual property protection strategies (e.g., secrecy or complementary capabilities) and weaknesses in the local intellectual property rights protection system.

more thorough understanding of the firms' capability stocks (Kragelund, 2005, p.105/106).

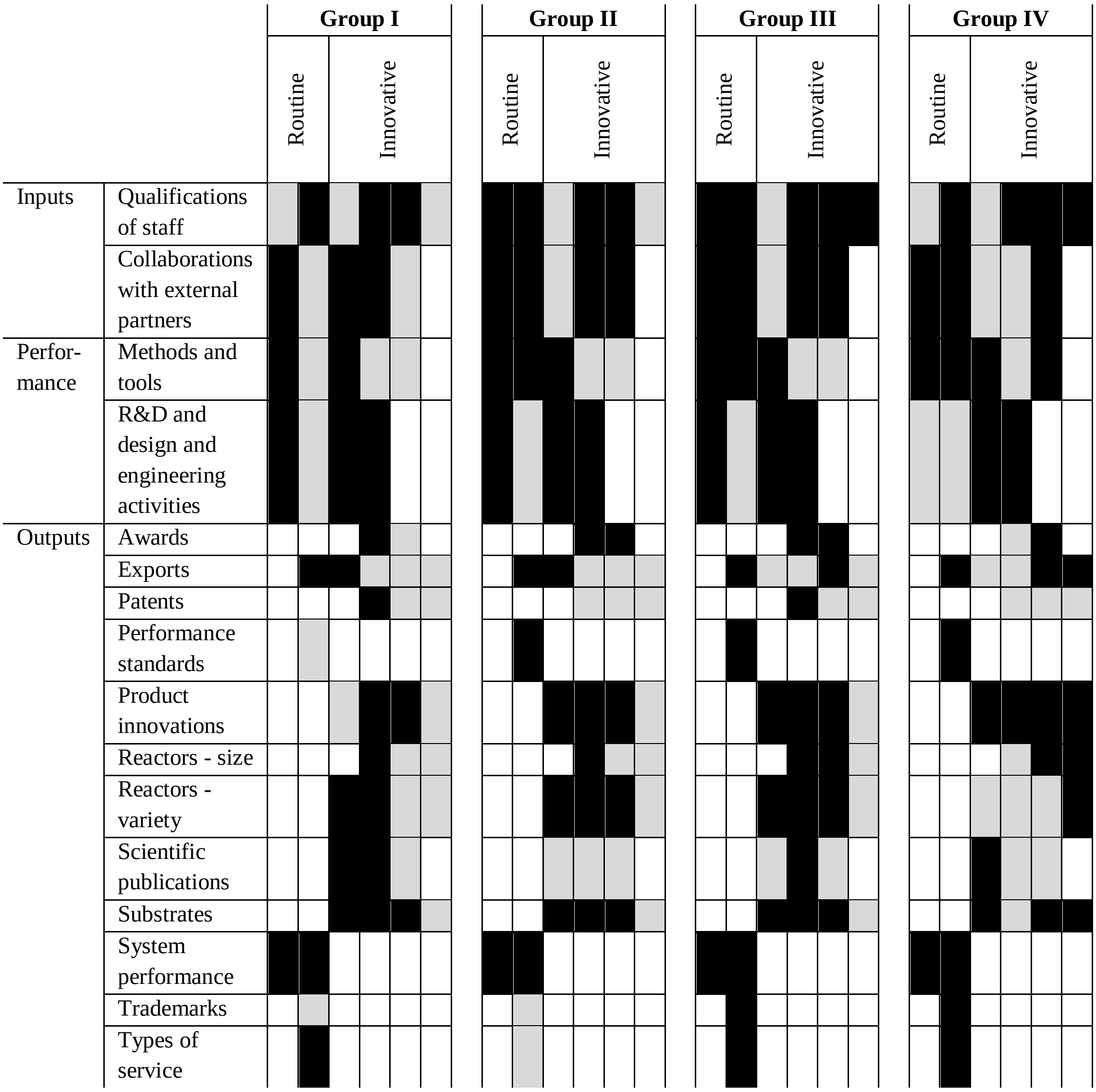

Table 19: Overview of data on capability indicators for the four groups. Grey shading: possible ranges of capability indicators. Black shading: capability levels at which data for firms in a particular group has been ranked at different stages in their lifetimes.

The remainder of this section presents the data on capability indicators that underlie the aggregated information presented in Figure 13 and the data shown in Table 19. Rather than going over each capability indicator for each group individually, only the most distinguishing features are highlighted.

Group I: No/limited changes in capability levels (Alpha and Theta)

While Alpha and Theta exhibit comparatively low levels of technological capabilities throughout their entire lifetimes, the two firms actually score high on the indicator representing the qualifications of the staff working in their R&D and other technical departments. In fact, the interviews with Alpha and Theta revealed that many of their founding members had earned Ph.D. degrees from renowned universities in Thailand and abroad, including universities in England, the United States, and Australia. The interviews also showed that the firms' founding members all have strong linkages to leading Thai universities. In fact, Alpha is a research and engineering unit based at a large local university which specialises in waste treatment and biogas. The founder of Theta used to work as a lecturer at another major university and regularly collaborates with other Thai and foreign scholars on biogas-related research projects. Furthermore, the interviewees indicated that Alpha's and Theta's founding members have accumulated much experience through their involvement with AD systems since the early days of industry-scale wastewater treatment in Thailand. Among other projects, this included the early experiments with industry-scale AD systems to treat wastewater at cassava starch and liquor factories in the 1980s (highlighted in the history of the Thai biogas sector in Section 4.5).

Despite the qualifications of their leadership and staff, Alpha and Theta have engaged in little innovative activity compared to the other firms included in this study. Based on the interviews, it appears that the two organisations only generated a limited number of new-to-firm and new-to-country innovations. One of the founding members of Alpha collaborated with an M.Sc. student in the mid-1980s to develop a small-scale pilot reactor which allows the micro-organisms involved in the AD process to grow on a fixed medium inside the reactor. According to one of Alpha's representatives, this system allows for a reduced reactor size while at the same time preventing micro-organisms from becoming washed out of the reactor. Alpha later used this design as a basis for most of the industrial-scale biogas projects it has developed. Similarly, the founder of Theta acted as an advisor for a research project of an M.Sc. student which aimed to develop a pilot-scale digester at a palm oil mill. The design developed for this project includes a mechanism to scrape settled solids at the bottom of the reactor to prevent clogging. In a later stage of its lifetime, Theta independently developed another reactor design which includes a certain type of feeding mechanism and a two-layered design separating the treatment of high-strength, high-solid and lower-strength, lower-solid substrates. Unlike most other firms included in the sample of this study, Theta decided to protect this design by registering a patent with the Thai Intellectual Property Office. Thus, while both Alpha and Theta introduced some changes in key components of biogas systems, this occurred rather infrequently. Furthermore, many of the changes introduced by Alpha and Theta are minor compared to those introduced by the firms included in Groups II-IV.

Regarding linkages to other organisations, the information from the interviews suggests that both Alpha and Theta only engage with a limited number and variety of other organisations. Both firms appear to have good connections to the Thai government; while Theta's CEO used to work for a government ministry prior to founding the firm, Alpha has a partnership agreement with a public research institute that is government-funded. However, based on the interviews, it seems that these connections did not play a major role for the technology development activities described above. Furthermore, Alpha and Theta highlighted that they source key components from local suppliers, but they did not mention that these interactions were particularly important for the development of reactor designs or for solving problems encountered during the implementation of these designs in projects. More generally, the representatives of Alpha and Theta did not emphasise any interactions apart from the previously mentioned collaborations with local universities during the early stages of the firms' lifetimes.

Another indication of their relatively low levels of innovative capabilities is the finding that, based on data from the monitoring reports of CDM projects, their projects are among the smallest in size of the ones developed by the firms included in this study (see Figure 14). Furthermore, the interviews revealed that both firms only work with two reactor designs, suggesting that they possess a limited ability to offer systems which are tailored to the specific characteristics of different substrate types. Correspondingly, the interviews revealed that both firms only work with a relatively narrow range of substrate types, which mostly include liquid wastes. The interview with Theta also revealed that the firm has recently begun the development of a design for a reactor which will run on Napier grass. However, as the interviewee explained, this design had not been realised by the time the interview was conducted due to uncertainty regarding policy support for projects based on this substrate type.

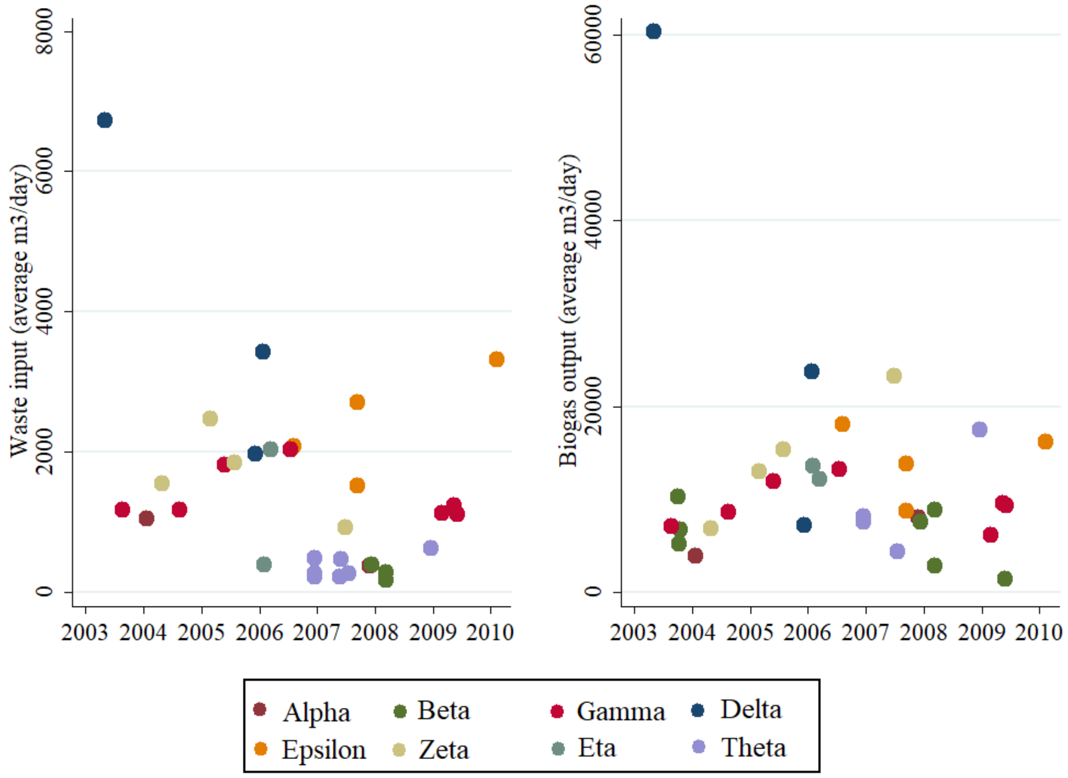

Figure 14: Sizes of biogas systems developed by firms included in this analysis. Data source: monitoring reports of CDM projects. Note: Iota and Kappa are not included in this figure as they have not registered any of their biogas projects in Thailand with the CDM.

Finally, Alpha's systems frequently experience problems due to clogging. This means that for this particular indicator, the firm's capability levels actually fall under the basic routine level. This issue was pointed out by several of its competitors that have been interviewed as part of this research. Also, one of Alpha's interviewees acknowledged that some of their projects face operational difficulties.

To summarise, while Alpha and Theta are led by experienced biogas experts, the available evidence suggests that the two firms have engaged in comparatively little innovative activity. Linkages to other organisations mostly revolve around one-off collaborative projects with local universities. Both firms work with a limited variety of reactor designs and substrate types.

Group II: Moderate increases in capability levels (Gamma, Eta, and Iota)

Gamma, Eta, and Iota all underwent transitions from the basic to the intermediate innovative capability levels.

As Group I, the three firms employ staff who have many years of experience in biogas. Gamma was one of the first private-sector firms in the Thai biogas industry and is perhaps the oldest locally owned firm. During the interview, its representatives stressed that the firm's founding members first gained experience with AD during their M.Sc. degrees at Thai universities. Eta and Iota were founded during the mid-2000s, a period when the Thai biogas sector underwent rapid and sustained growth. Eta's interviewee highlighted that he/she first gained experience with biogas during his/her Ph.D. studies at a renowned Dutch agricultural university. Furthermore, prior to the foundation of Eta, the core staff of the firm gained experience with biogas when working at a university-based organisation, first as part of the 1988-1995 Thai-German Biogas Programme (highlighted in Section 4.5) and later in a range of university-led projects. In the mid-2000s, they decided to found Eta as a spin-off firm to develop projects in the private sector. Iota's core staff gained experience with biogas when working at a governmental energy policy advisory agency and when implementing biogas projects as part of a university-based organisation. Same as Eta, the founders of Iota decided to spin off their own private sector firm in the mid-2000s.

Compared to Alpha and Theta, the firms included in Group II have been involved in more R&D, which has resulted in a range of innovations. For example, in the mid-1990s, Gamma was the first local company to adopt the Upflow Anaerobic Sludge Blanket design for the treatment of agro-industrial wastes in Thailand. At a later stage in its lifetime, Gamma also developed a limited number of projects based on a Completely Stirred Tank Reactor design. However, the interview and the information available on the firm's website revealed that most of the firm's projects are based on the Upflow Anaerobic Sludge Blanket design. Many of these projects involved minor adaptations of the basic design to the characteristics of the substrates available at these projects. Eta entered the market with a design containing a sludge removal device at the bottom of the reactor, which is similar to design developed by Theta described above. The interviewee of Eta explained that this design was based on his/her Ph.D. research in the Netherlands. At a later stage in Eta's lifetime, the firm adopted three additional reactor designs for different kinds of substrates with higher solids content. The interviewee of Iota explained that his/her firm adopted two different reactor designs: a Modified Covered Lagoon design and a Completely Stirred Tank Reactor design involving hydraulic or mechanical mixing processes, depending on the substrate type at hand. Additionally, the interview with Iota highlighted that the firm experimented with a variety of waste pre-treatment and biogas upgrading processes. Hence, the three firms included in this group have engaged in a range of innovative activities. However, as in Group I, the resulting technological changes are comparatively minor and mostly involve small changes in basic designs.

While there are some instances of new-to-country technology, most of the innovations discussed during the interviews are new-to-firm.

Furthermore, Gamma, Eta, and Iota interact more frequently with other organisations compared to the firms included in Group I. However, as in Group I, this most commonly involves interactions with local universities. For example, the interviewees of both Gamma and Iota explained that their firms have made use of testing facilities available at local universities. This has included both standard biogas methane potential testing and more advanced analysis of the micro-organisms involved in the AD process. Instances of technology co-development are rare. The interviewee of Gamma explained that a local advisor from Chiang Mai University provided key knowledge inputs for the firm's first project based on the Upflow Anaerobic Sludge Blanket design in the mid-1990s. The only other example of technology co-development among the firms in this group concerns a collaboration between Eta and a Chinese company which aims to adapt a waste pre-treatment process for substrates with high solids contents for the use of empty fruit bunches. This is likely the first time that somebody tries to use this process for this substrate type in the Thai context.[20] Hence, seeing that interactions mostly involve local universities and that there are only few examples of technology co-development, Group II's linkage capabilities are considered to be at or below the intermediate innovative level.

To conclude, Gamma, Eta, and Iota have adopted a larger variety of reactor designs than the firms included in Group I. They have also worked with a larger variety of substrate types, which includes some higher-strength wastes and wastes with higher levels of dry matter content. All three firms originally started out using only a single reactor design and focusing on only a single substrate type. In later stages of their lifetimes, all three firms diversified their portfolios of available technological options. However, despite some R&D on reactor designs, waste pre-treatment, and biogas upgrading equipment, the technological developments that they have generated are minor in comparison to those of Groups III and IV. Furthermore, the available evidence suggests that the firm's linkages capabilities are limited. As such, the capabilities of these three firms are considered to have progressed from the basic to the intermediate innovative capability level.

[20] Delta has recently engaged in R&D efforts to develop a similar process (see discussion of Group III below).

Group III: More substantial increases in capability levels (Beta, Delta, and Zeta)

The firms included in Group III have achieved more substantial improvements in their capability stocks than the previously discussed groups. While Zeta transitioned once from the extra basic routine to the intermediate innovative level of technological capabilities, Beta and Delta underwent two transitions and reached the advanced innovative level.

In the first stage of its lifetime, Delta actually exhibited rather low capabilities with respect to the qualifications of its staff. The interviews revealed that, at the time, the firm was run by two foreign-born financiers who early on recognised the potential of the market for AD in Thailand. However, the qualifications of the technical staff in the firm's engineering department were limited. This changed radically in later stages of the firm's lifetime as it repeatedly hired foreign biogas experts to augment its capability stock. Among other instances, this included the hiring of two internationally renowned, European biogas experts around the year 2000 as part of a wider effort to reorient and restructure the firm. Beta is a nationally and regionally renowned research centre on renewable energy. Since its foundation more than 30 years ago, it has accumulated a large body of experts in waste treatment and biogas technology. Today, the firm employs nearly 90 staff in its R&D and engineering departments. Zeta is the only company in Group III which has been led by highly experienced professionals since its foundation. This includes a foreign renewable energy finance expert and two local biogas experts, one of which had previously worked as a petrochemical engineer at a globally leading engineering conglomerate.

