DiBiCoo
Digital global
Biogas
Cooperation

Global diffusion of biogas technology

Research needs to fast track the renewable transition of developing economies

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Date:	10.09.2020
Deliverable N°:	D3.5

DiBiCoo – Digital Global Biogas Cooperation
Grant Agreement N°857804

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

Executive Summary of D3.5

The diffusion of circular technologies is a necessity if global and national decarbonisation targets are to be met. With biogas technology being exported by largely developed regions and technology imported by developing regions, there is a need to create the necessary conditions for effective diffusion on both sides of the import/export relationship.

This task uses data obtained from interviews with stakeholders from Argentinian, Ethiopian, Ghanaian, Indonesian, and South African industrial biogas markets to formulate a methodologically defined Barriers Matrix and Research Needs Matrix. Research needs were further analysed using an Open Coding approach, together with prominent technology diffusion theory (Roger's Diffusion of Innovations), to prioritise specific research areas that may contribute towards the fast-tracking of biogas technology adoption.

Results found that organisational research (network development, database generation, independent market and feedstock reviews, observability campaigns) take a priority over technical research (physical adaptation of biogas technology) in developing economies. Compatibility of technology is important to an importing region. Matching technology complexity with regional technical capacity is a research priority, with capacity building activities and technological simplification being expected solutions to this barrier. The development of demand-pull policies to the level of those existing in Europe is an unlikely scenario for many developing regions. Therefore, a focus on demand-based market growth, independent of significant external stimulus, is a priority for developing-country decisionmakers going forward.

A new model, the Renewable Energy Multiplier Paradox, seeks to express the experience gained through interviews and interview analysis. The take-home from this model is that there are a multidimensional set of research-derived, research-influenced and research-independent mechanisms that can influence a biogas market – creating positive emergent benefits for the entire sector. It is important to recognise which of these mechanisms best match local demand conditions, solve barriers on the regional level and produce the most positive outcome for both the market and wider society.

The products of this study (research needs and research prioritisation) stand as valuable and methodologically defined resources for research stakeholders interested in the global diffusion of biogas technology. Applying the general research needs defined in this study to a specific regional context would be a useful extension of this work.

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Summary of the DiBiCoo project

The **Digital Global Biogas Cooperation (DiBiCoo)** project is part of the EU's Horizon 2020 Societal Challenge 'Secure, clean and efficient energy', under the call 'Market Uptake Support'.

The target importing emerging and developing countries are Argentina, Ethiopia, Ghana, South Africa and Indonesia. Additionally, the project involves partners from Germany, Austria, Belgium and Latvia. The project started in October 2019 with a 33 months-timeline and a budget of 3 Million Euros. It is implemented by the consortium and coordinated by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

The overall objective of the project is to prepare markets in developing and emerging countries for the import of sustainable biogas/biomethane technologies from Europe. DiBiCoo aims to mutually benefit importing and exporting countries through facilitating dialogue between European biogas industries and biogas stakeholders or developers from emerging and developing markets. The consortium works to advance knowledge transfer and experience sharing to improve local policies that allow increased market uptake by target countries. This will be facilitated through a digital matchmaking platform and classical capacity development mechanisms for improved networking, information sharing, and technical/financial competences. Furthermore, DiBiCoo will identify five demo cases up to investment stages in the 5 importing countries. Thus, the project will help mitigate GHG emissions and increase the share of global renewable energy generation. The project also contributes to the UN Sustainable Development Goals (SDG 7) for 'Affordable and clean energy', among others.

Further information can be found on the DiBiCoo website: www.dibicoo.org.

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List of abbreviations

AD	Anaerobic digestion
CDI	Corruptions Perception Index
CSTR	Continuous stirred tank reactors
CVD	Commercial valley of death
DiBiCoo	Digital Global Biogas Cooperation
DOI	Diffusion of Innovations
DMRE	Department of Mineral Resources and Energy
EBA	European Biogas Association
EU	European Union
EPG	Engineering, procurement and construction
FIT	Feed-in tariff
GDP	Gross domestic product
GIZ	German Corporation for International Cooperation
GNI	Gross national income
HDI	Human Development Index
IEA	International Energy Agency
INTA	National Agricultural Technology Institute
INTI	National Institute of Industrial Technology
IRP	Integrated Resource Plan
kW	Kilowatt
LFG	Landfill gas
MBtu	Thousand British thermal units
MW	Megawatt
NGO	Non-governmental organisation
OFMSW	Organic fraction of municipal solid waste
PLN	Perusahaan Listrik Negara (State Electricity Company)
POME	Palm oil mill effluent
PPA	Power Purchase Agreement
PV	Photovoltaic
QDA	Qualitative data analysis
RED	Renewable Energy Directive

REM Paradox	Renewable Energy Multiplier Paradox
ROI	Return on Investment
RPJPN	Indonesia’s Long-Term Development Plan
SABIA	South African Industry Biogas Association
SDS	Sustainable Development Scenario
SNEP	Strategic National Energy Plan
SNV	Netherlands Development Organisation
STEPS	Stated Policies Scenario
TRL	Technological Readiness Level
TVD	Technological valley of death
UASS	Upflow anaerobic solid state (bioreactor)
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNSDG	United Nations Sustainable Development Goals
USAB	Upflow anaerobic sludge blanket
USD	United States Dollar

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Deliverable context

This study is written to be delivered in two forms: As Task 3.5 in the Horizon 2020 project, Digital Global Biogas Cooperation (DiBiCoo) and as a master's thesis for an MSc Sustainable Biotechnology from Aalborg University Copenhagen. The content of this study is intended to meet the needs of both recipients. This intention has been carefully planned and coordinated with all supervisors throughout the project-writing period.

The DiBiCoo deliverable was written under the supervision of Dominik Rutz, Felix Colmorgen and Rainer Janssen, WIP Renewable Energies. A description of the task as stated in the DiBiCoo Grant Agreement is as follows:

> Based on the current knowledge on the current biogas markets and framework conditions of partner countries, research and technical adaptation needs will be investigated. This will include all relevant topics along the biogas value chain starting from feedstock sourcing, to the conversion process and final use of the products (biogas, digestate). It will furthermore prioritize the identified needs in order to boost the biogas markets in the importing target countries as much as possible. (Digital Global Biogas Cooperation [DiBiCoo], 2020a, p. 17)

Research performed for this work was completed exclusively within the global DiBiCoo consortium through relevant partners in biogas technology importing countries.

This study was also written under the supervision of Cesar Fonseca and Cristiano Varonne, Aalborg University Copenhagen.

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1 Problem formulation

1.1 Reinventing modernity

The ability of humans to harness energy to a productive end has manifested in an age of modernity for global society. Beyond scarcity, modern society functions to maximise anthropogenic wellbeing and (though this wellbeing is not always distributed evenly) has created a world of opportunity and comfort for humankind. From washing machines to modern medicine to globalised trade systems, innovations and technologies that advance wellbeing have been enabled by fuel. In large part, fuel takes the form of coal, oil and natural gas; energy rich fossilised organic matter: Enormously useful but finite and destructive in their uncontrolled utilisation. Innovation and technological advance are deeply coupled with energy and access to it stands as the ultimate enabling condition for human development.

The global-scale use of fossil fuels in order to achieve modernity has long been associated with a complex trade-off between development and destruction. While humanity has reaped the benefits of unfettered energy supply, nature bears the brunt of the negative externalities associated with modern human existence. These externalities include carbon emissions released through the burning fossil fuels for energy and the impact of the wastes of human society. Anthropogenic waste and carbon emissions are produced at a rate that increasingly exceeds the sequestration capacity of the world’s oceans and biotic life, leading to systemic imbalances in natural cycles. These imbalances have caused global heating and widespread destruction of the global environment (Intergovernmental Panel on Climate Change, 2020).

Modernity has fossil fuels to thank for its existence. But the notion of modernity and what fuels it must change if the world is to remain a place of opportunity and wellbeing for humans in the coming centuries. Ideas of sustainability, circularity and limits to growth entered mainstream social and political discourse in the latter half of the twentieth century. It is however only within the last decade - perhaps marked best by the 2015 Paris Agreement - that society has committed to transition away from what is at present a linear, fossil-fuelled-based modernity to a circular, greener shade of modernity. Creating a modernity that can meet the needs of society and nature now without compromising the ability of future societies and ecosystems to meet their own needs in the future, and thus entering a sustainable development paradigm, is a global priority (Rogelj et al., 2016; World Commission on Environment and Development, 1987).

1.2 Problem formulation

Sustainability with respect to carbon emissions is and only can be considered a global ambition. This is due to the simple fact that carbon emissions are not confined by borders and their effects are distributed globally, so it is only when *global* society operates independently from fossil fuels that sustainability will be realised. Contrary to this necessity for global transition, research, innovation and the framework conditions to adopt renewable energy technologies are also not evenly distributed and are concentrated in regions or higher economic development. The inequality of access to the prerequisites to sustainable development between countries of varying economic development when considering the global nature of true sustainability stands as the problem formulated for the purposes of this study.

This disparity demands the development of the means by which the necessary framework conditions for renewable energy technology may diffuse out of innovation centres and into regions of low concentrations of renewable technology potential. This is the process that this paper aims to investigate and ultimately identify the key research areas that enable renewable energy technology diffusion.

1.3 Research questions

The present study stands as a part of a wider project aiming to facilitate the diffusion of renewable biogas technology with the underlying goal of decarbonising the global energy sector. The principal products of this study are research-generated, context-specific research needs that will enable the effective diffusion of biogas technologies from regions of renewable technology concentration (the European Union) to regions of renewable technology scarcity (developing countries, namely Argentina, Ethiopia, Ghana, Indonesia and South Africa). Research questions for the present study were generated with the ambition to address the problem formulated above.

After the problem-approach is outlined in Section 1 the foundational technology, concepts and theories used to answer the research questions are introduced in 2. The approach by which the research questions were investigated is described in3. Section 0 then applies the technology, concepts and theories introduced in1 to the context of this study. Results are presented in 0 discussed in 4.3. Finally, Section 5 will assess the extent to which the research questions have been answered and suggest considerations that must be taken in the future based on the experience gained from this study.

The research questions addressed in this study are:

- **Research Question 1:** What are the primary barriers inhibiting biogas sector development in developing economies?
- **Research Question 2**: How can research and technical adaptation address these barriers to enable biogas market growth in the developing economies?

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2 Introduction

2.1 Biogas production

Biogas is an energy-rich gas composed of methane (40-75%), carbon dioxide (15-60%) and trace amounts of other gasses. It is produced through the digestion of organic material by a consortium of naturally occurring microorganisms in the absence of oxygen (Bharathiraja et al., 2018). This process is generally termed anaerobic digestion (AD). Anaerobic digestion is a process that occurs extensively in nature. Swamps, sediments and the digestive systems of ruminant animals such as cows and sheep provide the necessary anaerobic, temperature and nutrient conditions for biogas production. The study of these natural conditions lays out the theoretical foundation for industrial biogas production.

Like in a cow's stomachs (a fairly efficient biogas system in itself), a mesophilic temperature (between 30 and 40˚C), constant mixing, supply of nutrients, and the absence of toxins are the key parameters for effective biogas production on an industrial scale. To take this analogy further, the input and output from industrial biogas systems reflect the input and output of a cow. Grass or feedstock rich in carbohydrates goes in, is ground and biologically broken down into smaller pieces and processed by a biogas consortium into the output products: A gas (biogas) and excreta (digestate). In modern biogas systems these very same processes occur, just in steel tanks and pipes instead of the organs of a cow (Schnurer & Jarvis, 2009).