The interviews revealed that, in the early stages of their lifetimes, all three firms included in this group only engaged in little innovative activity. Beta and Delta initially worked with a single design for small and medium-scale pig farms. The interviewee of Delta explained that these systems often performed poorly as the simplicity of their design frequently led to clogging inside the reactors:

> *"It's building a lagoon and covering it, essentially, right? And it doesn't work well because you've got very little control over the system. (...) You've got micro-organisms inside, but they are constantly getting washed out. So how are you replenishing them? It's difficult because typically it's got to be very low cost, so you won't have some sort of recycling-mixing tank. (...) You got no agitators in it, and you got no bottom-feeding, which [would] create an upflow. So, the solids*

will settle and over time they build up, so your reactor volume is decreasing, and your poor performance gets worse and worse and worse."

Zeta started out as a project operation firm and did not develop its own systems at first. Instead, its core focus was on operating biogas projects that it had purchased from other firms.

In later stages, the three firms engaged in innovative activities of increasing complexity. For example, the interviewees of Beta and Delta explained that their firms had adopted a variety of designs which allow them to offer tailored systems for various kinds of substrates. Having initially focused on pig farm digesters, the firms eventually began to focus on the liquid portion of agro-industrial wastes at cassava processing facilities and palm oil mills. As the amounts of waste produced at the latter are usually substantially larger than at pig waste farms, this means that the designs of the waste treatment reactors had to be adapted. In fact, in the beginning of the 2000s, Delta developed a biogas project based on a Modified Covered Lagoon design that was reportedly considered to be the largest in the world for some time (see Figure 14 above). More recently, as the market segments for cassava wastewater and palm oil mill effluent have become increasingly saturated, the two firms also began to focus on wastes with higher dry matter content, including cassava pulp, empty fruit bunches from palm oil milling processes, Napier grass, and others. While Zeta started out as a project operation company, it began to develop its own projects in later stages of its lifetime. In addition to introducing a range of minor changes to improve system performance, Zeta's representatives explained that, in the late 2000s, their firm built the first commercial and industrial-scale biogas project at a palm oil mill in Thailand.

Furthermore, the available evidence suggests that Beta, Delta, and Zeta all have strong linkage capabilities. For instance, both Delta and Zeta have established long-term partnerships with an advanced biogas engineering firm based in New Zealand. Delta's interviewee also highlighted a more recent collaboration with a European-based biogas process expert. Beta stands out with respect to its biogas-related R&D collaborations; throughout its lifetime, it has collaborated with a diverse range of organisations, including European donor agencies, universities based in high-income countries, leading equipment suppliers from Europe and China, and other European-based biogas engineering firms.

The interviews and supplementary information also show that Beta, Delta, and Zeta export their biogas systems to neighbouring countries in Southeast Asia and beyond. In the late 2000s, Zeta was one of the first locally owned firms to export commercial, industry-scale biogas systems to a neighbouring country. Beta has developed a large number of projects throughout Southeast Asia and licenses its technology to Thai and foreign biogas engineering firms. Delta also operates across Southeast Asia. Furthermore, the firm has recently developed a biogas project in Europe and has provided consulting service on biogas utilisation technologies to a large firm in Japan.

To conclude, the three firms included in this group have managed to substantially deepen their capability stocks over the course of their lifetimes. Today, they employ internationally renowned biogas experts, work with a variety of substrate types and reactor designs, have strong linkages to foreign partners, and even export their technology to other countries in Southeast Asia and beyond. As such, the firms included here are considered to have progressed from initially low levels of capabilities to the intermediate (Zeta) and advanced innovative capability levels (Beta and Delta).

Group IV: Continuously high capability levels (Epsilon and Kappa)

Finally, Epsilon and Kappa are considered to demonstrate high levels of innovative capabilities at the world-leading and advanced levels respectively. While previous groups have been discussed in terms of the capabilities that they exhibit at different stages of their development, this is omitted here since Epsilon and Kappa both exhibit continuously high levels of capabilities throughout their lifetimes.

Both firms are run by highly experienced and renowned experts who have multiple decades of experience in biogas based on their involvement in projects around the world. Some of their leading staff members were involved in the early-stage experiments with reactor designs which today are used across many countries and continents. For example, after having completed their Ph.D. studies at a globally leading biogas research institute in the United Kingdom, the founding members of Kappa travelled to the United States to work on some of the world’s first Modified Covered Lagoon-type digesters. Later, they were involved in a wide variety of projects in Southeast Asia, including in Thailand. The interview with Epsilon revealed that some of its staff members were involved in the development of the second-ever Upflow Anaerobic Sludge Blanket reactor pilot project in the early 1970s. Since then, they have worked together in a number of different firms in which they have completed a total of approximately 400 industry-scale biogas projects.

Kappa and Epsilon differ notably from the firms in Groups I-III with respect to the variety of countries they have worked in. While Kappa, as a firm, has mainly operated in Southeast Asia, its two founding members and leaders have been involved in a variety of projects across different countries and continents. Similarly, the interviewee of Epsilon explained that the firm had developed biogas projects in as many as 76 countries across the world by the time the interviews for this study were conducted.

Another distinguishing feature of Kappa and Epsilon is that they often develop biogas systems for advanced users. While the website of Kappa illustrates that the firm only does this occasionally, the interviewee of Epsilon highlighted that his/her firm's list of clients includes many Fortune 500 companies. In contrast, the vast majority of projects developed by the firms included in Groups I-III involve comparatively small and more local or regional clients.

Both firms have conducted a variety of R&D projects which have involved applied research and exploratory development and which have led to new-to-country and some new-to-world innovations. For example, the interviewees of Kappa explained that their firm was the first to introduce gas mixing in a Modified Covered Lagoon design. In recent years, Kappa developed two projects based on cassava wastewater and pulp which were considered to be largest reactors in terms of volume in the world for some time and which were awarded with internationally acclaimed prizes.[21] The interview with Epsilon revealed that the firm is currently working on the development of new-to-world processes for the pre-treatment of a by-product of sugar and ethanol production. Like Kappa, Epsilon has also been involved in the development of a number of mega-projects. Epsilon's interviewee explained that the firm recently developed a project which includes four reactors that together produce a volume of about 10,000 Nm^3 of biogas per hour.[22]

Based on the information available on Epsilon's and Kappa's websites, it became clear that the two firms work with substantially larger varieties of reactor designs and substrate types than the previously discussed firms. They also offer a wider range of pre-treatment processes and biogas upgrading equipment. This indicates that the two firms have accumulated deep and broad capability stocks which allow them to develop biogas systems that are tailored to the particularities of each project context. As Epsilon's interviewee put it:

[21] Note that these projects are not included in Figure 14 above as the figure only shows data for projects which have been registered with the CDM. The projects mentioned here have been developed at a time when the CDM was essentially inactive due to the low prices of the emissions credits that registered projects yielded.

[22] See previous footnote.

> *"Most competitors concentrate on one or two types of reactors and that's it, so they have to manipulate the feedstock to fit the reactors. (...) We adapt the type of reactor to the problem. And in the beginning that has put more burden on us, meaning that we [had to] make all the beginner mistakes of every single reactor type that exists. (...) But today we master all of them."*

To summarise, Epsilon and Kappa differ from the firms included in Groups I-III in a variety of ways. They employ highly experienced biogas experts, have developed projects in various countries around the world, often work with advanced users, frequently engage in technology development, and offer a substantially larger variety of technological solutions. As such, they are considered to possess technological capabilities of the advanced (Kappa) and world-leading innovative levels (Epsilon).

6.4.1.2. Discussion

The preceding section has provided an overview of the trajectories of technological capability accumulation that the 10 firms included in the sample here have undergone. This is based on a systematic and structured study of multiple indicators pertaining to the inputs, performance, and outputs of the routine production and innovation activities that these firms have engaged in throughout their lifetimes. As illustrated in Figure 13 above, the approach pursued here involves dividing the firms' lifetimes into different stages of capability building. This allows for detailed insights into how their capability stocks have developed over time. To my knowledge, there are only few studies which report such detailed information about how capabilities develop over time for a sample of firms (see Figueiredo [2017] for another example).

The results presented above suggest that there is substantial variation in the capability accumulation experiences of the firms included in the sample. Based on these observed differences, the 10 firms were categorised into four groups. This includes a group of firms which have remained at comparatively low capability levels throughout their entire lifetimes, a group of firms which have achieved minor improvements in their capability stocks, a group that has achieved more substantial improvements, and a group that has exhibited high levels of technological capabilities throughout their lifetimes.

This finding highlights the importance of considering firm-level heterogeneity in the study of technological capability formation among latecomer firms. The issue of inter-firm differences has been identified as an important concept in the literature on industrial dynamics in general (Dosi et al., 2010; Nelson, 1991) and by a number of studies on latecomer capabilities (Figueiredo, 2017, 2003; Gammeltoft, 2004; Hansen and Ockwell, 2014; Iammarino et al., 2008; Scott-Kemmis and Chitravas, 2007). However, country and sectoral-level research on technological capabilities tends to gloss over the issue of firm differences. Given the observed variety in capability levels and development pathways, it appears critical to account for them. Firms at different levels of development likely face different challenges with respect to the further deepening of their capability stocks. As such, detailed information on inter-firm differences of the kind presented above can provide useful information for the design of targeted interventions to support firms that find themselves at different positions along the capability trajectory.

6.4.2. Patterns of technological learning

The present section summarises the data on learning mechanisms. As the summary of the data on capability indicators, this section focuses on highlighting the most important trends. As explained above, learning mechanisms are distinguished by knowledge source (firm-internal, external-domestic, and external-foreign) and by type (human resources, project-related, R&D-based). To remind the reader, this section addresses the latter of the following two questions:

> *What types of knowledge and skills have Thai biogas system suppliers acquired through internal and external learning?* ***How have they acquired these?***

6.4.2.1. Results

Table 20 presents an overview of the data on learning mechanisms. It shows data for individual firms and allocates the learning mechanisms that they have engaged in to the corresponding stage in their lifetimes. As explained above, the lifetime stages have been determined based on marked changes in the observed types of innovation inputs, performance, and output indicators. The table lists the firms based on which group they have been allocated to in the previous section (i.e., Groups I-IV).

Gr.	Firm	Stage 1			Stage 2			Stage 3			Stage 4		
		Internal	***Ext.-dom.***	***Ext.-for.***	***Internal***	***Ext.-dom.***	***Ext.-for.***	***Internal***	***Ext.-dom.***	***Ext.-for.***	***Internal***	***Ext.-dom.***	***Ext.-for.***
I	Alpha	1986-1994: basic innovative			1995-1999: basic innovative			2000-2011: basic innovative			2012-2017: basic innovative		
		- Founders' experience - Pilot testing	- Local hire - Local res. collab.	- Foreign hire	- Project-to-project	- Local eng./constr. company			- Local eng./constr. company				- Int. res. collab.
	Theta	2004-2008: basic innovative			2009-2011: intermediate innovative			2012-2017: basic innovative					
		- Founders' experience - Pilot testing - Trial-and-error	- Local res. collab.	-Observing foreign company's project	-Founders' experience -Pilot testing								
II	Gamma	1991-2005: basic innovative			2006-2017: intermediate innovative								
		- Founders' experience - Pilot testing - Project-to-project	- Local biogas expert - Local hire	-Academic /technical literature -Observing foreign company's project	- Project-to-project	- Local hire - Local res. collab.	-Academic/ technical literature						
	Eta	2004-2007: basic innovative			2008-2017: intermediate innovative								
		- Founders' experience - Project-to-project - Trial-and-error		- Foreign component supplier	- Project-to-project		- Foreign component supplier - Foreign eng./constr. company						
	Iota	2009-2010: basic innovative			2011-2016: intermediate innovative			2017: intermediate innovative					
		- Founders' experience - Project-to-project	- Local hire - Local eng./constr. company	- Operating foreign company's project	- Project-to-project - Trial-and-error	- Local res. collab.	- Foreign component supplier			- Int. res. collab.			

		- Trial-and- error			- Pilot testing								
III	Beta	1991-1999: basic innovative			2000-2010: intermediate innovative			2011-2017: advanced innovative					
		- Project-to- project - Pilot testing - In-house lab. testing - Analysing operational data	- Local eng./constr. company - User feedback	- Foreign biogas system designer	- Project- to-project - Analysing operational data	- Local eng./constr. company - Local res. collab. - User feedback	- Foreign eng./constr. company	- Project- to-project - Pilot testing - Analysing operational data	- Local eng./constrs. company - Local res. collab. - User feedback	- Int. res. collab. - Foreign component supplier - Foreign biogas system designer			
	Delta	1999-2001: basic routine			2002-2004: intermediate innovative			2005-2008: advanced innovative			2009-2017: advanced innovative		
		- Founders' experience			- Project- to-project - Project operation - Analysing operational data		- Foreign biogas system designer	- Project- to-project - Project operation - Analysing operational data		- Foreign hire - Foreign component supplier	- Pilot testing - Project- to-project - Project operation -Analysing operational data - In-house lab. testing	-Acquiring local company's project	- Foreign hire - Foreign biogas system designer -Acquiring foreign company's project
	Zeta	2003-2008: extra basic routine			2009-2016: intermediate innovative								
		- Founders' experience - Project operation - Analysing operational data	- Local hire	-Acquiring foreign company's project	- Project- to-project - Project operation - Analysing operational data		- Foreign biogas system designer						

IV	Epsilon	2000-2017: world-leading innovative											
		- Founders' experience - On-site testing	- Local eng./constr. company	- Foreign hire - Int. res. collab. - Foreign component supplier									
	Kappa	2010-2014: advanced innovative			2015-2017: advanced innovative								
		- Founders' experience - In-house lab testing	- Local hire - Observing local company's project	- Foreign component supplier - Int. res. collab. -Academic / technical literature -Observing foreign company's project			- Foreign component supplier						

Table 20: Learning mechanisms used by firms across different stages of their lifetimes. Firms have been grouped based on observed similarities in capability development. Abbreviations: eng./constr. (engineering and construction), gr. (group), int. res. collab. (international research collaboration), and lab. (laboratory).

Group I: Continuously low levels of capabilities

To reiterate, Group I includes firms that have exhibited continuously low levels of capabilities (Alpha and Theta). Alpha has remained at the basic innovative level throughout its entire lifetime (Stages 1-4). Theta started out at the basic innovative level (Stage 1), briefly upgraded to the intermediate innovative level (Stage 2), and then reverted to the basic innovative level (Stage 3).

Based on the data collected for this study, it appears that, during Stage 1 of their lifetimes, Alpha and Theta predominantly relied on learning based on human resources. The interviews revealed that their technological know-how primarily stemmed from the experiences of their founding members, whose involvement in the Thai wastewater treatment and biogas sectors dates back to at least the early 1980s. As highlighted above (Section 6.4.1.1), some of the founding members and other leading staff obtained Ph.D. degrees from local universities and universities based in high-income countries. Furthermore, prior to the foundation of Theta, all of the firm's staff members worked at a wastewater treatment firm. This allowed them to gain experience with technologies that are very similar to those that they would later work with at Theta. The firm's interviewee highlighted that this experience was critical for the technology development activities which the firm engaged in, i.e. the development of the scraper-based and the two-layered reactor designs (highlighted in Section 6.4.1.1).

Alpha and Theta also made use of their close connections to local universities for R&D-based learning during Stage 1 of their lifetimes. Both firms collaborated with M.Sc. students in the development of their first reactor designs. As noted above, one of Alpha's founding members supervised an M.Sc. research project that developed a pilot project based on a new-to-country reactor design containing a medium inside the reactor to which the microorganisms involved in the AD process can attach. Similarly, Theta's CEO advised a project from another local university which aimed to develop a pilot project for a digester at a palm oil mill containing a device to scrape sediment at the bottom of the reactor.

The representative of Theta also highlighted that the firm learnt through trial-and-error testing when configuring key components into the overall design. For example, with respect to the scraping device used to remove sediment inside the reactor, the interviewee explained the process of how the device was configured: Rather than using computational modelling, Theta repeatedly changed the positioning of the scraper and observed changes in key system performance parameters until a satisfactory result was achieved. Thus, rather than using advanced engineering tools, the firm seems to have relied on rather simple methods.

In Stage 2 of their lifetimes, Alpha remained at the basic innovative capability level while Theta transitioned from the basic to the intermediate innovative level. During this time, Theta developed another pilot-project to test a new reactor design, i.e. the previously mentioned design that includes a particular type of feeding mechanism and the two-layered design. Theta's interviewee stressed that the development of this design was purely based on the founders' experience which they gained when working at the local wastewater treatment firm. Furthermore, he/she explained that this system was first introduced as a pilot project at a palm oil facility. Interestingly, this was done at the same palm oil milling factory which had previously hosted the pilot project for Theta's scrapper-based design. This shows that Theta and the facility owner had a good relationship and that the owner trusted Theta's capabilities to deliver well-functioning biogas systems.

During Stage 2 of its lifetime, Alpha also developed a number of projects based on the design containing the fixed medium inside the reactor, which it had developed in Stage 1. According to the firm's representative, this allowed Alpha to gather experience and to obtain feedback from local construction companies, which gave it the confidence to gradually increase the scales of its systems. Also, Alpha applied this design to a range of different waste types, although all of these fall in the category of liquid substrates.

The most recent lifetime stages of Alpha (Stage 3 and 4) and Theta (Stage 3) are characterised by a distinct lack of further learning efforts. Through a number of inter-university partnerships, Alpha has recently engaged in research-oriented projects with other local and foreign university-based partners. To my knowledge, these have not led to any concrete outputs that had become implemented in biogas projects by the time the interviews for this research were conducted. Theta has actually not engaged in any further learning mechanisms or innovative activities at all. This helps to explain why Alpha remained at the basic innovative level during these stages while Theta's capability levels have decreased from the intermediate to the basic innovative level.

Overall, the two firms included in this group have used a limited number and variety of learning mechanisms. Initially they combined mostly firm-internal learning mechanisms and external learning mechanisms involving domestic sources of knowledge. Foreign sources of knowledge were of only minor importance. In later stages, the firms engaged in little to no new learning mechanisms. The majority of learning for this group is based on human resource and project-related mechanisms.