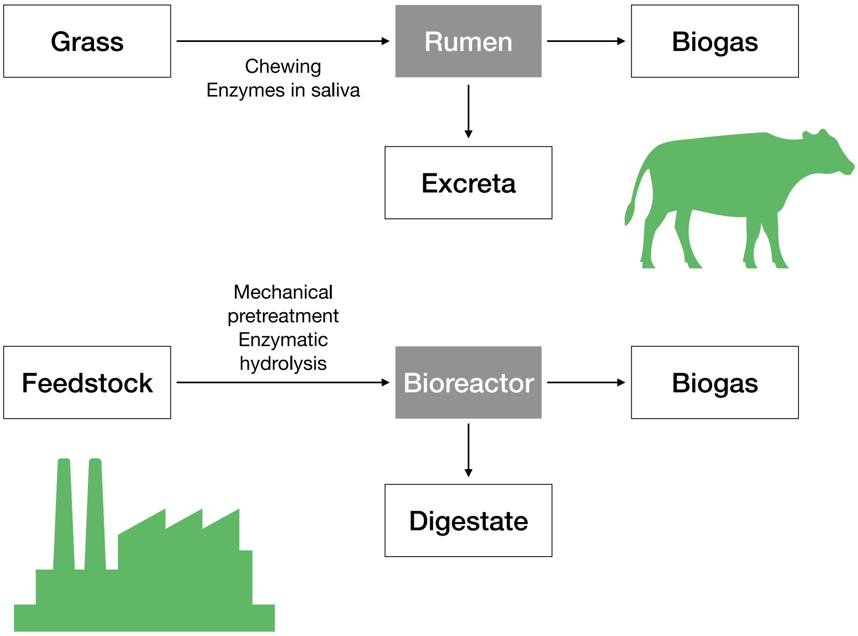

Figure 1. Simple diagram of cow-based and industrial biogas production.

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2.1.1 Feedstock

The feedstocks used in industrial biogas production fall into four main categories: Crop residues; animal manure; the organic fraction of municipal solid waste (OFMSW); and wastewater sludge (concise definitions are taken from International Energy Agency, (2020a) p. 15):

- **Crop residues** include residual biomass from the harvest of wheat, maize, rice and other coarse grains, sugar beet, sugar cane, soybean and other oilseeds.
- **Animal manure** from livestock such as cattle, pigs, poultry and sheep.
- **OFMSW** includes food and green waste, paper, cardboard and industry waste from the food processing industry. This category also includes the organic matter contained in landfill though the term OFMSW is not commonly used to reference the substrate for landfill biogas systems.
- **Wastewater sludge** is the semi-solid organic matter recovered from municipal wastewater treatment plants.

Another common feedstock, used extensively in German biogas systems for example, are energy crops. These are crops grown for the sole purpose of biogas generation. The use of this feedstock has been the subject of criticism due to land-use impacts and competition with food crops for agricultural space. This issue has led to energy crops being discouraged by major organisations in global biogas development. In the International Energy Agency's 2020 Outlook for Biogas and Biomethane, energy crops were not considered in any projections for biogas' contribution to the future global energy mix (International Energy Agency [IEA], 2020a, p. 15). It is for these reasons that energy crops will not be considered in the remainder of this study, although sequential cropping can be considered a sustainable way to produce biogas (EBA, 2020a).

Feedstocks for industrial biogas production must meet certain requirements to be considered for their effective employment on a large scale. Quality of feedstock is usually measured in terms of biogas potential (the amount of biogas that can be produced per unit of feedstock), water content and the presence of toxins or inhibitory compounds such as ammonia, hydrogen sulphide and heavy metals that disrupt function of the AD microorganisms (Cornet & Euverink, 2017). Quantity or availability of feedstock is also an important requirement for a functioning and sustainable biogas production facility. Quantity takes into account the abundance of feedstock, the consistency of supply (which may be affected by seasonal variation of agricultural produce) and mobility of feedstock, how the feedstock gets from its source to the biogas plant. The vast demand for feedstock, in the hundreds of tons per day in commercial-scale biogas production, can be met by utilising a combination of feedstocks from different sources that are transported to a central biogas plant and co-digested. Co-digestion has the ability to increase both the quantity and quality of feedstock entering a biogas system through diluting inhibitory compounds, adjusting the water content and optimising the carbon/nitrogen ratio, an important process parameter for maximising biogas yields (European Biomass Association, 2012, p. 26).

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The nature of biogas feedstocks, being organic wastes or crops, makes biogas a renewable energy. Upon inspection, the burning biogas to produce energy still produces carbon dioxide. However, because the organic waste material used as feedstock would be degraded in some way or another - by microorganisms or burning for example - to form methane or carbon dioxide, biogas generation can be seen as a method of intercepting this inevitable degradation and capturing the products to a useful end. That is not to say that there are no environmental concerns with biogas. If systems do not successfully capture the methane produced in the system, the greenhouse effect is far worse than natural degradation or burning due to the fact that methane's greenhouse effect is around 25 times greater than that of carbon dioxide (United States Environmental Protection Agency, 2020).

2.1.2 Products

Once biogas is produced and collected, it is a useful renewable energy carrier that can be burnt for cooking purposes in household stoves, heating or to generate electricity. The biogas can also be pressurised and stored, a feature that sets biogas apart from other renewable energies due the fact that it is a dispatchable energy-type. That is, it has the capacity to balance demand and supply in energy systems that suffer from intermittent generation from wind and solar systems. This dispatchable characteristic of biogas is extremely useful to grid systems, a service that biogas producers argue is economically under-rewarded at present (Lauer & Thran, 2018).

The electricity and heat produced by biogas plants have two destinations. The first is for direct use internally to meet the energy and heating demands of the plant itself. By being self-sufficient in terms of heat and electricity, biogas plants can operate independently from a fossil fuelled grid. The second destination is for external use where electricity can be fed into the grid and distributed and heat can be used to meet domestic or industrial demand. Another option for utilising biogas is through upgrading into biomethane, a process by which carbon dioxide and other contaminants such as hydrogen sulphide are removed. Biomethane is a near-pure source of methane that is chemically indistinguishable from natural gas. For this reason, biomethane can be injected directly into natural gas grids and hitchhike existing distribution infrastructure, resulting in reduced costs along the production-distribution pipeline (IEA, 2020a, p. 13). The removed CO_2 from the upgrading process can be used as an additional valuable product (EBA, 2020b). Moreover, biomethane can be used as renewable transport fuel, especially in sectors which are difficult to electrify such as heavy duty and maritime transport (EBA, 2020c).

Just as plants and mushrooms shoot up from piles of cow excreta, the digestate from a biogas system can be utilised in agriculture as a nutrient rich fertiliser. Due to the output gas containing only carbon, hydrogen, oxygen and to a lesser extent sulphur and nitrogen, the key elements required for healthy agricultural production namely nitrogen, phosphorus and potassium are cycled back into the land. Closing this nutrient loop is a factor of growing importance considering the rising issues of agricultural eutrophication and demineralisation in global agricultural systems (González-González, 2018).

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These features of biogas generation make this mode of producing power inherently circular and aligned with sustainable visions of the future. Imagining a biogas plant as a large, somewhat abstract, mechanical cow, industrial biogas systems operate inside natural cycles and rhythms but instead of "Moos!" the energy output of biogas plants drives renewable, circular societal activity within today's economies.

2.1.3 Biogas production technologies

There are a number of technologies (in addition to the 'cow model') which are used to commercially generate biogas. The mode by which biogas is produced is primarily dependent on the type of feedstock available. Four technologies will be discussed, with many variants of each of these technologies available on the market (IEA, 2020a, p. 13):

1. **Biodigesters**. Biodigesters in industrial biogas production are airtight containers or tanks in which any one of the previously described feedstocks are digested by microorganisms to produce biogas. Combinations of feedstocks are often mixed together for codigestion. Biodigesters are the most common form of biogas technology in Europe and are advantageous for a number of reasons: These systems are stirred and can be heated to maintain an optimal temperature inside the reactor. Other conditions such as pH, oxygen levels, and water content can also be monitored and controlled during the fermentation process. Because these are often closed systems, contaminants can neither enter or escape the production facility which makes these systems safe and reliable when in operation. Biodigesters can operate in a batch (all material is digested at once) or continuous process (material is fed in and out at a constant rate whilst being digested), with batch systems often being cheaper and easier to operate but less productive than continuous systems (Schnurer & Jarvis, 2009). There are unit operations tied to upstream and downstream processes from the digester itself. Upstream processes include feedstock storage, feeding systems, preparation tanks and pretreatment systems. Downstream processes include storage tanks, gas motors or combined heat and power systems and upgrading systems (for more information on downstream and upstream processes, see Deublein and Steinhauser (2011), Chapter 4.). Depending on feedstock type and water addition, fermentations can be wet or dry depending on whether the water content is above or below 85%. Wet systems (feedstock water content >85%) are usually preferred because of their wider applicability and process performance (Kampman et al., 2017). Types of reactors used in a biogas system depend largely on the water content, feedstock and desired operational parameters of the plant. Reactors can be open systems, as is the case for open lagoon reactors, or closed systems such as continuous stirred tank reactors (CSTR) (the most common in Europe) configured individually or in series, closed lagoons, plug flow reactors and up flow anaerobic solid state bioreactors (UASS) among others (Comparetti et al., 2013). On a domestic scale, fixed dome and floating drum reactors are the most common bioreactors which process small volumes of sewage or animal manure in uncontrolled conditions (Raja & Wazir, 2017).

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2. **Landfill gas recovery systems** capture and utilise the gas produced by the natural anaerobic digestion of organic material by microorganisms in landfill sites. As landfill sites are ubiquitous globally, there is a huge potential for these systems worldwide, especially in warmer countries and the developing world (IEA, 2020a). Landfill gas (LFG) consists of 45-55% methane and can be used for heat, power, combined heat and power, or upgrading to biomethane. These systems use perforated pipes fed into the landfill which carry LFG to purification systems to remove impurities (hydrogen sulphide in particular) before the biogas can be used. Sanitary landfills (SLF) often generate gas over a 30-50-year period, a time horizon that goes beyond LFG recovery systems lifetime. The efficiency of a LFG recovery system is estimated to be between 60 and 85%, though over the entire lifespan of a landfill, efficiency can drop to 20 to 30% (Hinchliffe, 2017). LFG recovery systems are significantly cheaper than all other biogas systems in both capital expenditure and maintenance and operating costs and are projected to make the largest contribution to growth in total global biogas production between 2020 and 2040 (IEA, 2020a, p. 50).

3. **Wastewater treatment plants**. The principle function of wastewater treatment plants is to separate the organic matter from wastewater. This is performed by removing particles via a series of mechanical and biological processes to produce cleaned water and sludge: An effluent which is rich in organic matter and nutrients. The sludge which is used for AD in biodigesters contains primary sludge, produced by a sedimentation process in the wastewater treatment plant, and secondary sludge, the product of biological treatment on wastewater. This sludge mix can be combined with co-substrates, from any of the aforementioned feedstock categories, to create a feedstock for biogas production. For the AD process, the sludge may be sieved to reduce the water content to around 7% as to reduce heating costs before being fed into a CSTR - from here biogas production is the same process as wet fermentation in a biodigester. After AD the digested sludge may be composted and used in agriculture (as is common in Spain, Italy, France and Belgium) or disposed of after further dewatering in landfill or incineration plants (Bachmann et al., 2015). Biogas generation in municipal wastewater treatment is essentially just one stage in a wider treatment process. Due to the high water content of the feedstock, certain biodigesters that use bubble agitation instead of mechanical agitation can be used. These include upflow anaerobic sludge blanket (USAB) among others (ElMekawy et al., 2016).

4. **Gasification systems** convert solid carbonaceous materials such as biomass into gaseous fuels. This process is also known as pyrolytic distillation or pyrolysis and the gaseous fuel product can take many forms depending on the operating conditions of the gasification plant (Basu, 2010, p. 1). The production of biomethane from woody biomass first involves a process of thermal gasification where feedstock is broken down at high temperatures (between 700 and 800˚C) under high pressure in a low-oxygen environment. The resultant gas from this process is a mixture of carbon monoxide, hydrogen and methane, collectively termed syngas. The syngas is then cleaned to remove any corrosive components. A process of methanisation whereby a catalyst is used to promote a reaction between hydrogen and carbon monoxide, or CO_2 finally

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produces biomethane. Remaining CO_2 or water is removed at the end of this process (IEA, 2020a, p. 13). Without the final step of methanisation, the resultant gas can be used for heat and power generation separately, or in combined heat and power (CHP) applications (European Biomass Industry Association, 2020). Gasification systems are distinct from the three other biogas production processes because it is a thermochemical process rather than a biological conversion. Another aspect that separates gasification is the ability of this technology to utilise lignocellulosic or woody biomass that cannot be easily converted into biogas by biological conversion. In addition to woody biomass such as residues from forest management and wood processing, feedstocks for gasification include municipal solid waste and agricultural residues. Characteristics of gasification feedstocks that influence performance are chemical composition, moisture content, particle size and ash content (Molino et al., 2018). Flue gas contaminants remain a main technical barrier in the way of successful commercialisation of biomass gasification technologies, with efficient tar removal being a high priority research need. Biomass gasification technologies are largely in the development stage due to its relatively high cost compared to combustion and the low reliability of long-term operation, features which negatively influence commercial attraction to this technology (European Biomass Industry Association, 2020). Under 100 biomass gasification plants are in operation today, with most of these at demonstration scale producing relatively small volumes of biogas (Global Syngas Technologies Council, 2020). Gasification remains one of the two pathways for the production of biomethane, the other being biogas upgrading. It is therefore an attractive technology due to its ability to process an abundant feedstock category: Woody biomass from forestry and wood processing residues (IEA, 2020a).

Fehler! Ungültiger Eigenverweis auf Textmarke. contains a summated overview of the advantages and drawbacks of each described biogas production technology.

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Table 1. Advantages and drawbacks of biogas production technologies.

Technology category	**Production technology**	**Advantages**	**Disadvantages**
Domestic/household/small scale	Biodigesters (household scale)	Low cost Simple technology Low maintenance demand No energy demand High quality digestate	No process control Open system Low production efficiency Large geographic distribution of systems
Commercial/industrial scale	Biodigesters (medium and large scale)	Improved production efficiencies Cost reduction gained from economies of scale High biogas output Closed system High quality digestate	High capital investment and running cost High energy demand Biogas treatment required
	Landfill gas recovery systems	Low capital input and operations costs for a commercial-scale system Small value chain: Cost reduction Low land requirement No competing technolog	Reliant on an inherently unsustainable practice Uncontrolled conditions Biogas requires cleaning
	Wastewater treatment plant	Abundant and consistent feedstock supply Low land requirement High quality digestate	Biogas treatment required High capital costs
	Gasification	Can utilise woody biomass: large feedstock potential Can be used near urban centres	Not widely demonstrated Difficult to make commercially viable

Table 2 compares the capital, operational and total costs of biogas production technologies.

Table 2. Costs of biogas production technologies (IEA, 2020, p.28). Gasification omitted due to lack of data.

Biogas production technology		**Capital costs (USD/MBtu)**	**Maintenance and operating costs (USD/MBtu)**	**Total costs (USD/MBtu)**
Biodigester	Household (basic)	2.7	0.4	3.1
	Household (advanced)	7.3	0.6	7.9
	Small	8.8	7.7	16.5
	Medium	6.9	5.9	12.8
	Large	5.2	4.1	9.3
Wastewater digester		10.3	4.3	14.6
Landfill gas recovery		0.8	1.6	2.4

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Upstream processes

Prior to AD, pretreatment may be incorporated into the biogas production pipeline. Pretreatment comes in many forms and is used to expand the range of potential feedstocks applicable for a biogas production system or to increase the productivity and yield of a feedstock. AD consortia have a limited pool of enzymes that degrade organic polymers (proteins, fats and lipids, and carbohydrates) into their respective monomers (amino acids, fatty acids and glycerol, and sugars) that can in turn be converted to methane and CO_2. Because this pool of enzymes cannot degrade certain structures within a feedstock, pretreatment is employed in most industrial biogas systems. Pretreatment is used to remove impurities of a feedstock, increase the surface area that AD consortia may interact with the organic matter and to change the chemical structure of feedstocks to improve their bioavailability to the microorganisms involved in the process. Feedstocks with high lignocellulosic content for example may be pretreated to make available substrates that could not otherwise be digested (Grando et al., 2017). Pretreatment falls into four main groups: Biological (enzymatic hydrolysis, microbiological treatment); chemical (alkali, acid, oxidative); physical (mechanical, thermal, ultrasound, electrochemical); and combined pretreatment (steam explosion, extrusion, thermochemical) (Montgomery & Bochmann, 2014). Biological, chemical and some physical pretreatments function through interactions with the interpolymer and intraploymer bonds in recalcitrant materials such as cellulose, hemicellulose and lignin. This leads to the disruption of lignocellulosic structures and in turn increases the bioavailability of the biomass (Jędrzejczyk et al., 2019). Physical processes in large part decrease the particulate size of the feedstock which increases the homogeneity of substrate, a characteristic that positively influences the mixing capabilities of a production system and increases the surface area on which microbial action can occur. Mechanical processes are almost always used in commercial biogas production whilst other physical, chemical, biological and combined pretreatments are selected based on specific properties of the feedstock

Downstream processes

After the AD process, the digestate may be treated to fit a consumer need. This can be through further energy recovery or creating high-grade organic fertilisers: Outcomes employed to increase the economic potential of the effluent stream. Methods of digestate enhancement fall into four categories: Physical enhancement through using mechanical units or filters to dewater, thicken or purify a digestate; thermal enhancement to dry digestate or convert the remaining organic material into a useful product via gasification for example; biological enhancement through composting or production of biofuels by various methods; and chemical enhancement for ammonia recovery for example (Frischmann, 2012). Enhancement methods are selected based on market demand conditions in which the biogas system is operating.

The economic benefits involved with adding upstream and downstream processes to the AD system are often outweighed by costs. For this reason, thorough cost benefit analyses must be performed to elucidate the economic potential of downstream and upstream processes. As market conditions fluctuate with time, different combinations of treatment options become the most viable option. Digestate is an often-overlooked product in industrial biogas production and some companies and governments are beginning to view digestate as the principle product of biogas production systems, above power and heat. Regions with no-till farming methods such as Argentina have a great demand for high-grade fertilisers. Thus, the digestate stream is a significant component of many biogas production balance sheets and can be the difference between an economically viable and economically non-viable project.

The stream of biogas originating from a bioreactor, landfill or gasifier must be cleaned prior to use in CHP systems. Water and H_2S must be removed before biogas is utilised further due corrosion, cavitation and efficiency issues these components incur. Cleaning refers to the removal of biogas impurities other than CO_2. While water can be removed with relative ease using a condensate trap which collects water as the biogas naturally cools after leaving the digester, H_2S is more cost intensive. Biological desulphurisation uses natural bacteria to convert H_2S into elemental sulphur in the presence of oxygen and iron. This is achieved in the industrial processes by introducing small quantities of air into the digester headspace. Other methods to remove H_2S include iron/iron oxide reactions or using activated carbon. Water scrubbing and membrane separation can also remove H_2S and CO_2 simultaneously and are explained below (Yang & Li, 2014).

The removal of CO_2 from biogas is known as upgrading. There are three common methods by which this is achieved. Water scrubbing uses the differential solubility of biogas constituents to selectively separate CO_2 and H_2S under high pressure using large quantities of water which must be purified and recycled. Pressure swing adsorption uses the adsorption characteristics of biogas component compounds to separate CH_4 and CO_2. Water and H_2S must be removed prior to this process. Membrane separation, the two methods in this class of upgrading method being high pressure gas separation and gas-liquid adsorption, can achieve high purity CH_4 (Navaratnasamy & Parkington, 2008).

There are various benefits and drawbacks of these methods on the process and economic level. Energy demand is an important consideration for all methods involved due to high pressure and chemical recycling demands (Yang & Li, 2014). Again, the method selection process is dependent on the profitability of adding a unit operation, often needing to reflect a market demand for a specific product.

2.1.4 The biogas value chain

The biogas value chain is defined in the present study as the operations and stakeholders that are involved in the biogas production process, from input (feedstock) to output (sold products). The stakeholders engage in a set of interdependent activities to reach a common goal. As is shown in the boxes in Figure 2, these stakeholders come from different sectors (public and

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private), different institutions (municipalities, public utility companies) and industries (agro-industry, power companies, biogas companies). With a diverse set of needs to be met by the various stakeholders, there is a high organisational demand that must be upheld for the entire operational lifetime of the plant. The complexities of the biogas value chain in terms of stakeholders, inputs and outputs relative to, say, the photovoltaics value chain, present an organisational challenge but also an opportunity for tailoring biogas systems to meet the specific needs of a socioeconomic context. Based on the selection of different combinations of the arrows displayed in Figure 2, highly variable value chains emerge. Inputs can be selected based on abundance and quality and outputs selected on the basis of market demand. An emergent property of the value chain system, in addition to sustainability benefits, is employment. This is an often-overlooked property of a value chain but can increase the competitiveness and attraction of a biogas production chain.

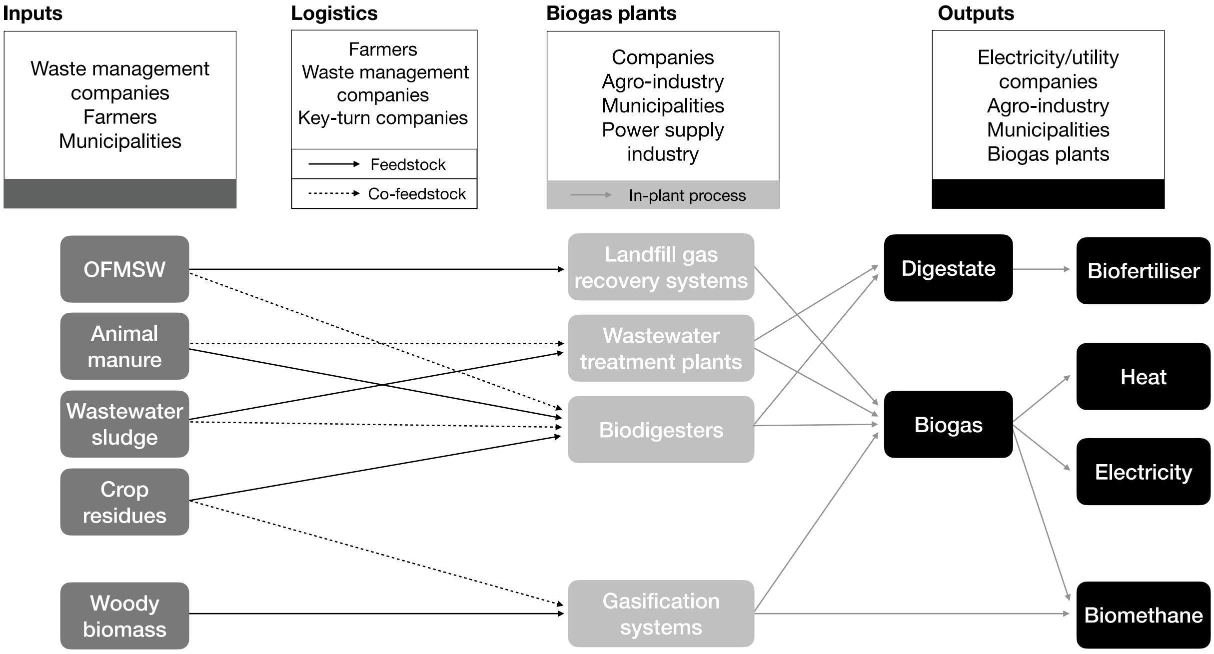

Figure 2. The biogas value chain with feedstock, product and production-system interactions displayed. Boxes contain stakeholders that may be involved in each stage of the value chain. Colours at the bottom of each box relate to the components of the flow diagram

Versatility is also an integral feature of a biogas value chain. In the 20-year period where plants are often operating under the same industrial partnerships, major changes in the economic, social or environmental systems in which a plant functions can cause stresses within the value chain (through the liquidation of a feedstock supply stakeholder or a recession for example). The ability of a value chain to meet changing market needs through modifications in configurations, feedstock supply, downstream processing etc. is a feature of growing importance in a turbulent twenty first century social and economic system. Biogas value chains are systems embedded in a wider economy, society and environment. For this reason, value chains cannot

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be considered a one-size-fits-all model. Extensive organisational preparation, research and assessments are vital prerequisites to successful and sustained biogas plant operation.