Group II: Moderate increases in capability levels

Gamma, Eta, and Iota have achieved moderate increases in their capability levels. All three firms started out at the basic innovative level in Stage 1 and subsequently transitioned to the intermediate innovative level in Stage 2 (Gamma, Eta, and Iota) and Stage 3 (Iota only).

As for Group I, the interviewees of the firms included in this group highlighted that they strongly relied on the experience of their founding members in the early stages of their lifetimes. Gamma's founding members and staff that was hired at later points in the firm's lifetime gained experience with AD during their education at local universities. The founders of Eta and Iota gained relevant experience through their prior involvement in a variety of biogas projects, as staff of university-based organisations and, in the case of Eta, as members of an governmental advisory agency on energy policy. Thus, similar to the findings presented in the discussion of Group I, it seems that a longstanding involvement in biogas projects and the resulting accumulation of experience among staff are important aspects of the capability building processes at these firms.[23]

Gamma and Iota also gained critical knowledge about design principles of biogas systems in the early stages of their lifetimes by observing and/or operating local biogas projects that had previously been developed by firms based in high-income economies. Gamma acquired much of the knowledge necessary to develop its Upflow Anaerobic Sludge Blanket digester design by observing a Thai project which had previously been developed by a foreign-based firm. Two competitors of Gamma mentioned this independently of each other and without specifically being asked about it during the interviews. Furthermore, the interviewee of Iota mentioned that he/she and his/her colleagues learnt about a particular variant of the Modified Covered Lagoon system when being involved in the operation of a project which had previously been developed by another foreign firm. This allowed them to learn about the design principles of the system and the importance of certain key parameters for system performance.

In addition, Gamma and Iota highlighted the importance of interactions with local biogas expert and construction companies for learning during the implementation phases of their projects. This includes Gamma's above-mentioned collaboration with a biogas

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[23] In fact, when I asked the interviewee of Eta about the kinds of methods and tools the firm uses when planning and implementing new biogas projects, he/she used his/her index finger to point at his/her head. This provides further evidence for the importance of gaining experience in designing and implementing biogas projects that are suitable to the particularities of each project context.

expert from Chiang Mai University during its first pilot-scale project based on the Upflow Anaerobic Sludge Blanket design in the mid-1990s. In the case of Iota, the interviewee elaborated on a project experience where a local construction firm provided advice when his/her firm tried to configure mixing equipment in a biogas system based on a Modified Covered Lagoon reactor design.

With respect to R&D-based learning, Gamma - the oldest of the three firms included in this Group II - developed a pilot plant for the above-mentioned project based on the Upflow Anaerobic Sludge Blanket design. Gamma's decision to invest in a pilot plant is likely related to the early developmental stage of the Thai biogas sector in the mid-1990s, which meant that few locals had experience with biogas projects. The two more recently founded firms - Eta and Iota - primarily relied on project-to-project experiences and trial-and-error experimentation at project sites to configure key system components. On the one hand, this was possible because these firms' staff had accumulated experience with biogas systems prior to the foundation of their firms. On the other hand, the market situation had changed substantially from the 1990s to the time when Eta and Iota developed their first projects in the mid-2000s. Due to the rapid growth of the Thai biogas sector, many firms had entered the market. In such an environment, testing each modifications of a reactor design in pilot-scale projects often results in prohibitive cost and time requirements. As such, firms often implemented such changes in full-scale systems. The interviewee of Iota captured this idea when stating the following:

> *"So, when we design, (…) I don't design [using] a very aggressive figure, I have to [use] a conservative figure in the design, because we don't know exactly when you first develop this system what will happen. But you cannot wait. We cannot test in the lab and scale it from the pilot to full-scale to deliver to the customer, because we know that in the market we have others that can deliver pretty much the same concept. So, if we (…) wait, we have to take about 10 years. It's too long."*

In Stage 2, all three firms transitioned from the basic to the intermediate innovative level of capabilities. The interviewees of all firms mentioned that, during this period of their firms' lifetimes, project-to-project experiences allowed them to incrementally improve the performance of systems based on designs that they had previously developed. This was often combined with trial-and-error experimentation to improve the configuration of the different system components.

All three firms also adopted new-to-firm reactor designs during the more recent stages of their lifetimes. Gamma's interviewees mentioned that the firm adopted a Completely Stirred Tank Reactor design and mainly relied on the experience of their staff as well as the academic literature for this. Eta's and Iota's representatives highlighted that they obtained detailed technological knowledge from foreign suppliers of key components for the adoption of a variety of Completely Stirred Tank Reactor-type designs. For example, Eta worked with a German substrate mixing equipment supplier over a number of consecutive projects and managed to obtain detailed design knowledge in this way. Iota collaborated with Danish and Malaysian component suppliers, who offered combinations of components and advised on how best to integrate these.

Finally, Iota, in Stage 3 of its lifetime, engaged in a research collaboration with a Chinese company to adapt a potentially new-to-country pre-treatment method for empty fruit bunches, a waste product of palm oil production processes that contains particularly high levels of dry matter content. According to the interviewee, this had not been implemented at full commercial or pilot-scale by the time the interviews for this study were conducted.

To summarise, the three firms included in this group have combined comparatively many and diverse kinds of learning mechanisms. As in Group I, most learning in this group is based on human resources and project experiences. There are only few examples of R&D-based learning. However, compared to Group I, this group has collaborated more frequently with foreign-based firms. While interactions with foreign firms have usually involved project-related activities (e.g., observing and operating projects and sourcing key components), Iota has recently also engaged in a more research-oriented collaboration.

Group III: More substantial increases in capability levels

The firms in Group III have managed to upgrade their capability stocks more substantially than the previously discussed groups. While Zeta transitioned once from the basic innovative to the intermediate innovative class, Beta and Delta transitioned twice and managed to accumulate capabilities of the advanced innovative level towards the end of the study period.

In the early stages of their lifetimes, all three firms exhibited comparatively low levels of capability levels. As explained above (Section 6.4.1.1), Beta initially only worked with small and medium-scale pig farm digesters. It obtained access to the design that these projects were based on in the late 1980s and early 1990s when it engaged in a collaboration with a European-based donor agency. This involved a joint pilot and demonstration project which aimed to transfer technology to Thailand and to disseminate knowledge about AD in the country more generally. Delta offered a similar design at the time and relied mainly on the limited experience of its founding members for this. According to the firm's interviewee, Delta did not engage in any substantial learning efforts during this stage of its lifetime, which meant that it was only able to provide comparatively small systems that would often perform poorly due to clogging. As explained above, Zeta started out as a project operation firm. Having acquired three large projects that had previously been developed by a foreign-based firm, Zeta learnt about the design principles and key parameters for system performance by operating these systems.

The three firms all managed to upgrade their capability stocks in subsequent stages of their lifetimes. Beta engaged in a variety of innovative activities, involving incremental changes across different substrate pre-treatment processes, reactor designs, biogas upgrading processes, and biogas utilisation options. Delta achieved a particularly remarkable upgrade of its capability stocks around the year 2000, from the basic routine to the intermediate innovative level (see Figure 13 in Section 6.4.1.1). This was possible due to a radical increase in learning investments facilitated through the involvement of foreign investors. For example, the firm entered into a close partnership with a multinational biogas engineering firm which is based in New Zealand. Furthermore, Delta worked with two internationally renowned biogas experts from Europe who first offered consulting services and were later hired to head the firm's technical departments. Having started out as a project operation firm, Zeta began to develop its own biogas projects based on its operating experience. Furthermore, the firm engaged in a range of other learning mechanisms, aiming to identify ways in which designs and performance in future projects could be improved. This included hiring a local Ph.D. graduate and a collaboration with a local university for detailed testing of the wastes used in their projects. It also involved entering into a close collaboration with the same multinational biogas engineering firm as Delta.

All three firms also highlighted that they substantially benefitted from operating their own projects and/or by actively monitoring system performance. When Delta became restructured around the year 2000, it began to operate its own projects. This meant that the firm began to actively collect and analyse data on system performance to optimise project operation and to find ways to improve designs for subsequent projects. As a project operation firm, Zeta put much emphasis on performance monitoring since its foundation. One representative of the firm explained that Zeta invested in an innovative online monitoring system which facilitates the collection of data on key performance parameters on a two-hourly basis, thus offering rich information about system performance. Beta's interviewees also mentioned that their firm actively collects data on system performance. In fact, when talking about the small and medium-sized pig digesters, the firm's interviewee mentioned that Beta had developed nearly 1500 of these systems across Southeast Asia over its 30-year lifespan. This has allowed for the collection of a wealth of feedback from technology users and construction firms, which Beta has used to inform subsequent R&D efforts.

Beta and Delta further upgraded their capabilities and reached the advanced innovative level - in Stage 3 and Stages 3 and 4 of their lifetimes respectively. As in previous stages, the two firms continued to improve their designs based on project-related learning mechanisms (through the operation of projects, project-to-project experiences, the collection and analysis of operational data, and through feedback from users and engineering/construction companies). Delta also continued to upgrade its knowledge stocks by hiring internationally renowned biogas experts for leading positions in its management and technical departments. In recent years, Delta also acquired a local firm and, as such, gained access to the knowledge embodied in the acquired projects.

Furthermore, the progression to the advanced innovative capability category was possible because Beta and Delta stepped up their efforts to learn from investments in R&D. For example, Delta developed a pilot and later a full-scale project for the treatment of cassava pulp, invested in a pilot plant for the digestion of empty fruit bunches, and also performed a range of firm-internal R&D activities to experiment with different pre-treatment options for these substrates. Beta collaborated with a German university in the development of a Completely Stirred Tank Reactor design for the treatment of Napier grass, developed a biogas system involving a new-to-country system component delivered by a world-leading German component supplier, and collaborated with a Chinese firm on a demonstration plant which generates biogas from separated municipal solid waste. These activities all involved knowledge-intensive technology search which was conducted firm-internally or in collaboration with foreign, technologically advanced partners.

To summarise, the firms in this group seem to have invested substantially more resources in learning efforts than those in Groups I and II. This has included a variety of firm-internal, external-domestic, and external-foreign sources of knowledge. Beta, Delta, and Zeta have collaborated more frequently with foreign-based organisations, especially once they had reached the intermediate and higher levels of innovative capabilities. They have also engaged more frequently in learning based on in-house and collaborative R&D. In general, the firms in this group appear to approach learning in a more continuous and intensive manner than the previously discussed groups.

Group IV: Continuously high levels of capabilities (Epsilon and Kappa)

The firms in Group IV (Epsilon and Kappa) have exhibited very high levels of innovative capabilities. Epsilon has exhibited world-leading innovative capabilities throughout the whole duration of its involvement in the Thai biogas industry. Kappa's capabilities fall under the advanced innovative category for its entire lifetime.

The interviewees of both Epsilon and Kappa highlighted that their firms benefitted greatly from the experience of their founding members. As explained in Section 6.4.1.1, Epsilon and Kappa are run by highly experienced professionals who come from and were trained at leading European and Northern American universities. Each of them has more than 30 years of experience in biogas and has worked on projects around the world. They all have studied and worked with some of the world's top researchers on AD and have been involved in the development of reactor designs that today are used across many countries and continents.

The interviews also revealed that Epsilon and Kappa managed to augment the capability stocks of their firms through recruitment. Prior to 2010, the two founders of Kappa used to work at another Thai biogas firm. When leaving the firm, they managed to take the technical team with them from that company. Similarly, the founder of Epsilon used to work with a number of biogas experts in the early experiments on the Upflow Anaerobic Sludge Blanket design. During the interview, he/she mentioned that, over the years, he/she managed to hire them back into Epsilon, such that the firm now employs many of the original experts involved in these experiments.

Both firms regularly engage in international collaborative R&D. The interviewee of Epsilon highlighted that he/she has maintained close connections to the members of a leading research centre on AD in Belgium. He/she also stressed that Epsilon does all of its R&D and some of the substrate testing which requires more advanced knowledge in collaboration with this centre. Kappa has also engaged in a number of collaborative, international R&D projects, although to a lesser degree than Epsilon. Kappa's interviewees mentioned an example of an R&D programme funded by the government of New Zealand on processes to strip biogas of hydrogen sulphide.

In contrast to the firms of Group III, Epsilon and Kappa do not regularly develop pilot projects to test new ideas. In the discussion of Group II, it was mentioned that pilot projects can involve substantial financial outlays and time requirements and that, therefore, some firms choose to implement and test new technologies at full-scale commercial projects. While this is perhaps also the case for the firms included in Group IV, the interviewee of Epsilon stressed that his/her firm usually does not develop pilot plants for another reason, namely because they have gathered sufficient experience to be comfortable to also introduce major changes to biogas systems at full-scale operational projects:

> *"Every time we have a new case, we do serious bench-scale research. But pilot-scale, we think it is only necessary for the customer. We do not need upscaling experience. We have done that, and we have built the biggest plants in the world. So why would we need a pilot? We don't need a pilot plant anymore."*

Hence, Epsilon's and Kappa's R&D typically involves on-site testing at fully operational, commercial projects. This is often done in collaboration with foreign-based suppliers of key components.

In sum, Group IV is characterised by the extensive experience of its founding members in the biogas industry, both in Southeast Asia and beyond. They have strong connections to globally leading research centres. They frequently engage with foreign component suppliers and, in some cases, experiment with components at fully operational projects. While both firms have also engaged in some learning based on domestic sources (by hiring locals, collaborating with local construction companies, and observing projects), they have mostly relied on knowledge from abroad. Among other things, this frequently involves knowledge acquired or co-created in international R&D collaborations.

6.4.2.2. Discussion

The preceding section provides summaries of the core learning mechanisms that the 10 Thai biogas engineering firms analysed in this study have engaged in throughout their lifetimes. This allows for a number of insights.

At a general level, the results suggest that a detailed analysis of technological learning mechanisms offers substantial analytical leverage to explain capability building processes. The data presented above demonstrate that learning mechanisms are key to explaining how firms create and nurture the knowledge, skills, experience, and organisational systems needed to engage in routine production and innovation activities of various levels of novelty and complexity. As such, the study supports the findings of a variety of other micro-level studies on latecomer learning (see Bell and Figueiredo [2012b] for a review). There are of course many other factors at the level of the firm, sector, and economy that influence whether and how firms accumulate their capability stocks (highlighted in Section 2.3). While these have not been dealt with in much detail here to reduce the complexity of the analysis, the learning mechanisms discussed above should be viewed in combination with these factors.

Furthermore, the results corroborate the idea that technological capabilities are built cumulatively through continuous engagement in learning processes. As Bell (1997, p.75) put it: "(…) dynamic technological capabilities are cumulatively built 'upwards' from simpler to more complex design, engineering, and managerial competences, not 'downwards' from R&D." Correspondingly, a recent report on latecomer catch-up by the World Bank argues that "[f]irms must walk before they can run" (Cirera and Maloney, 2017). As illustrated in Figure 13 above (Section 6.4.1) and discussed subsequently, most firms (aside from Epsilon and Kappa) started out at comparatively low levels of capabilities and managed to build their capability stocks, some more successfully than others, through repeated engagement in various learning activities. While some firms engaged in R&D early on in their lifetimes (e.g., Beta as part of the 1988-1995 Thai-German Biogas Programme), this did not lead to sudden jumps in the quality of their capability stocks. Instead, these firms still relied on prolonged periods of market-oriented learning through repeated engagement in biogas projects to achieve higher levels of capabilities.

The analysis also provides supporting evidence to the idea that firms which manage to progress through the different stages of capability development engage in learning over extended periods of time and via a variety of mechanisms (e.g., Figueiredo, 2003; Hansen and Ockwell, 2014; Scott-Kemmis and Chitravas, 2007). Moreover, the firms which have been most successful at increasing the quality of their capability stocks - those included in Groups II and III - are characterised by periodic changes in the kinds of learning mechanisms which they engage in. Section 6.4.3 of this thesis will further elaborate on this issue by analysing whether and how capability stocks and learning mechanisms co-evolve. Specifically, this section will provide a detailed discussion of what types (human resource, project, or R&D-based) and sources of learning mechanisms (firm-internal, external-domestic, external-foreign) are most relevant at different stages on the capability ladder.

In addition to these points, the data presented above also allows for two further insights that the present section will discuss in some more detail. On the one hand, the micro-level data presented in this chapter allows for more detailed insights about the kinds of knowledge spillovers through informal learning mechanisms that have been most important in the case of the Thai biogas industry. On the other hand, the detailed data on learning in biogas systems also allows for some insight about how the particular characteristics of this type of technology affects latecomer learning.

The role of informal learning

The analysis presented in Chapter 5 finds that many local Thai biogas engineering firms have accessed advanced foreign sources of technological knowledge via spillovers through informal learning mechanisms. The results presented here provide more detailed, micro-level insights about the precise kinds of learning mechanisms that have been most relevant in the case of the Thai biogas industry. While the data presented in this chapter includes a wide variety of informal learning mechanism types, only those which have been highlighted as being most important are discussed here. Also, whereas the analysis presented in Chapter 5 focuses exclusively on informal learning from foreign sources, the following discussion concerns informal learning based on both foreign and domestic knowledge.

A key learning mechanism that has been highlighted by most firms is labour mobility. Other studies on latecomer learning also find that this is an important channel for learning (e.g., Hoekman et al., 2005; Luo et al., 2013). Many of the firms analysed here indicate that they have hired local (Alpha, Gamma, Iota, and Kappa) and foreign staff (Alpha, Delta, and Epsilon). In many cases, the new personnel had previously worked at competing firms, which means that the hiring firm benefitted from being able to access the technical knowledge that these individuals had internalised. Furthermore, most of the firms mentioned the experience of their founding members as a key factor for learning in the early stages of their lifetimes. The importance of human resource-based learning and experience-based learning are discussed in some more detail in the subsequent section, which focuses on learning in the particular case of biogas systems.

Another informal learning mechanism that seems to be commonly used among the firms included in this study is learning based on reverse engineering. This has also been highlighted as a key learning mechanisms in other studies on latecomer capabilities (e.g., Bell and Pavitt, 1995; Chen, 2009). Usually, reverse engineering occurs when firms import end products or production equipment and study it in detail to learn about its underlying design principles. In the context of the Thai biogas industry, reverse engineering appears to occur through observation, e.g., during site visits (Gamma, Theta, and Kappa). One firm developed an understanding of the design of a competing firm by being involved in the operation of one of its projects (Iota). Other firms have acquired projects by competing firms, which allowed them to learn about the knowledge embodied in these systems (Delta and Zeta). In all of these cases, members of the firms were offered opportunities to learn about the design principles of competitors' biogas systems. Frequently, this also included insights about these systems' behaviours in the operation phases of projects. In many cases, this would later allow firms to imitate the observed/acquired designs and/or to modify similar designs based on the lessons learnt.

Finally, the data also suggests that interactions with component suppliers - particularly with foreign-based suppliers - are key channels for the transfer of advanced technological knowledge (see Beta, Delta, Epsilon, Eta, Iota, and Kappa). As the different components of AD systems interact in complex ways, biogas engineering firms often rely on assistance from suppliers to incorporate new components into an existing or an entirely new design. Large component-supplying companies often work with multiple firms in many countries, which allows them to accumulate experience across many project contexts (see also Chen, 2009). By making this experience available to their clients, they therefore constitute key sources of learning for biogas engineering firms. Some of the interviewees of the present research also highlighted that they repeatedly interacted with component suppliers over consecutive projects, thus increasing the amount of contact, joint project experiences, and opportunities to learn from the suppliers' experience.

Hence, the data on learning mechanisms collected in this study further corroborates the idea that informal learning is an important source for latecomer capability accumulation (Chen, 2009; Egbetokun, 2015; Kesidou and Romijn, 2008;

Radosevic, 1999; Westphal et al., 1985). While informal learning is usually difficult to assess empirically, the micro-level approach based on a multiple-case study design has allowed for some insight into precisely which learning mechanisms have been most important in the case of the Thai biogas industry. This is important as the evidence base on the precise nature of how informal learning affects latecomer learning is currently limited.

Learning mechanisms in biogas systems

In addition to highlighting the importance of informal organisational arrangements for technology supply, the analysis presented in Chapter 5 also finds that there are marked differences in the technology sourcing strategies that have been used for AD systems and biogas engine/engine-generator sets. Chapter 5 provides some more general and representative results about the kinds of cross-border channels for learning that have been most relevant in the Thai biogas industry. The analysis of the present chapter offers more in-depth insights into learning processes for biogas systems, focusing on AD systems and to some extent on waste pre-treatment and biogas upgrading technologies. This allows for an elaboration on some of the issues addressed in Section 5.4.2, i.e. the role that the particular characteristics of biogas systems play for latecomer learning processes.

The results presented above illustrate that project-related and human resource-based learning mechanisms have been key in the case of the Thai biogas industry. With regards to the latter, most firms indicated that they extensively relied on the expertise of their founding members. For firms at the lowest (Delta, Theta) as for those at the highest ends of the capability spectrum (Epsilon, Kappa), this research finds that the founding members had usually accumulated years and sometimes decades of experience in biogas or related industries (e.g., wastewater treatment or petrochemical engineering) prior to founding their firms. Moreover, the analysis identified local labour mobility as a key external-domestic source of learning. Finally, some firms also mentioned that hiring foreign experts has been key to their technological upgrading experiences. Thus, it appears that people-embodied, experience-based knowledge has played a critical role in allowing Thai biogas engineering firms to engage in various routine production and innovation activities. This provides further, more detailed insights about the importance of experienced and skilled engineers who are familiar with the particularities of the local context within which these activities take place (see also Chen [2009]).

Project-based learning mechanisms were by far the most frequently highlighted learning mechanisms in the interviews conducted for this study. With regards to firm-internal efforts, the interviewees have particularly often mentioned learning from consecutive project experiences. Here, firms learn by introducing changes in detailed designs at full-scale systems and by observing how these changes affect operational performance. The knowledge and experience developed in this way is then used to inform the designs of biogas systems in subsequent projects. While some of the technologically more advanced firms (especially Epsilon) have stated that they regularly experiment with major changes at fully commercial projects, most firms indicated that that they only introduce minor changes in this manner. The importance of project-to-project learning likely stems from the fact that testing each change in designs at pilot plants prior to developing commercial projects would result in prohibitive cost and time delays.[24] Furthermore, the importance of project-to-project learning illustrates the challenges involved in having to adapt each system to the given project circumstances. The need for adaptation introduces a variety of uncertainties, which means that firms need to continuously develop their knowledge of how project-specific characteristics - primarily related to feedstock characteristics - can be dealt with to achieve good system performance.

Project-based learning frequently also involves learning through collaboration with external partners. This includes interactions with component suppliers, which have been discussed in the previous section. Furthermore, interactions with project operation teams have often been highlighted as being key to technological learning. This includes interactions with firm-internal or firm-external project operation teams. The need to adapt each system to project contexts in combination with the uncertainties related to AD processes implies that the effects of changes in designs often only become clear during the operational phases of projects. This means that good user-producer relations are required to monitor system performance, to mitigate potential design faults, and to learn from operation experience. Thus, the research presented here corroborates the general idea that user-producer relationships are key for innovation (e.g., Harirchi and Chaminade, 2014; Lundvall, 1985). Furthermore, the case of AD systems illustrates that, for technologies with high levels of complexity and uncertainty, collaborate learning

[24] As explained in Section 6.4.2.1, this was highlighted by one of the interviewees. Magnusson et al. (2005, p.10) report a similar finding in their study on technological capabilities for power generation equipment.

mechanisms - involving users, component suppliers, or other partners - are most effective if they involve close interaction (Stock and Tatikonda, 2000; Tsang, 1997).

In contrast to human resource and project-related learning, R&D-based learning was mentioned less frequently as a key learning mechanism in the interviews. As will be discussed in more detail below (Section 6.4.3), this type of learning seems to be most relevant for firms that have achieved the advanced and world-leading levels of innovative capabilities. In comparison to project-related and human resource-based learning, R&D-based learning is observed comparatively infrequently at lower stages of capability development. As such, the data presented here supports Ariffin (2010, p.354), who argues that focusing the study of latecomer capabilities on R&D data alone leads to largely irrelevant results as it merely covers the "tip of the iceberg". Also, the data provides further support for Bell's (1997) claim that capabilities are built from the bottom-up through market-oriented learning activities and not from the top down through R&D. Interestingly, however, the R&D-based learning mechanisms observed in the present study (primarily on-site testing and pilot projects) also appear to have a strong project-component. This again highlights the importance of experience-based learning for biogas systems, even at the highest of capability levels.

6.4.3. Concomitant changes in capabilities and learning mechanisms

This section investigates whether the learning mechanisms that Thai biogas technology-supplying firms have engaged in change as they develop progressively higher levels of capabilities. It addresses the third of the following research questions:

> *What types of knowledge and skills have Thai biogas system suppliers acquired through internal and external learning? How have they acquired these knowledge and skills?* ***How do learning mechanisms change as latecomers build higher levels of technological capabilities?***

6.4.3.1. Results

Table 21 summarises the learning mechanisms that firms use at different capability levels. Learning mechanisms are distinguished based on whether they involve firm-internal, external-domestic, or external-foreign sources of knowledge. As the table illustrates, the amount of information that is available at the various capability levels differs. While the basic routine, extra basic routine, and world-leading innovative categories each only include information about a single firm, the intermediate innovative category includes as many as seven firms. This should be kept in mind when interpreting the results as it potentially affects their representativeness.

Delta is the only firm that has exhibited capabilities of the basic routine class in its lifetime. In its early stages, the firm exclusively developed small-scale AD systems for the treatment of manure at pig farms. According to the interviewee of the firm, most of these systems were performing poorly. At the time, the firm engaged in very limited learning, mostly revolving around the knowledge and experience of its founding members. Since these did not have technical backgrounds in biogas technology, their knowledge was limited in comparison to those of other firms included in this analysis. Based on the interviews conducted, Delta at the time did not engage in any other firm-internal learning mechanisms or learning based on external sources of knowledge.

Zeta is the only company that exhibits capabilities at the extra basic routine level (in Stage 1 of its lifetime). As outlined in some detail in Section 6.4.2.1 above, Zeta has invested substantial resources in learning. This included acquiring and operating three projects from another firm, hiring local graduates, and collecting and analysing performance data of the projects that the firm operates itself. The combination of these mechanisms allowed Zeta to develop a detailed understanding of the designs of the acquired biogas systems. Later, in Stage 2 of its lifetime, Zeta would use this knowledge to develop its own projects. Zeta's investments in learning in Stage 1 of its lifetime contrast sharply with the limited learning that Delta has engaged in while it was at the basic level of routine capabilities.

Capability level	**Firm**	**Learning mechanism**		
		Internal	***External-domestic***	***External-foreign***
Basic routine	Delta	- Founders' experience		
Extra basic routine	Zeta	- Founders' experience - Project operation - Analysing operational data	- Local hire	- Acquiring foreign company's project
Basic innovative	Alpha	- Founders' experience - Pilot testing - Project-to-project	- Local hire - Local res. Collab. - Local eng//constr. Company	- Foreign hire - Int. res. Collab.
	Beta	- Project-to-project - Pilot testing - In-house lab. Testing - Analysing operational data	- Local eng./constr. Company - User feedback	- Foreign biogas system designer
	Gamma	- Founders' experience - Pilot testing - Project-to-project	- Local biogas expert - Local hire	- Academic/technical literature - Observing foreign company's project
	Eta	- Founders' experience - Project-to-project - Trial-and-error		- Foreign component supplier
	Theta	- Founders' experience - Pilot testing - Trial-and-error	- Local res. Collab.	- Observing foreign company's project
	Iota	- Founders' experience - Project-to-project - Trial-and-error	- Local hire - Local eng./constr. Company	- Operating foreign company's project
Intermediate innovative	Beta	- Project-to-project - Analysing operational data	- Local eng./constr. Company - User feedback	- Foreign eng./constr. Company
	Gamma	- Project-to-project	- Local hire - Local res. Collab.	- Academic/technical literature
	Delta	- Project-to-project - Project operation - Analysing operational data		- Foreign biogas system designer
	Zeta	- Project-to-project		- Foreign biogas system designer

		- Project operation - Analysing operational data		
	Eta	- Project-to-project		- Foreign component supplier - Foreign eng./constr. Company
	Theta	- Pilot testing		
	Iota	- Project-to-project - Trial-and-error - Pilot testing	- Local res. Collab.	- Foreign component supplier - Int. res. Collab.
Advanced innovative	Beta	- Project-to-project - Pilot testing - Analysing operational data	- Local eng./constr. Company - User feedback	- Int. res. Collab. - Foreign component supplier - Foreign biogas system designer
	Delta	- Project-to-project - Project operation - Analysing operational data - Pilot testing - In-house lab. Testing	- Acquiring local company's project	- Foreign hire - Foreign component supplier - Foreign biogas system designer - Acquiring foreign company's project
	Kappa	- Founders' experience - In-house lab. Testing	- Local hire - Observing local company's project	- Foreign component supplier - Int. res. Collab. - Academic/technical literature - Observing foreign company's project
World-leading innovative	Epsilon	- Founders' experience - On-site testing	- Local eng./constr. Company	- Foreign hire - Int. res. Collab. - Foreign component supplier

Table 21: Learning mechanisms by capability levels.

Six firms have exhibited basic innovative capabilities in their lifetimes. This includes one firm that has stayed at this level throughout its entire lifetime (Alpha), one firm that started out and eventually reverted back to this level (Theta), and four firms that progressed to higher capability levels in later stages of their lifetimes (Beta, Gamma, Eta, and Iota). Virtually all of these firms highlight the importance of learning on a project-to-project basis, sometimes combined with trial-and-error experimentation at full-scale projects. Four of the six firms have developed pilot plants to test and experiment with new reactor designs or key system components. In all four cases, this was done in collaboration with local or foreign partners. Interestingly, three firms indicated that they learnt by observing and/or operating projects developed by foreign companies (Iota, Gamma, Theta). In general, firms at the basic innovative capability level indicate that they learn from domestic sources more frequently than from foreign sources of external knowledge. While domestic sources of learning involve a variety of types (human resource, project, and R&D-related), learning involving foreign sources of knowledge hardly involves any R&D and, instead, mainly revolves around human resources and project-related collaborations.

Seven firms have achieved innovative capabilities at the intermediate innovative level (Beta, Gamma, Delta, Zeta, Iota, Eta, and Theta). Compared to the basic innovative level, this level is characterised by a higher share of firms that actively collects and analyses performance data to learn about how designs for subsequent projects can be improved (three firms as compared to one). In two of these cases, the firms themselves operate the projects which they develop. Furthermore, compared to the previously discussed capability levels, the intermediate innovative level is characterised by a lower variety of learning mechanisms based on domestic sources of knowledge. This predominantly revolves around research collaborations with local universities and research centres (Beta, Iota, and Gamma). Other forms of domestic interactive learning are rare. The firms at the intermediate innovative level more frequently learn from foreign than from domestic sources of external knowledge. This includes collaborations with component suppliers (Eta and Iota), construction companies (Eta and Beta), and biogas system designers (Delta and Zeta). Research collaborations with foreign organisations are comparatively rare (only Iota in recent years).

Theta stands out in the group of firms that have reached the intermediate innovative level. Compared to other firms, it engages in very limited additional learning (pilot testing only). The lack of investments in additional learning is likely the reason why the firm has regressed to the basic innovative capability level in the most recent stage of its lifetime.

The advanced innovative group includes three firms: Beta, Delta, and Kappa. Same as the firms in the intermediate innovative class of capabilities, they actively collect and analyse performance data and occasionally develop pilot-scale plants. Delta and Kappa do in-house testing, which has rarely been observed at the previously discussed capability levels. The firms included here also make use of some external-domestic learning mechanisms, including project-related mechanisms, human resource-based learning, and, in one case, a domestic research collaboration (Beta). The advanced innovative level is characterised by an even stronger focus on learning from external-foreign sources of knowledge than the firms at the intermediate innovative capability level. Each firm in this group combines relatively many learning mechanisms based on foreign sources of knowledge. This mostly includes project-based learning, but also two cases of international research collaborations (Beta and Kappa). Delta also reported that it has extensively benefitted from hiring foreign experts into the firm.

Epsilon is the only firm analysed in this study that exhibits capabilities at the world-leading innovative level. It has maintained this level throughout all stages of its involvement in the Thai biogas sector. One of the defining features that sets Epsilon apart from the other firms included in this study is its close partnership with a world-leading research team based in Europe. Epsilon regularly collaborates with this team to work on new-to-country and sometimes new-to-world innovations. This often also involves the incorporation of new system components that are sourced from foreign component suppliers. Experimentation with these components often takes place at full-scale, commercial projects. Furthermore, Epsilon continuously upgrades its pool of human resources by hiring local and foreign staff and employs a number of biogas experts who are pioneers in the biogas industry. The interviews also revealed that, for some time, Epsilon collaborated with a local engineering and construction company which provided it with market access and detailed knowledge about substrate characteristics.

6.4.3.2. Discussion

The data presented above support the idea that the relative importance of the different learning mechanisms which firms engage in changes across the different stages of the capability accumulation trajectory. Thus, at a general level, the findings presented here support previous work by Figueiredo et al. (2013) on the Brazilian natural-resource processing industry and by Hansen and Lema (2019) on the Chinese wind turbine and Malaysian biomass boiler industries. The present section discusses the results summarised above in some detail, focusing on exactly how the observed learning activities change along the capability ladder, and how this compares to the findings of Figueiredo et al. (2013) and Hansen and Lema (2019). The section discusses changes within and across different sources of technological knowledge.

Changes within learning mechanism categories

A first insight is that firm-internal learning efforts are relevant at all capability levels. However, there appears to be a shift in the types of firm-internal learning mechanisms as one moves up the capability ladder, from predominantly project-related learning at lower levels to R&D-based learning at the top. This certainly has to do with the increasing knowledge, experience, and skills of firm personnel, which allow firms to autonomously engage in increasingly more novel and complex engineering and technology development activities. This corresponds with Hansen's and Lema's (2019) study, which finds that firm-internal learning mechanisms for firms at lower capability levels mostly centre on trial-and-error activities and gradual experimentation, while firms at higher capability levels more frequently learn from R&D conducted in formalised in-house units (see Table 5 in Section 2.2.2 for a stylised summary of their findings).

An additional explanation for the importance of firm-internal learning across the capability spectrum might be that such learning is a necessary complement to the acquisition of knowledge from external sources. In fact, some of these learning mechanisms might serve to convert knowledge accessed from external sources to achieve organisational learning. While knowledge conversion (as opposed to knowledge acquisition) has not been discussed in much detail in this thesis, it is key to diffusing knowledge within an organisation (Figueiredo, 2003; Kim, 1997; Nonaka, 1994). As will be argued in more detail below in this section, learning based on external (particularly external-foreign) sources of technology involves knowledge-intensive interactions. As the knowledge-intensity of such interactions increases, there appears to be a need to simultaneously engage in more advanced firm-internal learning efforts in order to be able to internalise the external knowledge. Figueiredo et al.'s (2013) study on natural resource-processing industries in Brazil reports a similar finding. Specific examples of firm-internal learning mechanisms that Thai biogas firms used to integrate external sources of knowledge into their capability stocks include experimentation at pilot plants, in-house laboratory experiments, and on-site testing.