2.2 Biogas in the global energy system

Biogas systems have the ability to address two major challenges facing society: The need to manage increasing quantities of organic waste and to reduce greenhouse gas emissions by increasing the share of renewable energies in the energy mix (IEA, 2020, p. 3). These two challenges are universal thus the case for biogas technology can be made for most global societies. As a standalone renewable energy, biogas systems produce expensive electricity that requires a high rate of subsidisation to compete against fossil fuels and other renewable energies such as solar and wind. It is only when the waste processing and environmental aspects are considered in addition to energy generation (heat and power) that biogas begins to make sense economically.

It is important to note here that biogas systems signal very different images in different parts of the world. In many developing regions, household scale biogas plants, a relatively rudimentary technology, are the most common type of plant. In developed regions, more complex, high throughput, thoroughly engineered systems are the technology-type considered. Though these different technologies produce the same product, the economic, social and environmental impacts associated with each system vary immensely. This is an important factor to keep in mind when discussing biogas in a global context and often overlooked in studies that discuss biogas in only one region.

As organic wastes are ubiquitous and abundant, the technical potential for biogas is great and largely untapped. Figure 3 shows the results of a detailed IEA (2020a) analysis of current production versus the potential for biogas and biomethane that can be produced from sustainable feedstocks with today’s technology. The 730 Mtoe potential for biomethane can replace 20% of worldwide gas demand with few infrastructural changes. The majority of biogas potential is concentrated in the world’s developing and emerging economies: Asia Pacific (211 Mtoe); Central and South America (134 Mtoe) and Africa (60 Mtoe) (IEA, 2020a, p. 7).

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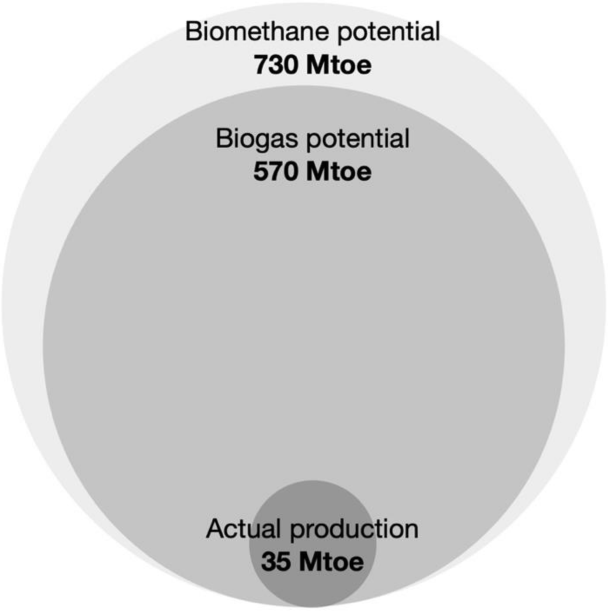

Figure 3. Actual production and technical potential for biogas and biomethane from sustainable feedstocks. Adapted from IEA (2020a) p. 6.

Today, biogas production is concentrated in developed economies, largely Europe and the United States (US), and China (Figure 4). The European biogas sector, in which Germany is the leading market, constitutes around half of the 35 Mtoe total current production, predominantly from cros, animal manure and OFMSW feedstocks. The primary pathway for biogas production in the US is landfill gas recovery systems. The biogas in Europe and the US is largely burnt in CHP systems to feed the grid electricity and heat for municipal or industrial purposes. In China, biogas is produced largely by household biogas plants with the primary objective of supplying rural homes with gas for cooking and lighting. The primary benefit in this case is that, in addition to management of waste and producing renewable energy, biogas users no longer burn solid biomass on open fires, a practise that is highly detrimental to human health. Biogas production in the rest of the world is through large numbers of household scale plants in India, Southeast Asia and parts of Africa, as well as larger scale industrial plants in India, Thailand, Brazil and Argentina: Countries with recently established government-led incentive schemes (IEA, 2020a).

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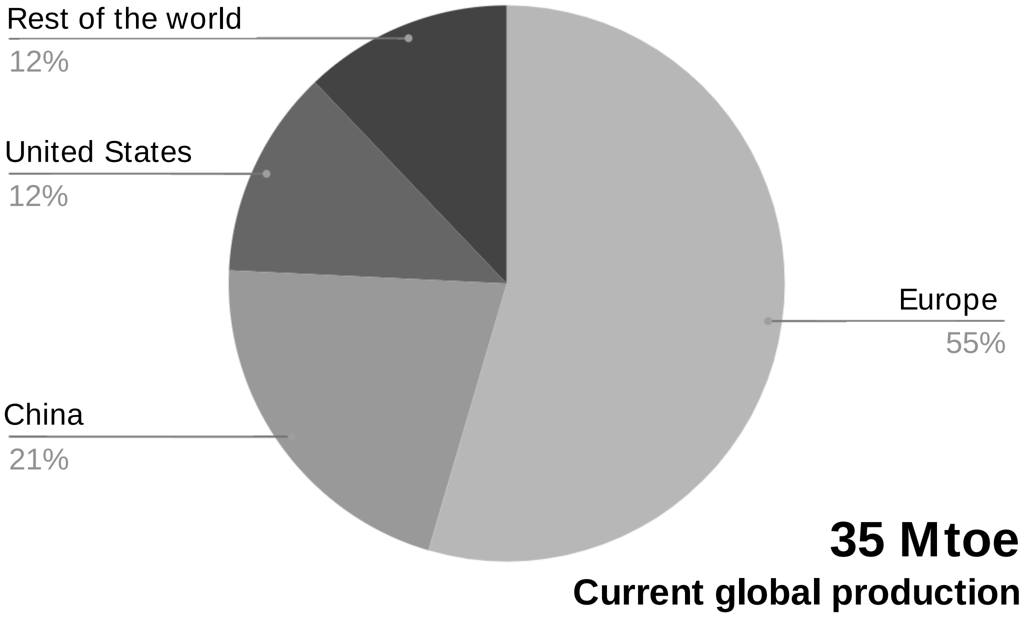

Figure 4. Regional breakdown of current total biogas production (Adapted from IEA (2020a) p. 16).

The two common factors shared between all regions with high present-day capacities for biogas production are policy support and feedstock availability. Policy support, which comes in the form of demand-pull incentives such as feed-in tariffs (FITs), tax relief schemes and subsidy grants, economically rewards the positive externalities of biogas such as contributing towards mandated decarbonisation targets. Feedstock, as seen in Figure 3, is in no short supply, but there is an organisational side to feedstock supply that must be in place to regard it as 'available'. Mobilising feedstock from its production source to an often-centralised biogas plant while maintaining feedstock quality and in consistent and large quantities is a key aspect of successful biogas plants. Once these two preconditions are in place, a region's biogas sector can grow to reach the sustainable potential described in Figure 3. The different statuses for these conditions between regions stand as the principal reason that biogas sectors have grown unevenly in the past (IEA, 2020a).

Though the global diffusion of biogas technology has been a slow mover compared to other renewables such as solar and wind, the sector is expected to witness significant growth in projections based on today's existing and announced policies (stated policies scenario, STEPS) and even more so under a sustainable development scenario (SDS). The SDS accounts for the necessary changes in the world's energy system that must occur if economies are to develop in a mode by which the energy-related United Nations Sustainable Development Goals (SDGs) are achieved (IEA, 2020b). Biogas is the fastest growing form of bioenergy in both the STEPS and SDS scenarios with three quarters of growth, on a demand basis, taking place in developing and emerging economies. The market share for biogas in total modern bioenergy demand grows from 5% today to 12% by 2040 in the STEPS and to 20% in the

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SDS, with a total addition of 114 Mtoe and 289 Mtoe to the global energy mix under each scenario respectively (IEA, 2020a, pp. 43-44).

2.2.1 Biogas in Europe

The European biogas sector has been allowed to prosper under favourable regulatory conditions and incentive schemes that have allowed industrial biogas plants to compete in national energy markets. On a macro-level, policies have originated from ambitious EU packages, plans and directives to curtail the bloc's greenhouse gas emissions. Though policies are written and implemented on a national level, targets and the development of necessary framework conditions originate from the EU and set the trajectory for market growth. Starting with an integrated Energy and Climate Change package in 2007, which included an EU commitment to a 20% reduction of GHG emissions compared to 1990 levels and a mandatory target of 20% renewable energy by 2020. The Renewable Energy Directive (RED) was passed in 2009 and supplied member states with the provisions for the development of renewable energy technologies to fulfil the aforementioned target. The commitments that began in 2007 remained strong, manifesting on a global level in the 2015 United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21) in Paris, where the European countries played a key role in establishing the global long term goal of limiting the increase of global average temperatures to well below 2˚C below pre-industrial levels. In 2016, the EU pledged to become a global leader in renewable energy through a revision of the Renewable Energy Directive (RED II), which included a mandated target of 27% renewables in the EU energy mix is achieved by 2030 (Scarlat et al., 2018). Before the end of 2019, the European Commission revealed the details of the European Green Deal that will make the EU climate-neutral by 2050.

In addition to policy support, activities performed by the EU to enable growth in renewable energy technologies, including biogas, include the development of detailed road maps, research schemes, institutional support and infrastructural development plans. Large sums of fiscal support have been mobilised through schemes like Horizon 2020, a research and innovation fund (which supports the DiBiCoo project), the Circular Economy Action Plan focussing on sustainable resource use, and the recently announced European Green Deal, a new growth model that will invest €1 trillion into environmentally responsible activities (European Commission, 2020a; European Commission, 2020b). Regarding biogas, these targets, investments and strategies have culminated in the world's strongest biogas market.

In 2018, there were around 18,202 biogas plants in Europe with an installed capacity of 11,082 MW. For reference, Ghana's total installed electrical capacity is 4700 MW (Africa Energy, 2019; European Biogas Association [EBA], 2019). Growth in the European biogas sector was at its peak around 2010 and despite having slowed in recent years as a result of relaxing incentive programmes, it is still growing ahead of EU targets, with an increase of 351 plants in 2017

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(EBA, 2018; Scarlat et al., 2018). Table 3 shows the key biogas-producers in Europe and the number of active biogas plants in each respective country.

Table 3. Number of biogas plants in selected European Union countries. Adapted from EBA (2018).

EU-27 Country	Number of operational biogas plants
Germany	10,971
Italy	1,655
France	742
(Switzerland)	(632)*
(United Kingdom)	(613)*
Czechia	574
Austria	423
Poland	308
The Netherlands	268
Spain	204

*EU-partnership countries in the European Economic Area. Applies to the United Kingdom until 2021.

2.2.2 Biogas in emerging and developing countries

As mentioned, in many parts of the developing world biogas systems take a very different form to the image that usually comes to mind in developed regions. Household scale biogas plants with no operational control are established to meet a very different set of needs than industrial plants do. For billions in the developing world, who use solid biomass for cooking and heating, biogas plants represent a transition to more modern fuel with social benefits often being the main motivation - above environmental and economic benefits - for biogas developments. Governments without the financial resources to provide the incentives to establish an industrial biogas market may choose to promote household scale digesters to poorer rural communities to achieve what is perhaps a more socially beneficial end than is achieved on an industrial level.

In reference to the scope of this project, household scale facilities are not included in the type of technology transition that DiBiCoo is trying to achieve. That is not to say that there are not enormous benefits to be achieved by well-constructed domestic biogas schemes, which are expected to move 200 million people away from traditional biomass in the next 10 years (IEA, 2020a, p. 48). Though there is an argument to be made for the two modes of biogas production as competing technologies, due to the fact that they operate on different scales and in different areas of a country’s economy they are considered as two technologies with no intersection, each serving their own uniquely beneficial service. The remainder of this section will exclusively introduce industrial scale biogas systems in developing regions but does not aim to overlook the merits of household scale plants.

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Developing nations tend to have certain common characteristics that on one hand paint a bright picture for industrial biogas sector growth but on the other present severe challenges that have hindered potential growth in the past. Factors such as large agricultural sectors with high feedstock potentials, fast growing economies and a high demand for electricity put developing regions in prime position for biogas market growth. However, there are a myriad of obstacles that stand in the way of realising this potential. Weak or non-existent policy support schemes and specific biogas targets, lack of funding mechanisms, unstable political or economic climates and lack of research present major barriers for these regions (Patinvoh & Taherzadeh, 2019).

A very small portion of industrial biogas capacity exists in developing regions as a result of the aforementioned obstacles. Projections by the International Energy Agency (2020a) see developing countries in Asia leading the growth of global biogas generation under existing policies. Factors such as low-cost feedstocks, increasingly supportive policies and relatively high natural gas prices underpin this growth. This growth also sees developing regions increase the share of biogas used for power and heat in industrial biogas plants rather than for cooking on a domestic scale. Energy crops are generally not considered by developing countries as they move forward with biogas sector development. Industrial, agricultural and municipal waste streams take feedstock priority, seeking to benefit from the waste-management ability of biogas systems (IEA, 2020a, p. 48). Developing nation governments stand on firm ground when developing biogas policies having learnt from the successes and failures of more developed sectors providing apt communication between developed and undeveloped regions occurs.

2.3 Biogas technology and levels of technological readiness

Technological readiness levels (TRL) are a method of estimating and tracking the maturity of programmes and technology, developed in the 1970s. These levels enable the cross-disciplinary discussion of technology and form a useful body of work surrounding the nature of technological development (Mankins, 1995). This grading system is used in EU and international literature on biogas technology development and implementation (De Rose et al., 2017).

The research process involved in bringing a biogas technology through the levels of technological readiness, from innovation and proof of concept (TRL 1 and 2) to system optimisation and launch (TRL 8 and 9), spans a multitude of disciplines and stakeholders along the value chain. Because of the multi-stakeholder nature of a biogas value chain, there is also a strong demand for organisational research to guarantee effective coordination between feedstock producers, plant operators and end product consumers. Though the framing of readiness in the present study may be better defined as System Readiness Levels (SRL) or Integration Readiness Level (IRL) as formulated by Sauser et al. (2006) due to the interaction of technologies involved in a biogas system, TRLs will be the starting point from which derivations or groupings of research areas will be drawn. The TRL framing as opposed to lesser known, more

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appropriate metrics such as SRL and IRL is consistent with EU literature and is thus more inclusive and best suited for the descriptive purpose of this paper (De Rose et al., 2017). This section begins to look at the purpose of biogas technology-related research and provides a clear framework for understanding the research needs suggested in the remainder of this paper.

The levels of technological readiness relate to the different areas of research displayed in Figure 5. These research groupings are important to consider when beginning to conceptualise the research demands of biogas technology transfer. The research and development associated with different levels of the TRL cascade, i.e. the research required to advance to a higher level of technological readiness - can be broadly categorised into three research areas (De Rose et al. 2017):

1. **Laboratory/industrial research and testing** is largely performed by specific research institutions in innovation hubs such as the EU. TRL 1 to 5 are performed in laboratory or bench scale where a new innovation is taken to a small-scale prototype biogas production unit up to around 10 litres in volume. Costs at this level are relatively low, being funded by government institutions, universities etc., and are often performed by a small number of researchers within academic research networks. Due to these features, risk here is small and many projects are taken to TRL 5 only due to a sudden increase in risk associated with taking a technology past this level. These levels of readiness are not relevant to the DiBiCoo research needs, given that technology will be transferred at initially a pilot (TRL 6) scale and ultimately at full scale (TRL 6 onwards).

2. **Simulation and modelling**: Performed in silico, simulation and modelling is employed around TRL 6 and 7 alongside real-world demonstration. Simulations and modelling use real world data collected from pilot demonstration plants and context-specific studies in synthesis with data compiled from other studies and databases to predict the outcome of certain configurations and scenarios at operational scale. Simulations and modelling can be at the reactor or value chain level and elucidate the process, economic and environmental bottlenecks associated with scaling up the production process. Process modelling, environmental impact assessments and techno-economic analyses are some forms of simulation and modelling. This mode of research is performed by stakeholders with high-level training and forms the biggest area of intersection between organisational and technical researchers due to the required cross flow of organisational and technical data. Robust analysis at this stage of research confirms economic feasibility and thus secures funding for a new technology and can stimulate policy support. Simulation and modelling research is therefore an important aspect of the financing and governmental support side of biogas system development as well as at the process level.

3. **Real world demonstration**: As mentioned above, real world demonstration is performed within the same stages of technological readiness as simulation and modelling. The goal of this mode of research is to confirm or prove plant efficacy and the economic

potential of a biogas system at scale. Pilot-scale prototypes are finely tuned at TRL 6 and 7 in the relevant environment, integrated with other subsystems and successful management of the facility is demonstrated. Social acceptance and operation within safety and environmental standards are also demonstrated here. At TRL 8 and 9, full funding for the plant is often attained, supported mostly by simulations and modelling of pilot plant data. Commercial biogas contractors, engineering, procurement and construction (EPC) companies, operators and businesses are bought in at this stage as a manufacturing approach is taken. The plant is constructed, and the full value chain begins to operate at a low production rate to identify any deficiencies at the process and value chain level. Finally, at TRL 9, full rate production is demonstrated, and performance guarantees are established to relax risk and maintain support for the project. Economic, social and environmental sustainability are ensured to drive regulatory support for present and future projects.

In addition to the three groupings described above, after-sales activities must be in place to ensure the sustained operation of the plant. Post-TR support is a vital service for a successful biogas plant and perhaps even more so for a wider biogas market. The ability of a plant to meet performance guarantees for the entirety of its lifetime in a socially and environmentally sustainable manner underpins investor, government, industry support for all parties involved in the operation of a single plant and the biogas market as a whole. Reputation is an important driving force of technology acceptance on a social level and should not be overlooked. Post-TR activities include adherence to changing regulations, plant maintenance and operations, the potential addition of new unit operations to the plant to increase process or economic performance and business and marketing.

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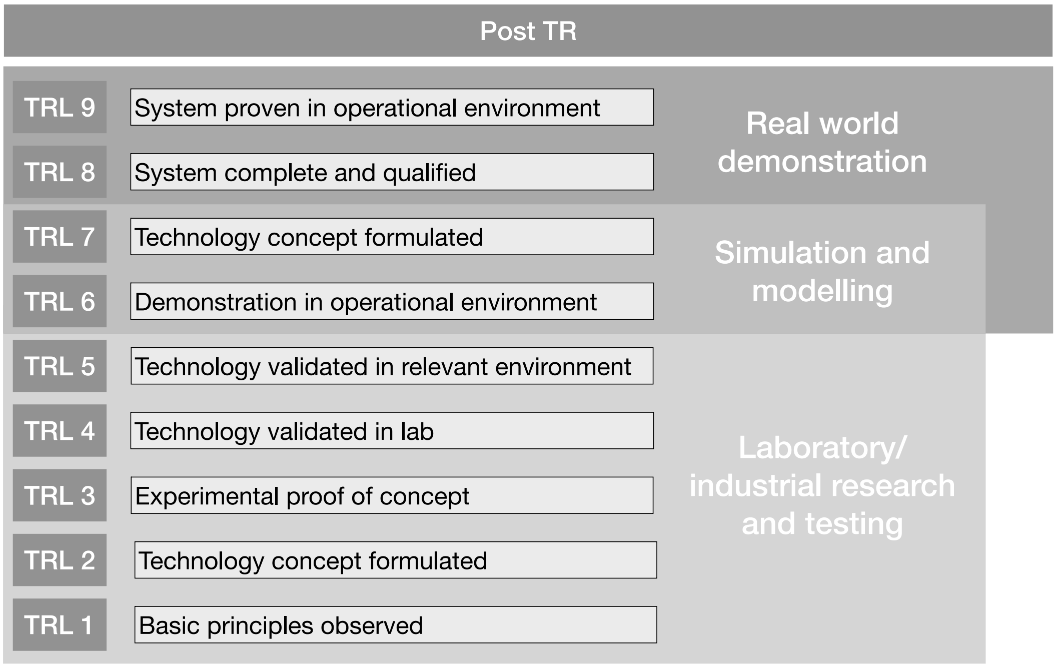

Figure 5. Research areas and description of technological readiness levels (TRLs) in the biogas technology development pipeline. Adapted from De Rose et al. (2017).

2.3.1 Biogas research in the context of this study

Research for biogas development takes many forms due to the diverse academic and industrial activities involved in the sector. Technical and organisational research must occur at every stage of technological readiness cascade by different stakeholders to generate the framework conditions required for the development of a biogas facility. Research is context-specific and thus the TRL system cannot be considered a one-size-fits-all approach. The technological development process must be versatile in order to adapt to different research demands. This fact highlights the importance of communication and responsive research actors especially when considering biogas technology transition between developed and emerging economies, as is the case with DiBiCoo.

2.4 Technology diffusion

Technology diffusion or technology transfer is a well-studied, multidisciplinary field. The term ‘technology diffusion’ appears in the titles of hundreds of books and academic texts every year and has a dedicated journal: The Journal of Technology Transfer. Primarily a sociological discipline, the study of technology diffusion employs knowledge from the fields of economics, management and anthropology among others, manifesting in a wide and complex research area (Bozeman, 2000).

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Defining technological change and diffusion is a tangled ordeal, with variable definitions stemming from different research traditions. Attention to this variability is important when exploring theories of technology diffusion. Roessner (2000) defines technology diffusion between 'sources' and 'users' as "the movement of know-how, technical knowledge, or technology from one organisational setting to another" (Roessner, 2000, p. 1). He goes on to note:

> "The term has been used to describe and analyse an astonishingly wide range of organizational and institutional interactions involving some form of technology-related exchange. 'Sources' of technology have included private firms, government agencies, government laboratories, universities, non-profit research organisations, and even entire nations; 'users' have included schools, police and fire departments, small businesses, legislatures, cities, states and nations (Roessner, 2000, p. 1)."

2.5 Technology diffusion models

Models for technology diffusion were developed in the latter half of the twentieth to study the macro-level patterns and trends of individual, micro-level, decisions to adopt an innovation (Rao & Kishore, 2010; Straub, 2009). A prominent foundational theory of technology adoption and diffusion is Roger's diffusion of innovations (DOI). DOI has been used widely across many disciplines to comprehend and predict technological change. Thus, through the replication of Roger's initial ideas in over 6000 studies, innovation diffusion has evolved to become a reliable and well-documented theory. Important insights gained from using a DOI approach to studying technological change include identifying what qualities make an innovation spread successfully, the importance of peer networks and an understanding of the needs of different user segments, shown in Figure 6 (Robinson, 2009).