Changes in external-foreign learning mechanisms along the capability ladder are equally pronounced as changes within the firm-internal category. At the level of routine production capabilities, learning mechanisms involving foreign sources of knowledge appear to be used relatively infrequently. However, this changes as firms move towards higher capability levels. As with firm-internal learning mechanisms, there appears to be a shift from project-related (and some human resource-related) learning to R&D-based learning. Generally speaking, this corroborates the findings reported by Hansen and Lema (2019), although there appear to be differences in the precise kinds of learning mechanisms used at lower capability levels. In addition to project-based learning mechanisms, licensing contacts and joint ventures seem to have been important in the cases of the Chinese wind turbine and Malaysian biomass boiler industries. As discussed in the previous as well as the present chapter of this thesis, the precise nature of the most relevant learning mechanisms likely has to do with the characteristics of the technologies in question. Probable reasons for the importance of external-foreign sources of learning at higher levels of capabilities are discussed below (in the section on changes *across* learning mechanism categories).

The pattern with respect to changes within the category of external-domestic learning mechanisms is less clear. With the exception of the basic routine level of capabilities, the frequency with which firms make use of learning based on domestic sources of knowledge is approximately the same at all capability levels. Certain types of learning mechanisms appear to be used equally often across almost all levels of capabilities. This includes local hiring and gathering feedback from users and local engineering/construction companies. A potential reason for the prevalence of this particular set of learning mechanisms might be the need to learn from local project experiences due to the specific natures of and variety in local feedstocks, and the resultant need to adapt biogas system designs. Learning from engagement with domestic technology users has also been highlighted as key in Hansen's and Lema's (2019) study, although mostly for firms which possess lower levels of innovative capabilities.

Interestingly, learning based on collaborations with local research institutions only appears to be important at the basic and intermediate levels of innovative capabilities. This differs from Hansen's and Lema's (2019) study, which finds that these particular kinds of collaborations are most relevant for firms at higher levels of capabilities. One potential reason for the absence of this learning mechanism at higher capability levels is that many of the private sector firms see university-based organisations as competitors (source: multiple interviews conducted for this study). In fact, the two university-based organisations included in this study - Alpha and Beta - have been actively involved in the development of biogas projects in the private sector, in Thailand and beyond. As such, private sector firms which hold more advanced technological capabilities fear that collaborating with these organisations might lead to unwanted knowledge spillovers (*ibid.*).

Changes across learning mechanisms categories

The data also offers some insights about changes across the different sources of learning. To begin with, the data shows that firms which rely on firm-internal learning mechanisms alone exhibit comparatively low capability levels. This especially concerns Theta in Stage 2 (after which it reverted back to the basic innovative level of capabilities) and Delta in Stage 1 of its lifetime (at which the firm exhibited capabilities of the basic routine level). This result mirrors the key message of the system of innovation approach, namely that linkages and knowledge flows among firms and other organisations are critical for innovation processes (Lundvall, 1992; Nelson, 1993). Relying on firm-internal learning alone prevents firms from benefitting from the variety of available external learning mechanisms. Especially small and medium-sized latecomer firms often lack the resources to engage in extensive technological search on their own and, therefore, stand to benefit from learning from external sources of knowledge (e.g., Caniels and Romijn, 2004, p.142-143).

Furthermore, the available data suggests that there appears to be a shift in the relative frequency with which firms rely on external-domestic and external-foreign sources of learning at different stages along the capability ladder. While external-foreign learning mechanisms are observed comparatively infrequently at lower capability levels, they seem to be more commonly used by firms which have achieved higher stages of capability development. This corresponds with the findings of previous case studies (e.g., Hansen and Lema, 2019; Hansen and Ockwell, 2014; Plechero, 2012; Scott-Kemmis and Chitravas, 2007). A likely reason for this finding is that foreign technological knowledge is often more advanced than domestic knowledge, which means that latecomers require high levels of absorptive capacity to be able to incorporate it into their capability stocks.

As explained above, learning mechanisms based on external-domestic sources of knowledge are observed at approximately similar frequencies across all stages of the capability ladder. This finding differs from those presented in previous case studies of latecomer learning (e.g., Hansen and Lema, 2019; Hansen and Ockwell, 2014; Plechero, 2012; Scott-Kemmis and Chitravas, 2007). These predominantly argue that learning based on external-domestic sources of knowledge decreases in relevance as firms progress to higher levels of capabilities. The study presented in this chapter provides a slightly different picture in this regard: While the *relative* frequency at which external-domestic learning mechanisms are observed decreases at higher levels of capabilities (in comparison to external-foreign learning mechanisms), the overall frequency across the different capability development stages remains approximately constant. As argued above, this likely has to do with the particular characteristics of technological learning in biogas systems, i.e. the need to adapt systems to project contexts and the importance of experience-based learning.

6.5. Summary of main points

This chapter presents a micro-level study of technological learning in the Thai biogas industry. The goal here is to provide a detailed analysis of the capabilities that Thai biogas engineering firms have accumulated and the learning mechanisms that they have engaged in for this purpose. Also, the study aims to provide insights about how these learning mechanisms change as firms move up the capability ladder. As such, it contributes to the literature on latecomer capability accumulation and a smaller body of literature that focuses on such learning among LCE technology-supplying firms. Furthermore, the study contributes to an as of yet small body of literature focusing on concomitant changes in capabilities and learning mechanisms.

The chapter provides a number of insights. With respect to the capability development pathways that the analysed firms have achieved, it finds that there is substantial inter-firm heterogeneity. In combination with the data on learning mechanisms, the analysis supports the idea that technological capabilities are built cumulatively from the ground up. In general, the data on learning mechanisms seems to provide substantial analytical leverage to explain differences in the capability stocks that the 10 firms included in this study have achieved. More specifically, the detailed study of Thai biogas engineering firms illustrates the importance of considering the role of informal learning mechanisms and technological characteristics in the study of latecomer learning.

With respect to the issue of concomitant changes in capabilities and learning mechanisms, the results indicate that the frequency and nature of external-domestic learning mechanisms which Thai biogas engineering firms engage in remains approximately the same across all stages of capability development. In contrast, the nature of firm-internal and external-foreign sources of knowledge changes notably as the firms move along the capability trajectory. Moreover, the study finds that those firms which have primarily engaged in firm-internal learning exhibit low levels of technological capabilities. Finally, it is observed that firms with higher capability levels are more likely to engage in learning mechanisms based on external-foreign sources of knowledge.

6.6. Chapter appendix

6.6.1. Information about interviews

Firm	**Included in study?**	**Interviewee role**	**Number of interviewees**	**Interviewer(s)**	**Date**	**Location**	**Duration**
Alpha	Yes	Leading technical personnel	3	Author	August 2017	Bangkok	57 min
Beta	Yes	Leading management and technical personnel	2	Author, research collaborator	July 2017	Chiang Mai	64 min
Gamma	Yes	Leading technical personnel	2	Author	August 2017	Bangkok	56 min
Delta	Yes	Leading management personnel	1	Author	July 2017	Bangkok	68 min
Epsilon	Yes	Leading management personnel	1	Author	July 2017	Bangkok	53 min
Zeta	Yes	Leading management and technical personnel	2	Author	July 2017	Bangkok	52 min
Eta	Yes	Leading technical personnel	1	Author, research collaborator	July 2017	Bangkok	60 min
Theta	Yes	Leading management personnel	1	Author	July 2017	Bangkok	52 min
Iota	Yes	Leading management personnel	1	Author, research collaborator	June 2017	Bangkok	54 min
Kappa	Yes	Leading management and technical personnel	2	Author	July 2017	Bangkok	118 min

Lambda	No	Leading management personnel	1	Author	July 2017	Bangkok	98 min
Mu	No	Leading technical personnel	1	Author, research collaborator	July 2017	Bangkok	101 min
Nu	No	Leading management personnel	1	Author	July 2017	Bangkok	89 min

Table 22: Information about interviews.

6.6.2. Interview protocol

General information about the firm

Historical background

- When was your firm founded?
- How was the company established? Please explain the ownership structure of the firm at the time of its foundation. Has this changed? How?
- Who are the founders of the firm? What are their backgrounds?
- Please describe the different units within the company and their functions. Have any units become added or terminated during the lifetime of the firm?
- How many people were employed when the firm was founded? How many are working there now? Please distinguish between numbers of workers in the firms' different units.
- Please explain your role in the company? Has this changed? How?

Business profile

- What is the strategic orientation or mission statement of the firm? Has this changed? How?
- What products and services does your firm offer? Has this changed? How?
- What is the main product or service that your firm offers?
- Which countries constitute your firm's main markets? Has this changed? How?
- Approximately, in how many AD reactor projects has your company been involved?

Identification of technological milestones

At the beginning of this section, the interviewee(s) was (were) introduced to some examples that constitute technological milestones and breakthroughs. The examples mentioned include: generation of new knowledge about the AD process, the development of intellectual property, land-mark projects, the development of new plant design, substantial modifications of existing plant designs, and the achievement of significant cost or performance improvements of plants. In addition, the interviewee(s) was (were) informed that the milestones should reflect a manifestation of the firm's increased level of knowledge, experience, and skill to understand, handle, and improve AD reactors, reactor components, and supporting systems.

- Could you please name and briefly describe between 4 and 6 of the major technological milestones that your firm has achieved since its foundation?

Details of each individual milestone

Revealed technological capabilities

- Could you please tell me about the concrete outcomes that this milestone has involved?
- How would you rate the milestone with regards to its technological originality at the time that it was developed? Was it new to the firm, new to a particular market segment, new to Thailand, or new to the world?
- What performance measures and indicators has your firm used to evaluate the success of the milestone?
- What strategic goals did your company pursue when working on this milestone?
- Questions about resources:
    - Did the milestone involve any major financial commitments?
    - Approximately how many employees were involved?
    - Which firm units were involved?
    - Was there any substantial coordination across firm units?
- Please explain the time horizon of the project.
    - Approximately when did your company start to work on tasks related to the achievement of the milestone?
    - When did the work finish?
- Could you please describe the specific methods and tools that your company has used to achieve this technological milestone? Please provide as much detail as you can.

- What qualifications did the key personnel involved in the achievement of this milestone have?

Learning mechanisms

- Internal learning mechanisms
    - Which types of firm-internal learning mechanisms did your firm use to address the specific challenges related to this particular milestone?
    - When exactly were these used? Were the learning mechanisms pursued continuously over long periods of time or rather as one-off events?
- External learning mechanisms
    - What kinds of external learning sources were used?
    - When exactly were these used? Were these learning mechanisms pursued continuously over long periods of time or rather as one-off events?
    - What kinds of organisations were involved in these learning experiences? Were these Thai or foreign organisations? Please provide their names if you can.
    - What exactly was the nature of the relationships between your firm and the external organisations?
- Importance of different learning mechanisms
    - Which of the mentioned learning mechanisms (internal or external) would you say were most important for achieving this milestone?
    - Please elaborate on the extent to which the different learning sources were prioritised and actively pursued by firm management (in terms of financial commitments, human resources allocated, etc.).
    - Were specific learning processes combined? If so, how?

6.6.3. Complementary information

The following files can be found on the CD ROM appended to the thesis:

- Appendix Chapter 6a_Description of indicators.xlsx
- Appendix Chapter 6b_Data from CDM monitoring reports.xlsx

6.6.4. Request-for-interview letter

UCL Energy Institute

Dear [NAME],

I would like to request an appointment for an informal discussion about the history of [COMPANY NAME]. This is part of the data collection process for a research project which I am currently working on within the context of my doctoral studies at University College London (United Kingdom). I am working on this project in collaboration with Ms. Rathanit Sukthanapirat, a researcher and lecturer in environmental engineering at Kasetsart University.

My research focuses on the role of local innovation and international technology transfer for the diffusion of large anaerobic digestion (AD) systems used for the treatment of agro-industrial wastewater in Thailand. The goal of the research is to generate a better understanding of how technology-supplying firms combine internal and external sources of design and engineering knowledge to develop the capacity to adopt, to adapt, to improve, and to develop new technology.

The discussion takes between 60 and 90 minutes and focuses on the following issues:

(1) I would like to find out about the historical background and the business profile of your company.

(2) I would like to talk about how your firm's design and engineering capabilities have developed over time. For this I would like you to help me establish a timeline of major technological milestones that your company has achieved since its foundation. Furthermore, I would like to find out about the resources that your firm has mobilised to achieve these milestones.

(3) I would like to discuss the internal and external sources of knowledge that your firm has utilised to develop its design and engineering capabilities. With regards to external sources, I am particularly interested in the ways in which your firm has interacted with other Thai and foreign organisations, including customers/clients, competitors, component suppliers, universities and other research institutes, etc..

As my research focuses on technology-related business strategies, I would be grateful if I could also meet with representatives of your firm's engineering, design, product development, and/or research and development units.

University College London has strict rules regarding data protection. As such, you can rest assured that your answers to my questions will be handled confidentially. Any information that you provide me with will be anonymised and will only be published in summarised form so that it will not be possible to identify your individual contributions to this study. Naturally, I will make the final output of this research available to you if you wish.

Your firm's participation is invaluable and very much appreciated. I look forward to hearing from you to arrange the date and time of the discussion (see contact details below). I will be in Thailand in June & July 2017.

Please do not hesitate to contact me if you have any questions or concerns. Thank you very much in advance for your assistance.

Yours sincerely,

[redacted]

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7. Summary and conclusions

This is the final chapter of the thesis. After Chapters 5 and 6 went into detail about processes of technological learning in the Thai biogas industry, the goal of this chapter is to take a step back to identify what lessons can be learnt from these analyses. In doing so, it aims to summarise insights that can inform future research and decision-making relevant for achieving low-carbon development in the countries of the Global South.

The chapter is structured as follows. Section 7.1 briefly summarises the approach that was pursued here. Section 7.2 briefly summarises the key results of Chapters 5 and 6 and synthesises these into four core insights. Section 7.3 discusses what these conclusions imply for the key stakeholders. Section 7.4 highlights some limitations of the study and offers suggestions on how future research could usefully address these. Section 7.5 concludes the thesis.

7.1. Summary of approach

The goal of this thesis is to contribute to a better understanding of how latecomer firms in developing countries accumulate technological capabilities. To reiterate, technological capabilities are defined here as "a set of resources [including the] skills, experience, knowledge, and organisational arrangements needed to acquire, use, adapt, and change existing technologies and/or to create new technology" (Van Dijk and Bell, 2007, p.151). Specifically, the study focuses on capability accumulation among technology-supplying firms. The key issue of interest is how these firms use various kinds of learning mechanisms to acquire the capabilities that allow them to engage in routine production and innovation activities of different levels of novelty and complexity.

The research focuses on technological upgrading in industries for the development and production of LCE technology, although its conclusions may also apply more widely to other technological areas. The decision to focus on LCE technology stems from the urgency to generate insights that can inform interventions aiming to accelerate the global diffusion of technologies which can help mitigate anthropogenic climate change. This is a particularly important issue in the economies of the Global South as these currently face the dual challenge of promoting social and economic development while simultaneously trying to limit the amounts of greenhouse gases which they emit into the atmosphere. The localisation of industries for the development and supply of LCE technologies can contribute towards the reconciliation of these goals (Byrne et al., 2014). As such, it is important to generate insights about how firms in low and middle-income countries accumulate the capabilities that allow them to develop and supply LCE technology.

The thesis presents a detailed analysis of technological learning in the case of the Thai biogas industry. A review of the literature on technological capabilities and learning among LCE technology-supplying latecomer firms suggests that most existing studies focus on particular subsets of economies and technologies (see Section 2.4.1). This mostly concerns a subgroup of large and rapidly industrialising developing economies – mostly China and India - which have become host to some of today's world-leading suppliers of LCE technology. Firms in these economies operate under conditions which often differ from those found in smaller developing countries (as highlighted in Section 2.3). Therefore, it is worth to study alternative cases. Furthermore, reviewing the case study literature on technological catch-up in LCE technology reveals that most existing studies have focused on firms supplying solar PV panels and wind turbines and, to a lesser degree, hybrid and electric vehicles including advanced batteries. Given that innovation dynamics differ across sectors (see Section 2.3 for a discussion), it is useful to study technologies exhibiting characteristics which differ from these cases.

The Thai industry for medium and large-scale biogas systems is a suitable case for this research. On the one hand, focusing on this case addresses the gaps in the literature with respect to the shortage of research focusing on smaller developing economies and less-studied types of LCE technology. Furthermore, the Thai biogas sector has experienced rapid growth in the 2000s and 2010s (see Section 4.5). Today, Thailand hosts one of the world's largest markets for biogas. Confirming previous studies and reports which provide bits and pieces of information about the supply-side of the Thai biogas sector (Mehner et al., 2017; Siteur, 2012; Suwansari et al., 2015), the analysis presented in this thesis illustrates that Thailand hosts a number of technologically advanced technology suppliers. Hence, this case is fitting for a detailed investigation about the ways in which latecomer firms accumulate the capabilities they require to develop and produce LCE technology.

The core research question addressed in this thesis is:

> *To what extent and how have Thai firms acquired expertise for the production and development of biogas technology?*

One potential criticism of the research presented here is that the focus on a single country and technology calls into question the generalisability of its results (Yin, 2003).

One way to assess their generalisability is by comparing them to the findings of prior research (e.g., see Rose, 2005). This allows for the identification of common trends among and differences between the technological learning experiences of various latecomer firms. Chapters 5 and 6 discuss how their core results compare to the findings of previous research on latecomer learning in LCE and other types of technologies. Of course, when doing this, it is important to keep in mind the contextual factors - e.g., at the level of the firm, sector, or economy - that might influence how capability accumulation and technological learning occurs in practice. While a thorough analysis of all relevant contextual factors is beyond the scope of this thesis, the most important aspects are highlighted in the discussion sections of Chapters 5 and 6.