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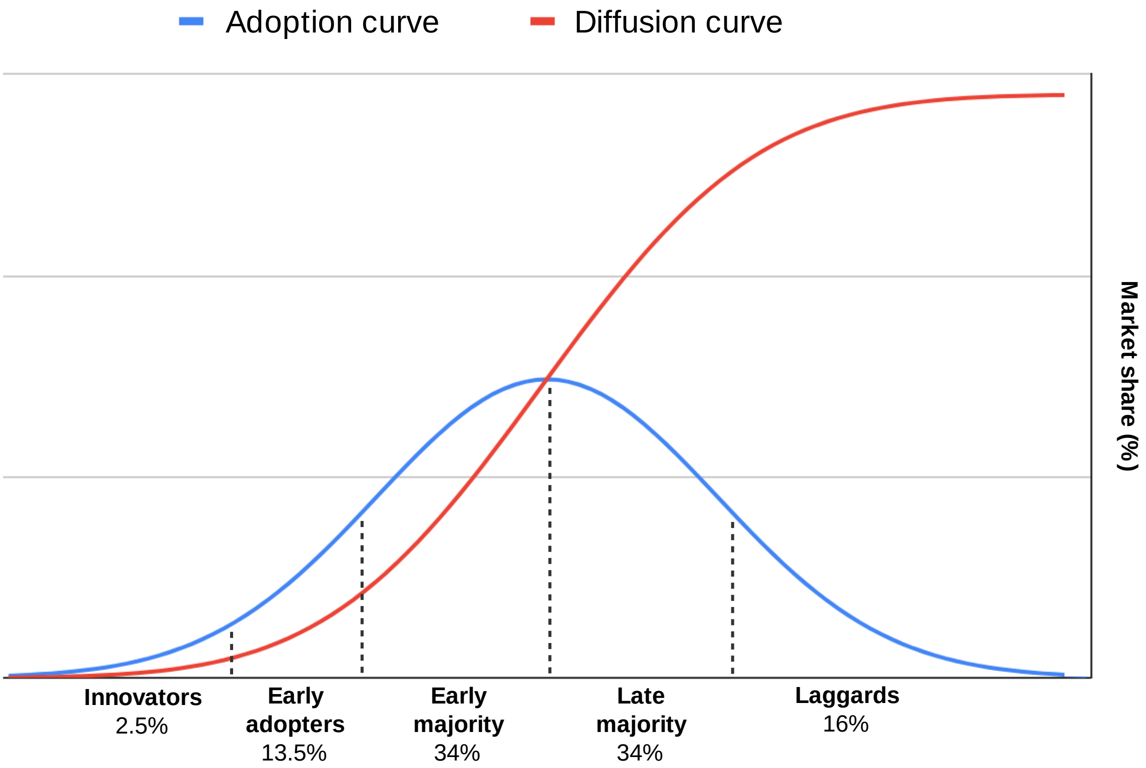

Figure 6. Adoption and diffusion curves with relative proportions of adopter categories (user segments) throughout the diffusion process. Adapted from Rogers (1995) p. 247.

There are two interdependent processes at the core of DOI. The first is adoption which, as mentioned, is the micro-level decision making process of an independent decision-making unit, the stages of which are described in Figure 7 and in the adoption curve in Figure 6. The second process, diffusion, is the aggregate phenomena of the many individual innovation-decision processes occurring in a social system, shown in the diffusion curve in Figure 6.

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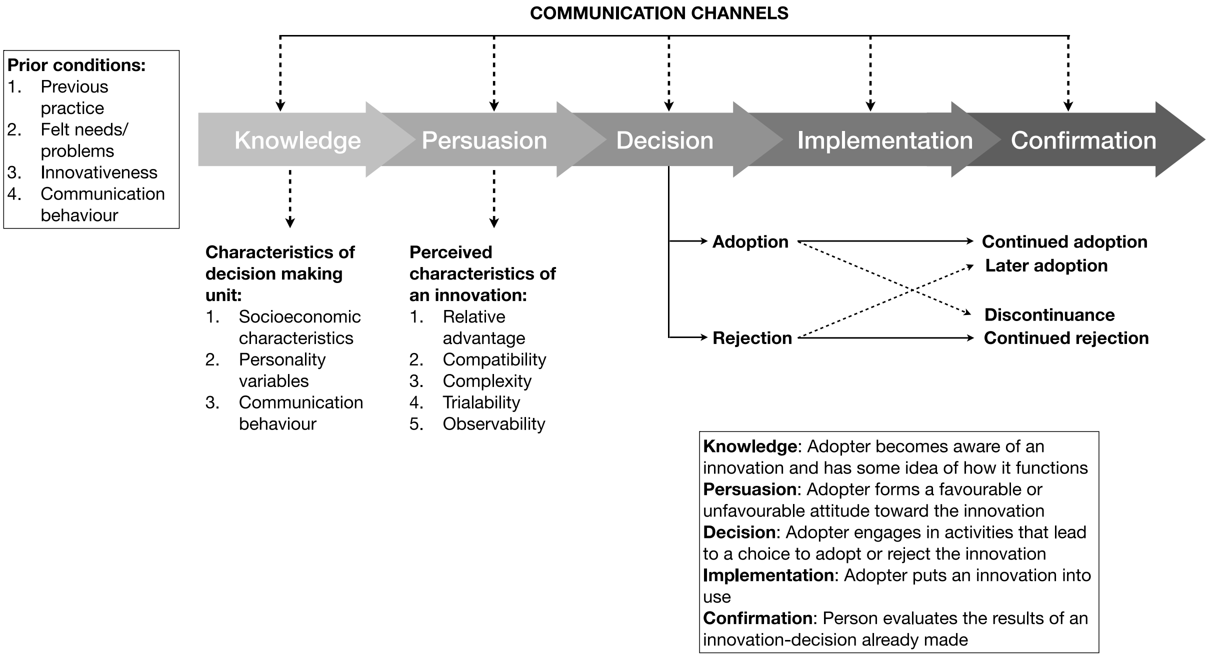

Figure 7. The five-stage generic innovation-decision process. Adapted from Rogers (1995).

Diffusion is defined as the process by which (1) an innovation (2) is communicated through certain channels (3) over time (4) among members of a social system (Rogers 1995). These four components provide ample social and communication theory by which to study biogas technology diffusion. They're described individually below:

1. An **innovation** is defined as an "idea, practice or object that is perceived as new by an individual or other unit of adoption" (Rogers, 1995, p. 11). In the context of this study, the innovation can be described as a technological object (biogas technology), a technological practice (biogas value chain) and the unit of adoption (a commercial biogas operator). Rogers posits five attributes of innovations that affect the mode by which technology spreads: relative advantage; compatibility; complexity; trialability; and observability (Figure 7).

2. A **communication channel** is the means of technological transfer through a social system. Communication channels can be analysed and optimised and are key to the effective diffusion of a technology. Communication channels can be interpersonal connections, through digital media, or through business links.

3. **Time** here refers to the non-uniform rate of diffusion and the innovation-decision process. The innovation-decision process takes place in five stages through which an individual or other decision-making unit (a bank, government or company for example) passes from knowledge of an innovation to choosing to adopt it (Figure 7).

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4. The **social system**, or social context is the set of interrelated actors that are engaged in employing technology to achieve a common end. The communication and social structure of a given system may either facilitate or hinder technology diffusion.

The innovation-decision process is an important consideration for projects aiming to facilitate or increase the adoption of a technology through a society. When adoption decisions begin to accelerate (as seen in the point of inflection as the ‘early adopters' user segment begin to adopt the technology), a learning curve as an industry brings together experience and learning about the technology that is subject to diffusion. This learning curve is important to sectors, such as biogas, where learning and experience correlates with decreasing technology costs as markets grow (Kampman et al., 2016, p. 10). Knowledge spillover effects are associated with market growth and learning curves and are important for sectors that have an underdeveloped technical capacity (Trachuk & Linder, 2019). The body of theory that surrounds innovation diffusion models provides a valuable resource to identify potential bottlenecks and opportunities to ensure successful diffusion of a technology. This can be achieved by relating a new technology to similar technologies and social contexts that have previously been studied under DOI.

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3 Methodology

The following methodology was developed to answer the research questions in a systematic and well-defined manner. When elucidating barriers inhibiting biogas sector development in developing economies (Research Question 1), a clear potential for bias was considered given the contextual distance of the author to the studied regions. Although barriers can be drawn from literature with relative ease, this approach was used only as a starting point in the methodological pipeline (Figure 8). Existing literature surrounding partner-region biogas sectors suffers from two key deficiencies: First, relevant literature was often written by authors in external institutions with little to no regard for a robust social sciences-type methodology describing the sourcing of barriers suggested. Second, literature is scarce for many of the partner regions, resulting in a dependence on dated studies. Given the rapidly changing socioeconomic conditions in developing countries, literature just four or five years old can become redundant. For these reasons, in addition to making use of the extensive network available through the DiBiCoo consortium, a methodological approach was developed with an emphasis on stakeholder engagement, illustrated below.

With reference to Research Question 2, research and technical adaptation were the primary focus of stakeholder engagement. Contextual accuracy and author bias elimination were pillars of the methodology defined below, aiming to attain a defined and region-specific set of research needs as a primary result. Evaluating the relative importance of the research needs was also a key outcome for which an open coding approach was employed.

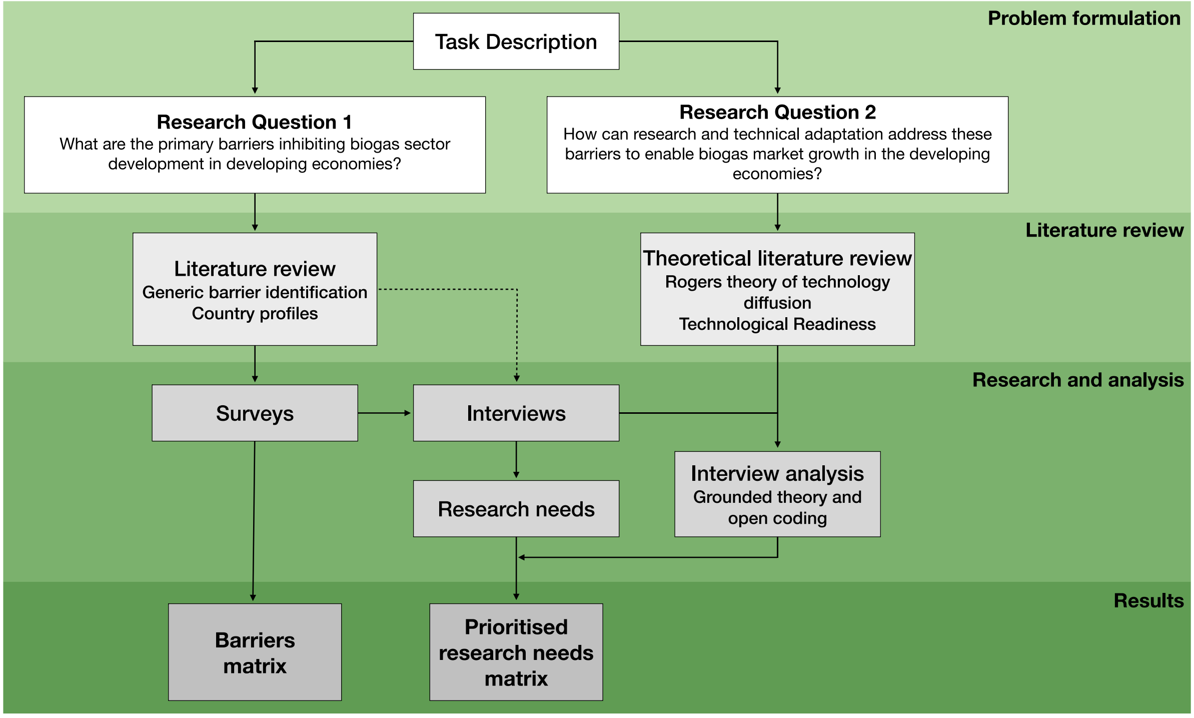

Figure 8. Methodological overview and workflow.

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The first green box in Figure 8, labelled ‘Problem formulation’, describes the research question generation process. Questions were formulated to meet the needs of the DiBiCoo-assigned task whilst simultaneously providing the grounds for academic inquiry. The task description can be considered as the basis for defining the start (research questions) and end (matrices) points of this study. The intermediate workflow (literature review and research and analysis) represents the route taken to achieve the given end: Prioritised, context specific research needs to be presented to the DiBiCoo consortium.