The two research projects conducted to answer the above-mentioned question are based on multiple-case study approaches in which the capability development experiences of several firms are compared and contrasted. This is mainly based on a deductive approach using qualitative data. The need to rely on qualitative data stems from the fact that quantitative indicators often only provide a coarse and partial overview of the kinds of routine production and innovation activities that firms engage in (e.g., see Section 2.4.2 for a discussion of quantitative indicators used in research on international technology transfer). However, technological capability accumulation and learning are complex concepts (discussed in detail in Sections 2.1 and 2.2). Analysing capabilities and learning, thus, requires access to detailed information which is often only accessible by talking directly to firm representatives or by drawing on detailed reports which document firm activities. As such, the use of qualitative information in a deductive framework is warranted (Yin, 2003).

The core research question stated above is addressed by means of two research projects. The first of these aims to answer the following question:

> *Through which organisational arrangements have Thai firms accessed foreign knowledge for the supply of biogas technology?*

Chapter 5 addresses this question by means of a comparative study of the organisational arrangement types that have been used to source AD systems and biogas engines/engine-generator sets in Thai biogas CDM projects. In particular, the chapter focuses on cross-border organisational arrangements based on FDI, international licensing agreements, international R&D collaborations, etc.. Information about these arrangement types is used as an indicator for knowledge transfer to and absorptive capacity at Thai biogas engineering firms. The goal here is to analyse a large sample of projects and firms and, thus, to produce results that provide a representative picture of cross-border learning in the Thai biogas industry. A review of the literature on international transfers of LCE technology to low and middle-income countries (see Section 2.5.2) shows that there is a lack of studies which simultaneously (i) provide generalizable results and (ii) consider some of the core ideas of the latecomer capability literature (see Section 2.1 and 2.2).

Additionally, the analysis investigates whether the distribution of organisational arrangement types used to supply AD systems differs from the distribution used to supply biogas engines/engine-generator sets. Hence, it also addresses the following supplementary research question:

> *How do organisational arrangements differ across technological components of biogas systems?*

The second research project is based on a micro-level analysis of technological learning among 10 Thai AD system-supplying firms. It addresses the following questions:

> *What types of knowledge and skills have Thai biogas system suppliers acquired through internal and external learning? How have they acquired these? How do learning mechanisms change as latecomers build higher levels of technological capabilities?*

This project first determines how the technological capabilities of a sample of 10 Thai biogas engineering firms have progressed over time. This is based on a detailed and structured approach to collecting data on a variety of capability indicators. Based on differences in the observed capability trajectories, the firms are divided into four groups. Furthermore, the study determines which learning mechanisms the firms have engaged in to develop their capability stocks. These mechanisms are distinguished by knowledge source (firm-internal, external-domestic, and external-foreign) and type (human resource-related, project-related, R&D-based). Based on the four previously determined capability trajectory groups, similarities and differences in the firms' learning activities are identified. Finally, the available data on capabilities and learning mechanisms is used to investigate how learning mechanisms change as firms develop increasingly higher levels of technological capabilities. This allows for insights about the co-evolution of capabilities and learning mechanisms, which is a topic that to date has received little attention in the latecomer capability literature (as discussed in Section 2.2.2).

7.2. Summary of results and key contributions

This section summarises the key results for each of the research questions re-stated above. Based on this, it then discusses the key contributions that this thesis makes to the study of technological learning at latecomer firms.

7.2.1. Organisational arrangements for cross-border technology transfer (Chapter 5 summary)

To reiterate, the key question addressed in Chapter 5 is:

> *Through which organisational arrangements have Thai firms accessed foreign knowledge for the supply of biogas technology?*

The analysis illustrates that Thai firms have interacted with foreign organisations in a variety of ways to supply biogas technology to CDM projects. With respect to AD systems, it appears that Thai firms most frequently learnt from foreign sources of knowledge via the informal and joint R&D types of organisational arrangements. Some projects are based on technology that has been developed locally. A few projects have sourced technology via imports or inward FDI, which do not involve any direct linkages between locally based and foreign firms. Overall, this suggests that there are some Thai firms which have developed substantial levels of absorptive capacity and which have managed to engage with foreign organisations in ways that likely involve high degrees of knowledge sharing. This is particularly the case for the joint R&D type of organisational arrangements. As explained in Chapter 5 (Section 5.4.3), the informal arrangement type is less clear in this regard as it groups together a variety of different learning mechanisms (learning by hiring, learning through reverse engineering, learning through interactions with component suppliers, etc.).

More generally, the analysis presented in Chapter 5 demonstrates that Thai suppliers of AD system seem to learn from foreign sources of knowledge through a wider variety of channels than the literature on international technology transfer tends to suggest. Much of this literature argues that imports and inward FDI are the main channels for cross-border transfers of technology (e.g., Glachant and Dechezleprêtre, 2017; Popp, 2011; Schneider et al., 2008). While these channels are certainly relevant, there are other mechanisms which appear to be equally, if not more important for latecomer learning. This highlights that processes of international technology transfer should not merely be thought of as cross-border flows of equipment and financial resources. Instead, international technology transfer should be understood as processes that include active learning on the part of the technology-adopting firm (Lema and Lema, 2012; Ockwell and Mallett, 2012). As the analysis presented here shows, such learning takes place through a variety of cross-border organisational arrangements.

Chapter 5 also addresses the following supplementary question:

How do organisational arrangements differ across technological components of biogas systems?

While AD systems were supplied via a variety of organisational arrangement types in the sample of Thai biogas CDM projects, biogas engines/engine-generator sets were almost exclusively supplied via imports by foreign firms that are based in high-income countries or in China. Contrary to the case of AD systems, this suggests that Thailand does not host an advanced industry for the supply of biogas engines/engine-generator sets. The differences in the observed distributions of organisational arrangement types are discussed in Chapter 5 with reference to the characteristics of the two types of technology.

AD units are complex systems. A large variety of parameters needs to be considered when aiming to design well-functioning systems. Also, AD systems require substantial adaptation to project contexts, mainly depending on the availability and composition of local feedstocks. The combination of these factors implies that the development of such systems relies on engineers who embody a detailed understanding of system design principles and local project particularities. Much of this knowledge is difficult to codify in detail and, thus, needs to be built through experience. Furthermore, the effects that changes in AD system designs have on operational performance often only manifest themselves in the operational phases of projects. This highlights the importance producer-user relationships to address system faults during operation and to learn from project experiences.

It was argued above that these factors can help explain the observed patterns of organisational arrangement types. In fact, in the sample Thai CDM biogas projects, most AD systems were supplied via channels that involve close interaction between local firms and foreign sources of knowledge. Hence, these channels are well-suited for the transfer of knowledge that contributes to the development of tacit knowledge at the local firm. This includes the joint R&D and the informal learning categories.[25] Similarly, the inward FDI category of organisational arrangements involves close contact between local subsidiaries and foreign-based headquarter locations. Thus, at a general level, this study corroborates ideas by Stock and Tatikonda (2000) and Tsang (1997), who argue that international transfers of technology which involve high levels of complexity and tacit knowledge usually occur through channels that are based on close interaction between knowledge providers and recipients.

In contrast, biogas engines/engine-generator sets involve a comparatively high degree of standardisation. Furthermore, they can be shipped across large distances due to their relatively smaller size. This combination of factors means that manufacturing plants do not need to be located in close proximity to users. It also implies that manufacturing plants can benefit from economies of scale, which can create substantial market entry barriers for firms located in developing countries (Schmidt and Huenteler, 2016). This is reflected in the fact that the vast majority of biogas engines/engine-generator sets in the sample of Thai biogas CDM projects were sourced via the import category of organisational arrangements.

7.2.2. Micro-level dynamics of technological learning (Chapter 6 summary)

The first question addressed in Chapter 6 is:

> *What types of knowledge and skills have Thai biogas system suppliers acquired through internal and external learning?*

The results presented in Section 6.4.1 provide detailed information about the capability stocks of a sample of 10 Thai biogas engineering firms. This also includes information about how these firms' capability stocks have developed over time. Contrary to most previous studies on firm-level technological learning in developing countries, the temporal dimension was explicitly taken into consideration in the presentation of the results (exceptions include Ariffin [2010] and Figueiredo [2017]). As a consequence, the data provides rich insights about the nature of the firms' capability trajectories, including

[25] As stated above, the informal category of organisational arrangements combines a variety of learning mechanisms. Many of these can conceivably contribute to the development of tacit knowledge at latecomer firms. This includes learning through labour mobility, learning by observing/operating plants, and learning from partnerships with component suppliers.

insights about the rate of their progress. On this basis, the 10 firms were categorised into four groups based on similarities and differences in their observed capability trajectories: firms which have experienced no or only very small changes in their capability stocks throughout their lifetimes; firms which have moderately increased their capability levels; firms which have achieved more substantial increases; and firms which have exhibited high levels of capabilities throughout their lifetimes.

The analysis illustrates the need to consider firm-level heterogeneity in the study of latecomer capability accumulation. This issue has been highlighted in the literature on industrial dynamics in general (Dosi et al., 2010; Nelson, 1991) and some studies on latecomer capabilities (Figueiredo, 2017, 2003; Gammeltoft, 2004; Hansen and Ockwell, 2014; Iammarino et al., 2008; Scott-Kemmis and Chitravas, 2007). Firms at different levels of development face different challenges when aiming to further develop their capability stocks. Therefore, detailed information on inter-firm differences can provide useful information for the design of targeted interventions to support further progress.

The next question addressed in Chapter 6 focuses on the learning mechanisms that latecomer firms use to build their capability stocks. Specifically, the question reads (see text highlight in bold):

> *What types of knowledge and skills have Thai biogas system suppliers acquired through internal and external learning?* ***How have they acquired these?***

This part of the chapter presents detailed information about the kinds of learning mechanisms that the 10 Thai biogas engineering firms have engaged in during the different stages of their lifetimes. Table 20 in Section 6.4.2.1 provides a comprehensive overview. The key insight here is that the firms in the four capability groups mentioned above have engaged in different varieties of learning mechanisms. This concerns both the sources of knowledge they engage with (firm-internal, external-domestic, and external-foreign) and the types of the learning mechanisms they use for this purpose (human resource-based, project-based, or R&D-based).

At a general level, the analysis corroborates some findings from previous studies on latecomer learning. Firstly, it suggests that data on learning mechanisms indeed has substantial analytical leverage to explain the capability levels that latecomers achieve (Bell and Figueiredo, 2012a). Secondly, it supports the idea that capabilities are built cumulatively “from the ground up” as opposed to through top-down R&D programmes (e.g., Bell, 1997; Watson et al., 2015). Thirdly, the data provides supporting evidence to the idea that firms are most likely to progress through the different stages of capability development if they engage in learning over extended periods of time and via a variety of mechanisms (e.g., Figueiredo, 2003; Hansen and Ockwell, 2014; Scott-Kemmis and Chitravas, 2007). As discussed in Section 6.4.3 (and summarised below), the data also suggests that firms which progress along the capability ladder go through periodic changes in the kinds of learning mechanisms which they engage in.

Furthermore, the data on learning mechanisms provides more detailed insights on two issues that are discussed in Chapter 5: the role of informal learning mechanisms and technological characteristics in latecomer capability accumulation. With regards to the former, Chapter 6 provides more detailed information about precisely which informal channels of learning appear to be most important in the case of the Thai biogas industry. This includes learning through labour mobility, learning by observing and/or operating competitors' biogas systems, and learning through collaborations with component suppliers. Hence, the analysis contributes to a body of literature which aims to analyse the relative importance of knowledge spillovers for latecomer learning compared to learning based on more formalised channels (Chen, 2009; Egbetokun, 2015; Kesidou and Romijn, 2008).

With respect to the role of technological characteristics, the analysis suggests that the need to adapt biogas systems to project circumstances has a decisive impact on the importance of certain learning mechanisms. Specifically, the study finds that project-based and human resource-centred learning seems to have been most important. Human-resource based learning centres around the experience of the founding member, domestic labour mobility, and in some cases also foreign hires. The most relevant project-based learning mechanisms include project-to-project learning (by introducing minor changes in commercial projects), partnerships with component suppliers, and close interaction with project operation teams (which are often firm-internal). Chapter 5 discusses that these findings can likely be explained because of the need to adapt biogas systems to project contexts. As a result, the successful design of system critically depends on the availability of skilled engineers with locality-specific project experience. The learning mechanisms summarised above all seem to be appropriate to develop this kind of experience. An interesting additional finding is that R&D-based learning was mentioned less frequently as a key learning mechanism. This supports Ariffin (2010, p.354) who argues that focusing the study of latecomer capabilities on R&D data alone leads to largely irrelevant results.

Finally, the research presented in Chapter 6 also addresses the question of whether and how capability levels and learning mechanisms co-evolve along the capability trajectory:

How do learning mechanisms change as latecomers build higher levels of technological capabilities?

The results reported for this research question support the idea that there are changes in the relative frequencies at which different kinds of learning mechanisms are observed along the different stages of the capability ladder. Thus, at a general level, the results presented in Section 6.4.3 support the findings by two previous studies which have addressed similar research questions to the one stated above (Figueiredo et al., 2013; Hansen and Lema, 2019). Given the micro-level nature of the available data, the results allow for some additional insights about exactly how the use of different learning mechanisms changes along the capability trajectory. This includes changes within and across categories of learning mechanisms based on different sources of knowledge (firm-internal, external-domestic, external-foreign).

With respect to changes within learning mechanisms categories, the results suggest that there is a shift in *firm-internal learning mechanisms* from mostly project-based learning at the bottom to more R&D-based learning at the top of the ladder. This likely reflects the increasing ability of firms to engage in innovative activities of higher levels of novelty and complexity as they build their knowledge stocks. Furthermore, firm-internal learning is often a necessary complement to acquiring knowledge from firm-external sources (Figueiredo, 2003; Kim, 1997; Nonaka, 1994). As such, the changes in firm-internal learning mechanisms might also reflect the need to engage in increasingly complex firm-internal, complementary learning mechanisms in order to be able to engage with more novel and complex forms of firm-external knowledge (Figueiredo et al., 2013). Changes in *external-foreign learning mechanisms* along the capability ladder are equally pronounced. As in the case of firm-internal learning mechanisms, there appears to be a shift from project-related (and some human resource-related) learning to R&D-based learning. Generally speaking, this corroborates Hansen's and Lema's (2019) findings, although there appear to be differences in the precise kinds of learning mechanisms used at lower capability levels. Finally, the data suggests that the frequency at which firms make use of *learning based on domestic sources of knowledge* is approximately constant at all capability levels. This contrasts with Hansen's and Lema's (2019) study, which finds that learning based on domestic sources of knowledge is primarily observed at low capability levels.

With respect to changes across different learning mechanisms, a first insight is that firms which rely on firm-internal mechanisms alone tend to exhibit low levels of technological capabilities. Furthermore, there appears to be a shift in the relative frequency with which firms rely on external-domestic and external-foreign sources of learning at different stages along the capability ladder. While external-foreign learning mechanisms are observed comparatively infrequently at lower capability levels, they seem to be more commonly used by firms which have achieved higher stages of capability development (this is similar to findings by Hansen and Lema, 2019; Hansen and Ockwell, 2014; Plechero, 2012; and Scott-Kemmis and Chitravas, 2007). However, as mentioned above, learning mechanisms based on external-domestic sources of knowledge are observed at approximately similar frequencies across all stages of the capability ladder. This finding differs from those presented in previous case studies of latecomer learning (*ibid.*). These studies predominantly argue that learning based on external-domestic sources of knowledge decreases in relevance as firms progress to higher levels of capabilities. The study presented in this chapter provides a slightly different picture in this regard: While the *relative* frequency with which external-domestic learning mechanisms are observed decreases at higher levels of capabilities (in comparison to the frequency at which external-foreign learning mechanisms are observed), their *absolute* frequency across the different capability development stages seems to remain approximately constant.

7.2.3. Synthesis and key contributions

This section synthesises the results presented above into four key findings. This includes (i) the extent of inter-firm differences in capability accumulation and learning, (ii) the co-evolutionary nature of capability accumulation and learning activities, (iii) the ways in which technological characteristics affect learning, and (iv) the role that knowledge spillovers through informal mechanisms play for learning. The section discusses these findings with respect to what the existing literature on latecomer learning has to say about them. In doing so, it also aims to highlight relevant areas for future research.

Inter-firm heterogeneity in latecomer learning

A first insight that emerges from the research presented in Chapters 5 and 6 is that there seem to be substantial inter-firm differences in the observed processes of technological capability accumulation and learning. The approach pursued in Chapter 5 shows that Thai biogas engineering firms have engaged with foreign organisations in a variety of ways for the supply of AD systems to CDM projects. Using a more micro-level approach, Chapter 6 provides insights about how a sample of 10 Thai biogas engineering firms have built their capability stocks over time. As summarised above, this analysis identified substantial differences in the capability development trajectories that these firms have undergone and the learning mechanisms that they have engaged in.

These findings highlight the importance of considering inter-firm heterogeneity in the study of latecomer capabilities. Studies using entire sectors or economies as their units of analysis often ignore this issue. This is problematic as these studies miss out on nuance and variety in the dynamics of firm-level capability accumulation. Hence, there is a risk that such research leads to one-size-fits-all recommendations for policy and business which do not accurately reflect the opportunities and challenges faced by firms that find themselves at different stages along the capability trajectory.

There are, of course, many studies which assess latecomer capabilities at the level of the firm - the most relevant of these have been reviewed in some detail in Chapter 2. However, most of these studies focus on firms that are large and that have been relatively successful in deepening their capability stocks. In fact, almost all of the key studies which have had a substantial impact on shaping our understanding of how technological upgrading occurs in latecomer firms focus on so-called “national champions” or “high-growth firms” (e.g., Dutrénit, 1998; Figueiredo, 2003; Kim, 1997; Lema and Lema, 2012). Studying these kinds of firms in developing economies is clearly important given their role in bringing advanced technology into the country - through interactions with advanced foreign organisations and their own innovation efforts - and because of their contributions to vertical and horizontal knowledge spillovers to other local firms. Furthermore, they play an important role in generating local jobs and economic growth. For example, a recent report by the World Bank on high-growth firms in a selection of developing economies emphasises that they make up around 80 percent of all new sales and jobs in their respective sectors despite only constituting 20 percent or less of the total number of firms (Goswami et al., 2019).

However, the analysis presented in this thesis suggests that it also important to focus research on how and why some latecomer firms are relatively unsuccessful in upgrading their technological capabilities. In fact, a large share of the firms studied in Chapter 6 have remained at low levels of technological capabilities or have only managed to achieve modest improvements in their capability stocks. This begs the question of precisely what firm-internal and external conditions have prevented them from progressing along the capability trajectory. There appear to be very few studies focusing on failures in latecomer capability accumulation. This mostly includes studies which - similar to the research presented in this thesis - are based on multiple-case study frameworks (Figueiredo, 2017; Hansen and Ockwell, 2014; Scott-Kemmis and Chitravas, 2007). However, these studies tend to be rather brief in their descriptions of the factors that prevent firms from achieving higher levels of capabilities. While the research presented in this thesis goes into detail about the learning mechanisms that unsuccessful latecomer firms have engaged in, there are a variety of other firm-level factors that merit attention (e.g., organisational and managerial aspects). To my knowledge, there are only few studies that allow for detailed insights about why firms fail to upgrade their capabilities (e.g., Karabag, 2019; Van Dijk and Bell, 2007)

Hence, the first key conclusion of this thesis is that research on latecomer capabilities should devote more attention to the role of intra-industry, inter-firm differences in technological catch-up. Analysing technological learning at the level of the economy or sector and focusing on only a subset of highly successful firms only provides limited insights. These can potentially lead to misleading recommendations for policy and business. Instead, more research is needed on the conditions that different firms find themselves in, both with regards to the development of their capability stocks and other relevant factors at the level of firm.

Concomitant changes in capabilities and learning mechanisms

Another key finding of the research presented in this thesis concerns the co-evolutionary nature of changes in capability stocks and learning mechanisms. The analysis of 10 Thai biogas engineering firms presented in Chapter 6 shows that there are some discernible patterns in how learning mechanisms change as firms move from lower to higher levels of capabilities. As summarised above, this includes both changes *within* and *across* different sources of learning (firm-internal, external-domestic, and external-foreign).

While the relevant results have been discussed in detail above, only the more general points are reiterated here. First, this piece of research offers supporting evidence to the idea that the internal resources of a firm affect the kinds of learning activities - performed firm-internally or in collaboration with other organisations - that it can engage in (Dantas and Bell, 2011; Figueiredo et al., 2013; Hansen and Lema, 2019; Yoruk, 2011). Furthermore, and contrary to other firm-level studies on technological learning (Hansen and Lema, 2019; Hansen and Ockwell, 2014; Plechero, 2012; and Scott-Kemmis and Chitravas, 2007), the findings presented here suggest that external-domestic learning mechanisms are of approximately equal relevance across all stages of capability development. This has been explained with reference to the particular characteristics of learning processes for AD systems (the role of technological characteristics for learning are revisited in more detail below). Despite the relevance of domestic learning across the capability ladder, the analysis also suggests that high levels of capability attainment appear to be associated with some form of foreign knowledge inputs. In this regard, the research presented here agrees with the previously cited studies (*ibid.*).

This study primarily focuses on identifying the relative importance of different learning mechanisms along the capability trajectory. However, based on the latecomer capability literature (e.g., see Hansen and Ockwell, 2014) as well as the analysis of the data, it is clear that learning mechanisms rarely operate in isolation. Aside from references to the need to complement external knowledge acquisition with firm-internal efforts to achieve organisational learning, the present study puts relatively little emphasis on the importance of considering different combinations of learning mechanisms. It might well be the case that certain foreign-external sources of knowledge also require the involvement of external-domestic learning (e.g., in cases where foreign equipment imports necessitate testing that is only possible using equipment available at local universities or research institutes). Future research could usefully extend the approach pursued here by focusing closer attention to how the complex mixtures of learning mechanisms which firms engage in change as they move from lower to higher levels of capabilities.

In general, only little empirical evidence is available on the co-evolutionary nature of technological capabilities and learning mechanisms. While this research has provided additional evidence on the subject, there is a clear need for further study. Existing research to date has mainly focused on addressing this issue in the context of single or multiple-case study frameworks based on qualitative data collected from a handful of firms. While these approaches allow researchers to collect detailed information on capabilities and learning mechanisms, the resulting findings are usually limited with respect to their generalisability. Therefore, the challenge for future research lies in finding ways to combine large-N approaches with (quantitative) indicators that allow for detailed insights about the relationship between technological capabilities and learning mechanisms for larger numbers of firms. Ideally, this would also include insights about how the co-evolution of capabilities and learning mechanisms differs across technologies and sectors. Given that understanding the co-evolutionary nature of capabilities and learning mechanisms is critical to manage the latecomer capability upgrading process (Bell and Figueiredo, 2012b, p.69), there is a clear need for more research on this subject.

The role of technological characteristics in learning

The research presented in Chapters 5 and 6 also provides insights about how technological characteristics affect the ways in which latecomer firms build their capability stocks. Chapter 5 illustrates that Thai biogas CDM projects have sourced biogas engines/engine-generator sets almost exclusively via foreign equipment imports. This was explained with reference to the fact that firms in developing countries face substantial barriers for the localisation of the large production facilities required to produce this kind of technology. In contrast, AD systems have been supplied through a variety of organisational arrangements. Chapter 6 goes into some detail about the micro-level learning mechanisms that underlie these arrangement types. It finds that learning based on locality-specific project experience is key, which stems from the need to adapt each system to the project context. Such context-specific learning appears to be most easily facilitated through human resource and project-based learning.

Hence, another key conclusion of this thesis is that research should pay close attention to the role that technological characteristics play for latecomer learning. This is often not emphasised in enough detail. In fact, many influential papers in this field of study only mention technological characteristics as a side note (for example, see Dantas and Bell, 2011; Figueiredo, 2003; Hansen and Ockwell, 2014). In most cases, this does not include discussions about how exactly these characteristics influence learning processes. Of course, the analytical frameworks of these studies focus on other phenomena and, therefore, do not have much space to elaborate in detail on the impact of technological characteristics on learning. Furthermore, many of these studies are based on explorative approaches that investigate a single technology and, as such, are not well-suited for a comparative analysis of learning processes for two different kinds of technology - e.g., as the analysis presented in Chapter 5. Nevertheless, it would be useful to include more information in studies on latecomer learning about how exactly technological characteristics are likely to relate to the dynamics of learning. This would allow for a more detailed assessment of the generalisability of these studies' results and could help avoid potentially misleading recommendations for decision-makers.

Recently, a strand of literature has emerged which explicitly focuses on how the characteristics of technologies impact the potential of low and middle-income countries to localise industries for their development and supply (Binz et al., 2017; Quitzow et al., 2017; Schmidt and Huenteler, 2016; Zhou et al., 2018). Essentially, these studies distinguish technologies based on the degree to which they rely on capabilities required for manufacturing and/or design processes. Technologies which primarily rely on manufacturing capabilities are characterised by high production volumes at centralised production facilities and high degrees of technological standardisation. Technologies which rely more strongly on design capabilities are project-based, are produced in small batches, and require significant adaptation to project contexts. Hence, this strand of literature is important for the research presented in this thesis. However, a key limitation of these studies is that they analyse capabilities and learning mechanisms at a comparatively abstract level. This prevents them from going into much detail about the firm-level dynamics involved in processes of technological learning. The analysis presented in this thesis provides such detailed insights and, thus, offers complementary insights to this literature.

A potential critique of the research presented in this thesis, as well as the aforementioned strand of literature, is that technological characteristics are only one of multiple factors that differ across sectors. There are other aspects that impact the opportunities and challenges that latecomer firms face when aiming to build their capability stocks. As argued in Section 2.3, the perhaps most influential theoretical framework in this regard is Malerba's (2002) Sectoral Systems of Innovation approach, which has also been applied to catch-up in developing country contexts more recently (Lee and Malerba, 2017; Malerba and Mani, 2009; Malerba and Nelson, 2011). In addition to the aspects considered in this thesis, Malerba's framework explicitly considers demand structures, formal and informal institutions, and processes of variety and selection. However, the breadth of issues addressed in studies based on this approach limits the level of detail they can provide about firm-level learning dynamics. As such, rather than seeing a focus on technological characteristics and the Sectoral Systems of

Innovation approach as conflicting, they should be regarded as complementary approaches which provide insights at different scales.

Informal learning mechanisms

A final core insight that emerges from the research presented in this thesis concerns the importance of learning based on knowledge spillovers through informal channels. In Chapter 5, the informal category of organisational arrangements between local Thai biogas engineering firms and foreign sources of knowledge is the most frequently observed arrangement type. The available data also indicates that this arrangement type involves the largest number of local firms. The micro-level analysis of learning in Chapter 6 provides further insight into the role of informal learning and focuses on learning mechanisms involving both foreign and local sources of knowledge. Its results suggest that learning through labour mobility, learning through the observation and/or operation of competitors' projects, and learning through interactions with (foreign) component suppliers have been key in allowing Thai biogas engineering firms to build their capability stocks.

At a general level, the analysis illustrates the importance of considering knowledge spillovers through informal learning mechanisms in the study of latecomer learning. While there is a large body of literature on the subject of knowledge spillovers in developing countries (e.g., see Keller [2010] and Saggi [2002] for often-cited reviews), there is only little evidence available about how such knowledge spillovers contribute to the ability of latecomer firms to build their technological capability stocks. To my knowledge, there are only a handful of studies that focus specifically on this topic (Chen, 2009; Egbetokun, 2015; Kesidou and Romijn, 2008). This is rather surprising, given that key researchers in the field of technological catch-up in developing countries have long ago highlighted that informal learning mechanisms likely play a major role for latecomer learning (Radosevic, 1999, p.147-148; Westphal et al., 1985, p.199).

It is important to note I do not wish to suggest that formal channels for knowledge transfer are unimportant (e.g., knowledge transfer in collaborative cross-border R&D projects or via FDI). In fact, the analysis presented in Chapter 6 offers some evidence that these channels are indeed important. For example, it was argued that the 1988-1995 Thai-German Biogas Programme has had a decisive impact on the development of the Thai biogas industry as a whole because of its role in adapting foreign-developed technology to local circumstances. Furthermore, multiple members of Thai biogas engineering firms which today are leaders in the market have been involved in this project in some capacity, suggesting that this project had an important role in offering local engineers first experience in developing biogas projects. Hence, rather than arguing that formal learning mechanisms are unimportant, the intention here is to point out the need to develop a better understanding of the importance of informal learning mechanisms. Also, it would be interesting to analyse how these informal learning mechanisms are combined with (or are perhaps used as substitutes for) formal learning linkages (e.g., see Freitas et al., 2011).

Future research could also usefully try to determine how the relevance of different types of informal learning mechanism changes as firms progress along the capability trajectory. For example, Hansen and Ockwell (2014) argue that imitation based on informal knowledge channels plays an important role in the early stages of technological capability building processes. Bell and Albu (1999) and Kesidou and Romijn (2008) argue that knowledge spillovers in industrial clusters play an important role for latecomer firms. Maskell et al. (2006) focuses on the role of international trade shows in allowing latecomer firms to learn about frontier technology and to expand their networks. While the analysis presented in Chapter 6 provides some insight about the relative importance of different kinds of informal learning mechanisms along the capability ladder, more research is needed to develop a more robust understanding of this issue.

7.3. Implication for decision-makers

The findings summarised above have implications for stakeholders involved in the localisation of low-carbon industries in developing countries. The present section discusses some key implications for (i) firm managers, (ii) national and sub-national policy makers, and (iii) international donor agencies and bi-/multilateral institutions.

Firm management

The research presented in this thesis suggests that they ways in which firms engage in different types of learning mechanisms have a decisive impact on their ability to build capability stocks. As such, a first recommendation for businesses is that they should approach technological learning as a strategic issue. The management literature provides some conceptual frameworks that can provide guidance in this regard. For example, this includes the "learning systems" (Scott-Kemmis and Chitravas, 2007), "extended learning" (Rush et al., 2004, p.328), and "integrated learning" frameworks (Bessant et al., 1996). At the core of these is the idea that, in order to build their technological capabilities, firms should follow a sequence of steps (i) to develop an awareness of existing capability gaps, (ii) to determine a set of ambitious but realistic capability development goals, (iii) to search for suitable sources of knowledge, and (iv) to engage with these knowledge sources using learning mechanisms that are appropriate in the given context. Of course, this is only possible if managers have a good overview of both the firm-internal and external environment. Furthermore, firms require good linkage capabilities and absorptive capacities to be able to approach and exploit available external sources of knowledge.

A related implication concerns the co-evolutionary nature of capability accumulation and learning activities. The analysis in Chapter 6 shows that firms which have achieved substantial improvements in their capability stocks have periodically changed the types of learning mechanisms which they engage in. This corroborates findings by in-depth case studies which focus on the management of learning processes and highlight that "discontinuities" in the use of learning mechanisms appear to be important to overcome plateaus in capability building efforts (Figueiredo, 2003; Tacla and Figueiredo, 2006). For firm managers, this underlines the point made above about the importance of identifying capability gaps, setting learning goals, finding appropriate knowledge sources, and exploiting these via suitable learning mechanisms. While more research is needed to determine precisely which (combinations of) learning mechanisms are most important at different levels of capability development, there seems to be a consensus that higher levels of capability attainment require some form of foreign knowledge inputs (as discussed in the previous section). As such, firms which find themselves at the intermediate stage of the capability ladder should consider this in their learning strategies.

Another relevant insight for firm managers concerns the importance of firm-internal learning. The analysis presented in Chapter 6 suggests that such learning is important at virtually all levels of capability development. Also, it was argued that firm-internal learning is a critical complement to externally accessed knowledge (Cohen and Levinthal, 1990; Kim, 1998). In the analyses presented above, this is reflected in the shift from predominantly human resource and project-related to R&D-based firm-internal learning as firms move along the capability trajectory. Similar findings have been reported in previous micro-level studies on latecomer learning (as discussed in Section 6.4.3.2). Hence, firm managers might wish to consider to critically evaluate what role firm-internal learning efforts play for their firms and how these can be improved upon, both to generate knowledge firm-internally and to aid the incorporation of external knowledge into the firm's knowledge stock.

The research presented in this thesis can also be used to issue some specific but more tentative recommendations for managers of latecomer firms which supply AD systems or other technologies that exhibit similar characteristics (i.e., complex technologies which require substantial adaptation to local project contexts). One of the core findings of the research presented above is that learning in AD systems depends heavily on experience accumulation, which is often facilitated through learning mechanisms that do not involve formalised channels for knowledge transfer. Specifically, the results of Chapter 6 indicate that for firms at the lower ends of the capability spectrum, experience-based learning mostly depends on human capital formation and repeated involvement in projects.

Firms can increase their human capital stocks by hiring skilled engineers (as discussed in Chapter 6; see also Chen [2009, p.529]). A key issue here is the availability of a local labour force that has appropriate training and experience. In fact, multiple of the firm managers who were interviewed as part of this research indicated that the limited availability of skilled labour in biogas in Thailand has presented a key challenge for their businesses. As a result, many of the firms which exhibit higher levels of innovative capabilities have decided to hire foreign experts to fill leading positions in the technical and managerial units of their firms (as discussed in Chapter 6). Hence, the ability to identify suitably trained and experienced personnel is a key issue for firm management. The analysis presented here implies that if such personnel is not available locally, managers should look beyond the boundaries of the national economy. This can perhaps be facilitated by making information about the firm more easily available in foreign countries, e.g., by maintaining a company website in English or by regularly participating in international trade shows.

The results presented in this thesis also suggest that experience-based learning on a project-to-project basis is key for latecomer learning in AD systems and comparable technologies. Specifically, the analysis presented in Chapter 6 highlights that many firms in the Thai biogas industry introduce (mostly minor) changes in system designs in commercial projects, observe how these changes impact operational performance, and then incorporate the lessons learnt in subsequent projects. Managers have an important role to play to ensure that such activities contribute to effective organisational learning, and there are a number of tools available to facilitate this (Brady and Davies, 2004; Eriksson and Leiringer, 2015). For example, the lessons learnt from repeated engagement in projects can be captured in databases. This facilitates knowledge codification and communication and, thus, can be an effective way to share experiences. Furthermore, firms might benefit from developing and maintaining project management standards and methods which are to be applied across all projects. The challenge here lies in defining standards which are detailed enough to ensure that lessons learnt from previous projects can be taken on board while also allowing for enough flexibility to encourage experimentation and new learning.

National and sub-national policy makers

The findings summarised above can also be used to inform the design of policy interventions at the national and sub-national levels aiming to support technological learning at LCE-supplying latecomer firms. For example, the findings about the importance of inter-firm differences in capability building and the co-evolution of capabilities and learning mechanisms offer a basis for decisions about how best to support groups of firms that are at different stages in their development. The present section briefly discusses some suggestions for policy interventions that are considered appropriate for different groups of firms. Specifically, it distinguishes between recommendations for firms at the level of routine production capabilities (basic and extra basic), low innovation capabilities (basic and intermediate), and high innovation capabilities (advanced and world-leading).