3.1 Literature review

The research undertaken for the purposes of this study began with a literature review with three objectives in mind. First, the partner countries' respective biogas sectors, research state of the art and socioeconomic conditions were studied to achieve a baseline level of knowledge required for productive discussion in the interviews. A certain depth of knowledge for each partner country’s variable biogas market conditions was deemed a necessary prerequisite for any stakeholder interaction. This research is largely contained in Framing. Second, through a process of context-specific and theoretical literature, barriers were described and collected to form a state of the art in terms of barrier identification which stood as that primary heuristic device for the survey and interview formulation. The barrier collection process is not presented in the study but was an important tool used to configure the groupings and relative importance of preconceived barriers. Third, theoretical literature (Research and development of biogas technology and Technology diffusion) was studied to form the basis of analysis which, when coupled with an open coding approach to qualitative data analysis, may be used to effectively analyse interview data. In addition to analytical applications, theoretical literature is also employed in this study to discuss the key findings from stakeholder engagement.

Literature was gathered from various academic journals covering engineering, resource conservation and energy policy and reviewed to map the current research landscape of partner countries. On a national level, energy outlook publications and various open source governmental documents were used to assess overarching (renewable) energy goals and performances in biogas technology-related fields. Sources of important governmental reviews on biogas research and policy were in part provided by consortium partners. Deliverables submitted by partners were also utilised in this review. The key literature sources are described in Table 4.

Table 4. Key literature review sources. All literature referenced in bibliography.

Literature name	Reference and Year	Content
Deliverable 3.1. Report on the Stakeholder Mapping for Importing Countries. Open source DiBiCoo document.	DiBiCoo (2020b)	Country-specific biogas sector state of the art, barriers, stakeholder overview
Deliverable 3.3. Biogas markets and Frameworks in Argentina, Ethiopia, Ghana, Indonesia, and South Africa. Internal DiBiCoo document.	DiBiCoo (2020c)	Country-specific biogas sector state of the art, barriers, stakeholder overview
EurObserv'ER - Biogas Barometer	EurObserv'ER (2017)	European biogas technology overview
Ethiopia's Second Growth and Transformation Plan	National Planning Commission (2016)	Resource and energy policy
Ghana's Strategic National Energy Plan (SNEP)	Energy Commission (2006)	Resource and energy policy
Indonesia's Long-Term National Development Plan 2005-2025 (RPJPN)	Ministry of National Development Planning (2005)	Resource and energy policy
International Energy Agency Countries & Regions: Argentina, Ethiopia, Ghana, Indonesia and South Africa	IEA (2020c)	Energy mix breakdown, emissions and generation capacity data, energy demand and supply over time
International Energy Agency Policy Database: Argentina, Ethiopia, Ghana, Indonesia and South Africa	IEA (2020d)	Energy policy overview
National Agricultural Technology Institute - National survey of biogas plants	National Agricultural Technology Institute [INTA] (2016).	National biogas technology state of the art
International Energy Agency. Outlook for biogas and biomethane: Prospects for organic growth.	IEA 2020a	Global trends in biogas production
South Africa's Integrated Resource Plan	Department of Mineral Resources and Energy (2019)	Resource and energy policy

3.2 Stakeholder interaction

As displayed in Figure 8, the research and analysis stage of the workflow begins with surveys and interviews. Surveys were distributed prior to conducting the interviews so that the data obtained from the surveys - largely suggestions for barriers for biogas implementation in respondents' respective region - may form the basis of interview discussion. The dashed arrow connecting literature review and interviews denotes the potential for literature-derived barriers to be used as the basis for interview questions if appropriate data was not collected from the survey process, a backup of sorts. This two-phase approach stands as the core method for the stakeholder interaction, illustrated in Figure 9. Each phase will be covered separately

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below. All interviews and surveys were conducted in accordance with EU data protection regulations as specified in the DiBiCoo grant agreement (DiBiCoo, 2020a).

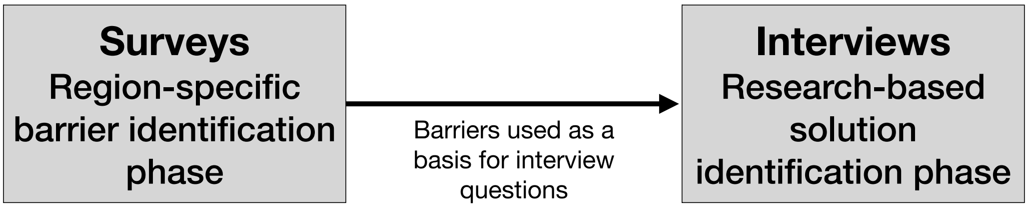

Figure 9. Illustrated relationship between surveys and interviews and their respective phases of the stakeholder interaction methodology.

3.2.1 Survey formulation

The surveys were developed using key information gathered in the initial literature review, with an intended outcome of region-specific barrier identification, covering a range of areas including technical barriers. The survey was created on Google Forms due to platform familiarity amongst respondents and ease of distribution. Prior to distribution, Argentinian and Indonesian surveys were translated by partner institutions into Spanish and Indonesian. The surveys were distributed online or manually through a printed interview by each regional partner to at least five relevant stakeholders. Relevant stakeholders were defined as being experienced in the field of technical biogas research and stakeholders involved in a range of research activities (private and public) were contacted. Survey writing was conducted in close collaboration with RDI (Indonesia) and Greencape (South Africa) to avoid overlapping with other DiBiCoo research already performed, with all material being approved by the relevant DiBiCoo partners prior to distribution. An overview of the 20-question survey is shown in Appendix 2.

Though an emphasis on biogas technologies can be seen through the large number of questions included for this section (7/20), the political, social and economic barriers associated with biogas sector growth were not excluded from this survey. This is due to the value that the identification of these barriers may bring to the wider consortium and the potential for technical adaptation and research to address non-technical barriers.

3.2.2 Survey analysis

Surveys were analysed by drawing out individual statements from stakeholders that suggest certain barriers for biogas sector growth in their respective region. These statements were reframed to suit the format of a barriers matrix. The barriers were also collected and reframed to be presented to interviewees and in turn stimulate the solution-oriented discussion of barriers.

Questions were formulated to provide a combination of quantitative (Likert scale and tick box) and qualitative (written) responses. This approach enables both qualitative and quantitative analysis of responses, broadening the modes analysis that can be used to explore responses.

3.2.3 Interview formulation

As illustrated in Figure 9, the interviews were constructed and performed through a barrier-solution oriented approach with an emphasis on solutions that can be achieved via research and technical adaptation. The interviews were split into three parts and lasted approximately 90 minutes each. Prior to conducting the interviews, DiBiCoo partners were asked to suggest between three and five interviewees to be contacted with the objective of interviewing at least one stakeholder from each technology importing country. The criteria for interviewee selection was: A knowledge of biogas technology and salience in their respective biogas market. A plethora of stakeholders from research institutions, governments and private developers were successfully contacted. Due to language barriers, interviews from Indonesian and Argentinian stakeholders were conducted externally by DiBiCoo partner institutions, transcribed and translated into English for analysis.

A semi-structured approach was selected for the interviews conducted for this study. This qualitative data collection strategy involves a conversational-type interview process where responses are not limited to a fixed range. An interview question guide, shown in Table 12, was developed to cover key barriers and stimulate discussion surrounding research-oriented solutions to predefined barriers. Though this structure provides an outline of questions and topics covered, semi-structured interviews allow for additional, reactive questioning and topics to be discussed outside the question guide. This approach was selected to create an informal research setting where interviewees may freely suggest research needs (Ayres, 2008). In addition to the generic question guide displayed below, region-specific questions were asked to elucidate targeted research needs. An overview and details of the interviews conducted can be found in Appendix 3.

3.2.4 Interview analysis

A qualitative data analysis (QDA) approach was selected to log, code and interpret the data collected through the interviewing process. QDA involves a process of ‘noticing’, ‘collecting’ and ‘thinking’ about qualitative data such as interviews and surveys (Seidel, 1998). These three component processes are interdependent and completed in an iterative, progressive and non-linear manner. Noticing involves creating a coherent dataset and making observations largely through coding and memoing. Codes (identified concepts under specific criteria) are used as a heuristic to facilitate discovery and further investigation of the data (Benaquisto, 2008). Collecting here refers to a method of deconstructing the data into its parts or elements as to break down complex phenomena into manageable information. Once disassembled, the

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data can be interpreted by the researcher and reconstructed in a meaningful and comprehensible fashion (Charmaz, 1983). The thinking component of QDA looks to examine the relationships, categorisations and contradictions within the coded data. With the goal to discover the emergent properties of the system of data, QDA can elucidate typologies and general consistencies that form the bases of novel theories (Seidel, 1998).

Grounded Theory and coding

Grounded Theory was used in this study as the framework through which collecting, noticing and thinking about data was undertaken. Formulated by sociologists Glaser and Strauss (1967), Grounded Theory offers systematic but flexible guidelines for conducting inductive qualitative inquiry (Bryant & Charmaz, 2007). The first and most methodologically defined pillar of Grounded Theory, open coding, involves identifying potentially interesting features of data. It aims to build concepts and generate ideas without much concern for relationships between codes. The two other pillars of Grounded Theory are axial coding (homing in on a category) and selective coding (looking at links and relationships), functionally synonymous with the collecting and thinking stages of QDA described above (Benaquisto, 2008; Khandkar, 2009). Here, open coding is used to categorise data and assess the prevalence of certain barriers and research-based solutions. Axial and selective coding are employed as tools for expanding on certain themes and discussion that may emerge from the interview data.

Constructivist formulations of Grounded Theory recognise that both the research process and studied world are socially constructed. Thus, social conditions influence the research and analytic process (previously described as the contextual distance of the author to the studied regions) (Bryant & Charmaz 2007). The present methodology has been formulated to mitigate this constraint in two ways. First, the open-ended nature of the output matrices circumvents the potential for contextually ill-defined generalisations, leaving this final analytic process to researchers who operate within the appropriate region. Second, a rigid coding structure is employed to arrive at partial conclusions that are linked with well-known social and technological concepts. This way, further analyses and development of these partial conclusions can be conducted with relative ease without consulting the author. Though providing a coding method as such drifts away from traditional open coding methods, the flexibility of Grounded Theory encompasses this approach.

Open coding and code formulation

In definition, open coding is the abstracting of concepts from qualitative data through labelling (Khandkar, 2009). Open coding is a broad category of research, used in many disciplines to achieve different outcomes. Thus, the open coding approach must be well defined, particularly in regard to code/label selection (Bryant & Charmaz, 2007). There are two modes of code generation, both of which are employed in this methodology. In vivo coding involves the generation of codes within the open coding process itself i.e. the labels are created whilst analysing

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the data. The second mode of code generation used predefined, constructed codes (Khandkar, 2009). These codes call on the theory defined in the Introduction and Framing sections of this study in order to embed these theories in data and in turn drive theoretical discussion.

Table 5. Constructed codes by section introduced.