Before moving into the discussion of specific policies, a few comments are necessary. Given the observed heterogeneity in capability development among latecomer firms, it would seem useful to pursue a broad portfolio of policy support programmes that addresses the specific opportunities and challenges that are most relevant at the different stages on the capability ladder. However, governments in low and middle-income countries often operate under severe budget constraints. Therefore, it would be useful to conduct capability audits to identify what levels of capabilities local firms in key strategic sectors possess. This way, government agencies can focus their efforts on designing and implementing policies that are likely to have the biggest impact.[26] Furthermore, government agencies carefully need to think about whether they can spend their limited

[26] Basing such audits on interviews (as in the present thesis) would probably result in prohibitive time and resource commitments. Therefore, it might be better to base such efforts on surveys, e.g., following the tool developed by Rush et al. (2007).

resources on supporting firms across the capability spectrum. One might legitimately ask whether it is worth spending resources on the least-capable firms or whether these should simply be left to their own devices. The discussion here does not aim to advocate the use of any particular policy support tool but merely points out a few examples of relevant options. It should also be noted that the list of policies discussed here is by no means exhaustive.

As discussed in Section 2.1, firms which exhibit capabilities at the routine production level primarily concern themselves with the execution of pre-defined processes such as the execution of externally developed and imported process specifications. This primarily revolves around the build-up of technology operation capabilities and capabilities for product and processes engineering that are needed to introduce incremental changes which do not alter the designs of the underlying technologies. As such, for firms at this level of development, policy interventions should aim to ensure that high-quality technology is accessible and that firms develop the resources necessary to absorb such technology effectively. Management extension services might be useful in this regard (Cirera and Maloney, 2017). These services are usually provided by consultancy groups which help firms build a basic level of management and organisational capabilities (by benchmarking performance characteristics, developing a plan for short to medium-term improvements, and providing ongoing support during the implementation of this plan). In the case of the Thai biogas industry and other industries involving similar technology, such services could, for example, play an important role in helping firms attract and retain suitable talent, implement processes which facilitate learning across projects, and strengthen the capabilities needed to link up with other organisations that are important for the development of successful biogas projects (technology users, component suppliers, design consultants, etc.).

In addition, national and sub-national governments can assist firms which possess capabilities of the routine production level by facilitating opportunities to gain project experience. For example, this could be achieved through the promotion of tenders involving multiple projects which are to be developed over extended periods of time (see Kiamehr et al. [2015, p.1250] for a similar suggestion). In combination with the above-mentioned management extension services, this would give firms an opportunity to engage in active project-to-project learning. Furthermore, it would allow them to redirect resources which they would otherwise spend on preparing bids for individual projects to efforts aimed at upgrading their technological capabilities. A key issue to consider here is the risk that clients face when signing up to work with comparatively inexperienced technology suppliers for investment-intensive projects. For state-owned as for private sector clients, governments could potentially help in this regard by addressing some of the financial risks involved in these projects, for example, by providing guarantees.

Firms at the low and intermediate levels of innovative capabilities engage in some advanced and exploratory technology development and, in some cases, also in applied research. However, this usually involves comparatively minor adaptations in technological designs that have been developed externally to the firm. Given the observation that transitions to higher-level innovative capabilities often involve some form of foreign knowledge inputs, support services for firms at the basic/intermediate innovative level could aim to ensure that such knowledge becomes accessible more easily. For example, this could be facilitated through so-called technology transfer and extension services (Cirera and Maloney [2017]; see Mathews and Hu [2007] for a case study of the role that such services have played for technological upgrading in Taiwan). Since AD systems and comparable kinds of technology involve substantial adaptation to local circumstances, these services could be usefully provided by local technology centres or public research institutes, as these likely have a good understanding of the particularities of the local context. Here, it is key to ensure that the activities of these centres and institutes are closely aligned with the needs of industry.

In addition, governments can promote learning among firms in the mid-range of capabilities by creating demand for innovative solutions. For example, this could be in the form of running public procurement programmes focused on innovative projects (Edquist et al., 2015). The award of such benefits could be tied to specific requirements, e.g., the involvement of foreign project partners (component suppliers, design consultants, etc.). In addition to allowing firms to learn from these collaborations, such projects might also be useful to address specific technological challenges that exist in the country and/or sector. As for firms at the lower end of the capability spectrum, it would be useful if such projects were not awarded on a one-by-one basis but, instead, were bundled to allow for more effective project-to-project learning. A key challenge in setting up such innovation procurement programmes is that government agencies require detailed knowledge of the challenges and opportunities in the sector. This could perhaps be addressed by including sectoral experts based at national research centres and universities in their development.

Firms at the advanced and world-leading innovative levels of capabilities operate at or close to the global technological frontier. They frequently engage in high-quality

R&D that results in new-to-country and new-to-world innovations. As such, they usually have already built up the firm-internal resources and networks of partners that allow them to engage in high-level innovation. In these cases, policy interventions could focus on mitigating the factors that prevent firms from investing in more R&D. Specifically, governments could provide some redress for the externalities generated from R&D (Cirera and Maloney, 2017; Jaffe et al., 2005), for example, in the form of tax incentives or direct grants for innovative projects. As the innovation procurement programmes discussed above, such tax benefit and grant schemes could be designed in a way so that they address particular technological challenges. Furthermore, they could perhaps be linked to some sort of collaboration with less advanced local firms (e.g., component suppliers or construction companies) to encourage knowledge spillovers.

Moreover, governments could assist advanced firms to further develop their capability stocks by helping them move into export markets. The most advanced firms included in the analysis presented in Chapter 6 are all involved in export markets, in neighbouring countries in Southeast Asia and other regions. Participating in competitive international markets can be an important impetus for firms to further develop their capability stocks, because of the need to adapt technology to local circumstances and the high performance requirements of advanced users (e.g., see Ernst et al., 1998). Governments can assist firms to move into export markets by providing detailed information about markets, institutions, and technical challenges.

Alongside these comparatively specific policy interventions, governments should also support the development of the broader business environment in which firms can successfully build their capabilities. As discussed in Section 2.3 of this thesis, this includes a wide variety of aspects. For instance, it involves maintaining a stable political and economic environment, regulating the openness of the economy, and promoting efficient labour and financial markets. It also includes supporting the development of legal frameworks to support industrial activity, institutions to support linkages among different actors in the economy, and institutions for training and the more basic research that firms are unwilling to invest in. While a thorough discussion of available policy instruments to support these different factors is beyond the scope of this thesis, national and sub-national policy makers should nevertheless consider the roles that they play in enabling firms to build their capability stocks.

International donor agencies and bi-/multilateral institutions

The results of the research presented in this thesis also provide relevant insights for international donor agencies and bi-/multilateral institutions which provide finance and/or technical knowledge for low-carbon development in the countries of the Global South. International donor agencies are typically based in high-income countries and include, for example, the German Corporation for International Cooperation, the Danish International Development Agency, and the UK Department for International Development. Relevant bi-/multilateral institutions include organisations with a particular focus on renewable energy (e.g., the International Renewable Energy Agency), market-based mechanisms (primarily the CDM), organisations for the distribution of climate finance (e.g., the Green Climate Fund), programmes to help governments develop technology selection strategies (e.g., through Technology Needs Assessments), and technology centres and networks (e.g., the Climate Technology Centre and Network under the UNFCCC or the Climate Innovation Centres supported by the World Bank). This section briefly discusses some key implications for these kinds of organisations and programmes. In doing so, it provides general recommendations and, occasionally, highlights how existing institutions could be adapted to reflect some of the lessons generated though the research presented in this thesis.

At a general level, there is a need for international donor agencies and bi-/multilateral institutions to define more precisely what low-carbon development and technological learning is and how different kinds of support mechanisms should contribute it. Perhaps the most frequently critiqued initiative in this regard is the CDM (e.g., Byrne et al., 2011; Lema and Lema, 2016, p.234). While the Marrakesh Accords specify that the CDM should contribute to some form of international technology transfer, they do not describe in much detail what exactly this implies (UNFCCC, 2001). At least in the context of Thai biogas CDM projects, this has meant that many project developers simply claimed that technology transfer has taken place as part of their projects, whether or not this was actually the case (source: multiple interviews conducted as part of this study; see Section 5.6.1 for a quantitative assessment of CDM project developers' claims regarding technology transfer). The organs of the more recently established Technology Mechanism under the UNFCCC describe how they aim to support low-carbon development and learning in some more detail.[27] For example, the Climate Technology Centre and Network addresses a wider range of activities that are relevant for latecomer learning than the CDM. This is evident in the core services it provides, which include (i) offering technical assistance for technology transfer, (ii) offering and distributing information and knowledge about low-carbon technologies, and (iii) supporting collaboration and networking among relevant stakeholders (see CTCN [2015] for more detail on these services). Similarly, the Technology Executive Committee seems to have adopted a more nuanced conceptualisation of technological learning than, e.g., the CDM. This is evident in some of its recent work which builds on the innovation systems approach (TEC, 2015).

However, based on the micro-level research presented in this thesis, it appears that these and other initiatives might benefit from adopting even more nuanced conceptualisations of how technological learning takes place in practice. Most importantly, such conceptualisations should acknowledge the importance of technological capabilities and linkages among key stakeholders. Specifically, donor agencies and bi-/multilateral institutions should put more emphasis on the idea that firms undergo a progression of capability development. Furthermore, they should aim to foster specific kinds of interactions with technology users, component suppliers, design consultants, research institutes, etc. that are key for learning. As pointed out by Ockwell and Byrne (2016, p.165), most multilateral centre and network-type institutions focus primarily on linking high-level national and international experts. A recognition of the need to foster linkages within the economy - and perhaps also linkages to specific kinds of advanced foreign knowledge - might make these networks more relevant to the actual needs of latecomer firms. Furthermore, rather than relying primarily on foreign-based experts for technical assistance, such an extended network might also allow for linking latecomer firms with locally based technology experts. This might help to ensure that experts have a detailed understanding of the local context, which has been found to be important in the case of AD systems and comparable kinds of technology.

[27] The Technology Mechanism was established during the Cancún Climate Change Conference (UNFCCC, 2010b). The Climate Technology Centre and Network is the operational entity of the Mechanism. It involves a headquarter office and a network of technical experts and centres of excellence. The Technology Executive Committee is the policy arm of the Mechanism. It also provides strategic guidance to the Climate Technology Centre and Network.

Another recommendation stemming from the research presented in this thesis is that technological characteristics should be considered explicitly in the development of technology selection strategies. For example, this concerns the development of Technology Needs Assessments or the technology strategies that are part of the Nationally Determined Contributions under the UNFCCC. Essentially, technology selection strategies identify priority technologies which governments can support to promote low-carbon development. International donor agencies and bi-/multilateral organisations have an important role to play in helping national government agencies to draft these. In the context of Technology Needs Assessments, the preparation of technology selection strategies usually involves an assessment of key institutional, political, and regulatory barriers for technology development and diffusion (Nygaard et al., 2017, p.708). Based on the research presented in this thesis, it would seem useful to also consider the role that technological characteristics play in this regard. As argued above, technological characteristics appear to have a decisive impact on the ability of latecomer firms to accumulate technological capabilities and, by extension, on the ability of low and middle-income countries to localise industries for the development and production of low-carbon technology (see also Schmidt and Huenteler, 2016). As such, considering technological characteristics in technology selection strategies could allow governments in these countries to focus their efforts on technologies that have a high potential for industry localisation.

A final recommendation is that international donor agencies and bi-/multilateral organisations could assist policy makers at the national and sub-national level in the development of appropriate policies aimed at promoting technological learning at latecomer firms. Governments in the Global South often suffer from weak institutional capacities and, as a result, struggle to introduce effective policies for innovation and technological catch-up (Cirera and Maloney, 2017). Seeing that donor agencies and bi-/multilateral organisations usually work with governments in multiple countries, they are potentially in a good position to determine which policies will likely have the biggest impact in a given national context. For example, donor agencies and bi-/multilateral organisations could assist governments to introduce policies that are targeted at firms at different levels along the capability ladder (a number of illustrative examples of such policies are discussed in the preceding section on implications for national and sub-national policy). Here, as a first step, it would be useful to offer assistance in conducting capability audits of the type discussed earlier. As argued above, this would help to determine what stage of development local firms are at and what policies would likely have the largest impact for further technological learning. Once suitable policy options are identified, donor agencies and bi-/multilateral organisations could also (co-)finance and manage the design and implementation of some of these. This would be particularly useful for investment-intensive and long-term programmes, such as the innovation procurement policies outlined above.

7.4. Limitations and suggestions for future research

As any research project, the study presented in this thesis has certain limitations. Most obviously, this concerns the focus on a particular technological and national context, which raises concerns about the generalizability of the results. However, a case study approach was considered appropriate because of the need to explore the technological capability and learning concepts in detail. Future research could investigate learning in other technological and national contexts to test the key findings presented here. As argued above (Section 2.5.1), most research on latecomer capabilities in LCE technology has focused on a subset of technologies and low and middle-income countries. As such, there is much scope to provide new insights by focusing on other contexts.

Furthermore, there are a number of other limitations that stem from the choice for the particular analytical framework used in this thesis. This includes limitations regarding the representation of the capability accumulation process within the firm and limitations regarding the representation of the firm-external environment. The remainder of this section discusses these.

Firm-internal aspects

A key limitation of this research concerns the focus on the technical aspects of the latecomer firm’s operations. This has been justified based on Dutrénit's (2007, 2004) work, who argues that latecomers operating below the advanced level of innovative capabilities are predominantly concerned with building a base of technical capabilities. However, there is a range of other activities that firms perform for which they need to develop capabilities. Importantly, many of these also impact the accumulation of technical capabilities. For instance, this includes capabilities for project management, which allow firms to successfully move through the project life-cycle - from placing a project bid to offering post-project services. It would be interesting to investigate how technical and project management-related capabilities co-evolve, and how both kinds of capabilities change as firms approach the technological frontier.

Capabilities for technology deployment are another example of a relevant capability type. While the analysis presented here makes some reference to deployment, this issue has not been investigated in much depth. However, capabilities for deployment are important for industry localisation in low and middle-income countries as they involve high value-added activities and have large potential for job creation (Hansen, 2018; Lema et al., 2018, p.334; this point was also raised in one of the interviews conducted for this study). To my knowledge, few studies on latecomer capabilities have analysed the development of these kinds of capabilities in detail.

The framework used here also provides only limited insight about the importance of firm strategy for technological learning. Strategic capabilities concern decisions about insourcing and outsourcing, moving up or down the industry value chain, entering or exiting certain markets, and focusing on particular kinds of technologies (Kiamehr, 2012; Kiamehr et al., 2015). Such decisions clearly have an impact on the development of technical capabilities at the firm. As such, it would be interesting to determine in more detail how these factors have influenced the accumulation of technical capabilities in the Thai biogas industry or other industries in latecomer countries.

Finally, the research presented here does not provide much information about how particular firm characteristics relate to capability accumulation and the use of certain kinds of learning mechanisms. While the research presented in Chapter 6 allows for some insight into this issue, a thorough discussion of the relationship between firm characteristics and capability accumulation/learning mechanisms was omitted to reduce the complexity of the analysis. Some latecomer capability studies based on statistical approaches have investigated the relationships between capabilities, learning mechanisms, and firm characteristics (Gammeltoft, 2004; Iammarino et al., 2008). This area of research could be usefully extended by focusing in more detail on the differences or similarities in the learning mechanisms that different kinds of latecomer firms engage in.

Firm-external aspects

Another limitation of the research presented here concerns the focus on technology-supplying firms. While this was chosen to allow for detailed insights about the capability accumulation process, there are other aspects that are useful to consider in a study of latecomer learning. For example, this includes the roles that sub-national and national governments play in terms of planning and offering policy support for technology deployment and development. The policy schemes that have been most important for the development of the Thai biogas sector have briefly been summarised in Section 4.5. However, it would be useful to link these more closely to the results of Chapters 5 and 6 to determine what impact they have had on firm-level learning. Similarly, it would be useful to analyse policy developments and latecomer capability accumulation in an integrated manner in other LCE technology and national contexts.

A further interesting aspect of the latecomer capability accumulation process that has not been investigated in much depth here is the role of complementary or otherwise related sectors. For example, this concerns the co-evolution of industries for the supply of the final product and industries for key system components. Such an investigation could also focus on the roles of other, related industrial sectors that generate transferable capabilities. The literature on "related diversification" might provide useful insights here (e.g., Boschma et al., 2013; Markides and Williamson, 1994). The interviews conducted for the present research indicate that the wastewater treatment sector and certain other sectors (e.g., petrochemicals) have been important in generating some of the capabilities that were later adapted to and used in the Thai biogas industry. Hence, to inform the design of low-carbon industrial strategies of developing economies, future research could usefully explore in more detail the role of related or complementary sectors.

Finally, there is a need for a better understanding of how certain core events shape an industry's development and initiate long-term processes of local capability accumulation. As briefly mentioned in Section 4.5, the 1988-1995 Thai-German Biogas Programme was a turning point in the development of the Thai biogas sector. This programme combined foreign and local knowledge resources and led to the adaptation of foreign biogas system designs to local contexts. Given the success of this project, the Thai government subsequently began to subsidise further biogas programmes at a large scale. Furthermore, the interviews conducted as part of this Ph.D. research revealed that many individuals who were involved in the Thai-German Biogas Programme work as leading professionals in the Thai biogas industry today. Further insights are needed to understand the impact that such events can have on technological learning and the long-term development of industries in low and middle-income countries. Here, the literature on strategic niche management in latecomer contexts provides useful insights that could guide such an investigation (Berkhout et al., 2010; Byrne, 2011; Romijn et al., 2010).

7.5. A final word

This thesis aims to contribute to a better understanding of technological learning processes among LCE technology-supplying firms in low and middle-income countries. In doing so, it hopes to offer insights that can inform future research and decision-making that is relevant for achieving low-carbon development in the countries of the Global South. This is an important topic in light of the pressing need to mitigate anthropogenic climate change while at the same time promoting social and economic development in these countries. I hope that the research presented here and the work building on it can contribute to these goals.

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