Label group [code]	Section introduced	Label name [code]
Research type [R]	4.1.4.1.1 Organisational and technical research	Organisational research [RO]
		Technical research [RT]
Characteristics of decision -making [DM]	4.1.5.1.1 Biogas technology diffusion rate	Socioeconomic characteristics [DMS]
		Personality variables [DMP]
		Communication behaviour [DMC]
Technology characteristics [T]	4.1.5.1.1 Biogas technology diffusion rate	Relative advantage [TRA]
		Compatibility [TCB]
		Complexity [TCX]
		Trialability [TT]
		Observability [TO]
The biogas value chain [VC]	2.1.4 The biogas value chain	Inputs: Feedstock, water, associated regulation, associated stakeholders [VCI]
		Logistics: Mobility, associated regulation and organisational features, associated stakeholders [VCL]
		Biogas plants: Pretreatment, AD, associated regulation, associated stakeholders [VCP]
		Outputs: Back end processes, products (digestate, biogas, heat, electricity, biomethane), associated stakeholders [VCO]
		Emergent value chain properties: Employment, acceptance, spillover, learning [VCE]
		Maintenance and operation [VCM]

The constructed codes in Table 6. were used in the line-by-line analysis of transcribed interview data. The abundance and content of each label were recorded and analysed. This approach is grounded in the need to prioritise certain research activities that will result in boosting the biogas markets of importing target countries and identifying the type and position of research and technical adaptation (DiBiCoo, 2020a, p. 32). Due to the fact that the theories that form the basis of the constructed codes are concerned with technology diffusion and development or value chain research dynamics of industrial biogas facilities, this coding approach will prioritise research needs in direct accordance with the given Task. This method addresses *what* aspects of the technology need to be adapted (T), *where* research is best placed (VC, R)

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and *who* can best address technological adaptation and research needs (VC, DM) in a regional context.

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4 Results and discussion

The following section contains three main sections: Results, Framing and Discussion. Framing constitutes the large part of literature review used to identify initial barriers (as illustrated in Figure 8) and apply the theories introduced into the study context. The Results and discussion section presents key findings obtained through the methodology described above, readdressing the theories used to assess and prioritise data in order to make theoretically determined recommendations in

4.1 Framing

4.1.1 Biogas technology importing countries

Five countries were selected to be partnered with EU biogas technology stakeholders through the DiBiCoo project on the bases of their high market potential for biogas technology adoption and existing relationships with EU members of the consortium. The partner countries include (in the order they're discussed below) South Africa, Ethiopia, Ghana, Indonesia and Argentina. Each partner country reflects variable socioeconomic conditions and framework conditions; in turn creating equally variable barriers which must be addressed for effective market entry. Partner countries cannot be grouped on many grounds other than their mutual classification within the wide grouping of developing economies and for the purposes of this study. Per the United Nations Conference on Trade and Development (2019) classification, Argentina, South Africa and Indonesia are emerging markets of high, upper-middle and lower-middle income developing respectively. Ethiopia and Ghana, by the same classification system, are both grouped within the low-income food-deficit countries and heavily indebted poor countries. Though of a similar economic status, Ghana is a lower-middle income country and Ethiopia a least developed country, the lowest subcategory of economic development. The states that make up the EU are largely developed regions with some emerging regions to the east of the bloc (United Nations Conference on Trade and Development, 2019).

The DiBiCoo-partner-region's global location and performance in five popular socioeconomic and sustainability indicators are displayed in Figure 10. The performance of each region in the charts in the lower portion of Figure 10 reflect their respective economic classification described above: The more developed a country is, the higher their performance in socioeconomic indicators. High variance in GDP and HDI, even when normalised to the global average, highlights the variation of social, economic and sustainability conditions present within each region. For example, the GDP per capita in Ethiopia is roughly half that of Ghana's. Ghana's GDP per capita is around half that of South Africa's and a third of Argentina's. The GDP per capita in the EU is over twice that of Argentina and 16 times that of Ethiopia. The spread of partner countries over four continents also stands as a challenge due to diverse cultural settings but also an opportunity for substantial knowledge spillovers which can influence larger portions of global society than a localised consortium.

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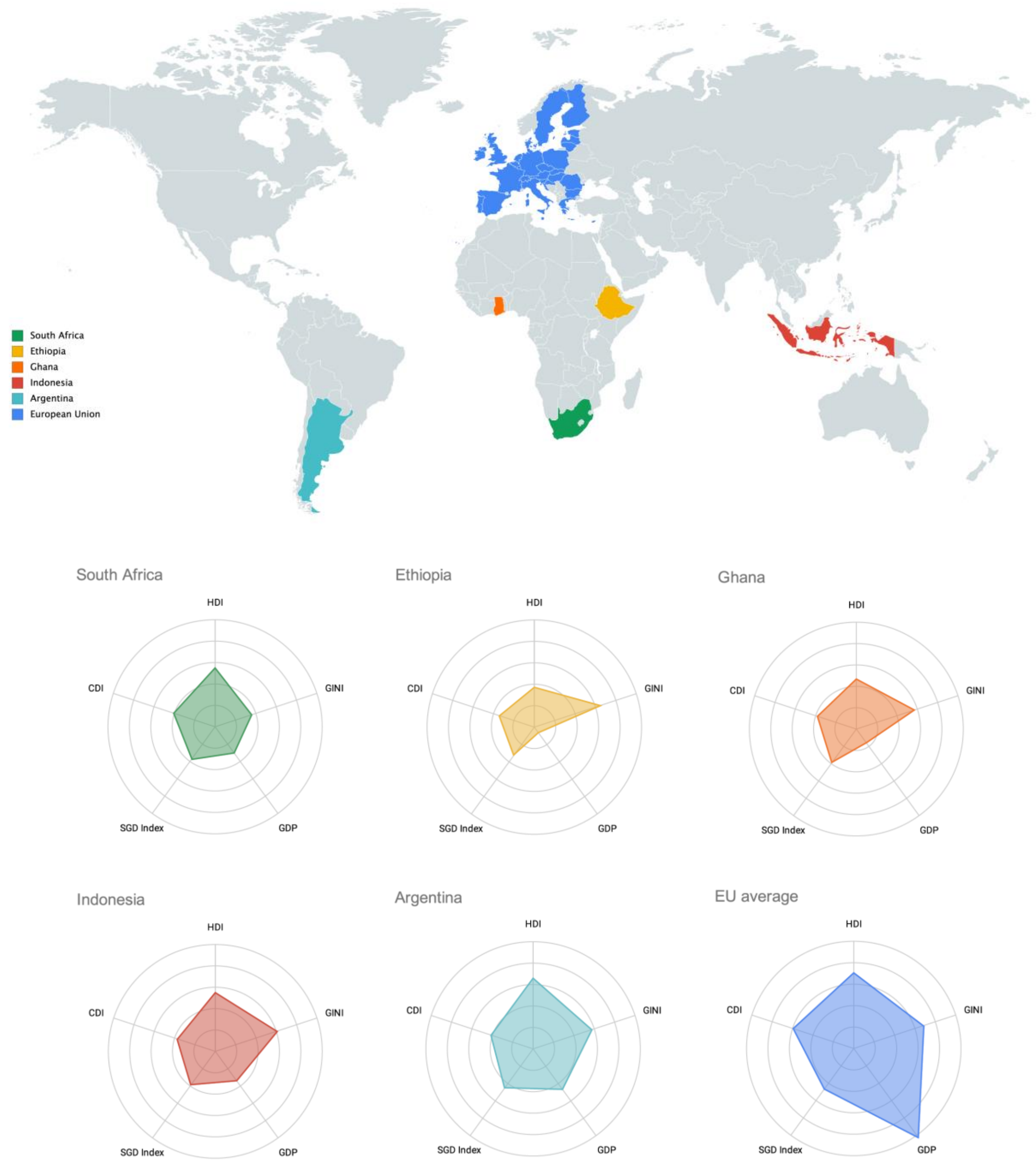

Figure 10. Partner countries map and respective radar charts displaying popular socioeconomic metrics. See Appendix 1 for methodology and references.

The successful operation and installation of biogas plants - and in turn the successful diffusion of technology - is a process dependent on various social, technical, economic, governmental and environmental factors. For this reason, the following section describes general and biogas-specific characteristics of each country to ensure the effective reading of this study.

The following section aims to introduce the economic and social features of each partner country. The status of renewable energy and the policy, targets and strategies surrounding each renewable energy sector will also be addressed. Specific to biogas, the state of the art on technology, number and distribution of plants and status of the sector is described where available data allows. For some of the partner countries, data is scarce resulting in an incomplete picture of the biogas market. Though this is far from an ideal outcome for this study, there is an important message carried in the absence of information: Data is not available or presented in a suitable form to biogas developers or stakeholders interested in biogas opportunities in the technology importing market. This message carries the central motivation for establishing DiBiCoo, a project which aims to address this lack of robust and reliable information surrounding infant biogas markets in the developing world. Salient stakeholders within each country's biogas sector are also stated. A combination of documents produced by DiBiCoo partners, governmental reports, multinational institutional data and academic literature and reviews are used in this section.

African partner countries

Three of the five technology importing countries, or partner countries, are located in Africa. This allows for some general characteristics of these countries to be described before each country is addressed separately.

The African continent is a region historically characterised by instability, economic hardship and rural populations. This image has been reinforced as Africa remains the subject of much Western aid. A largely postcolonial continent, Africa continues to suffer from the legacy of extractive relationships with wealthier countries, with some theorising that this relationship is maintained today by the Bretton Woods institutions (Adedeji, 1995). Human development within the region is amongst the lowest in the world and, though hugely resource rich, economies remain in the earliest stages of development. That is not to say that it is all doom and gloom for Africa on the economic side of things. Many African countries (including Ghana and Ethiopia) are amongst the world's fastest growing economies, currently exhibiting economic growth north of 7%. This growth has led to vast improvements in human development and the market driven emergence of African economies onto the international scene (African Development Bank [ADB], 2020, p.157). Africa will continue to focus on inclusive and equitable development, electrification and education as populations rise to over 2 billion in 2040 from 1.29 billion in 2018 (IEA, 2019a).

From the perspective of energy, Africa's grids continue to expand to supply urban and rural populations with reliable, modern, affordable and sustainable energy. Movement away from traditional forms of energy such as solid biomass stands as a policy priority for the majority of African countries (IEA, 2019a). Given the significant developments in renewable energy technologies in recent years - especially with regard to cost - doors have opened for Africa to grow in a manner that is distinctly different and greener than the carbon-intensive Western model of economic and human development.

When biogas is discussed in Africa, household scale biogas projects installed in association with development aid organisations are often the images that come to mind. Larger-scale projects are emerging on the continent with many of these technologies being imported from European suppliers. Large agricultural sectors and many national efforts within Africa to internalise agricultural processing, create a favourable setting for both household and large-scale biogas project development.

Ethiopia

Ethiopia is the world's most populous landlocked country and sits in the Horn of Africa with neighbouring Sudan, South Sudan, Kenya, Somalia and Eritrea. The oldest independent African country and home to the African Union Commission, Ethiopia is an important cultural and political power (British Broadcasting Corporation [BBC], 2019). With a population projected to grow by 56% to 145 million people by 2050, Ethiopia has an important future ahead to secure energy, education and livelihood for its people (United Nations [UN], 2010, p. 92).

Ethiopia's rapidly growing economy (7.7% in 2017/2018) is built in large part on the service, construction and agriculture sectors. Though the Ethiopian population is getting wealthier, poverty is still a pressing national concern, with a 24% share of the population living below the poverty line in 2016 (World Bank, 2019a). This issue is planned to be addressed by Ethiopia's Growth and Transformation Plans (GTP): Two five-year plans from 2010 to 2020 to stimulate inclusive growth and ultimately for the country to achieve lower-middle-income status (GNI per capita between USD 1,006 and USD 3,975) by 2025 (National Planning Commission [NPC], 2016, p. 6). The Plan aims to improve the productivity of Ethiopia's agriculture sector by shifting from subsistence agriculture to the production of higher value agricultural products. This goal involves strategies, such as an emphasis on a single-crop cultivation for groups of smallholders that would have otherwise cultivated a variety of subsistence crops: A strategy that synergises well with the feedstock-level enabling conditions for larger-scale biogas technologies (NPC, 2016, p. 24). With 70% of households earning income from agricultural activities, developments within this sector are set to have a far-reaching social benefit, diffused between smallholders and larger commercial stakeholders (World Bank, 2020a).

The Ethiopian electricity sector is one of the few in the world where the grid is almost completely supplied with renewable energy, in large part by hydroelectricity (World Bank, 2018a). Though this is a great starting point for Ethiopia's ambitious plans to develop a climate resilient, green electricity sector, the realities on the ground stand in contrast to this advantage; with 55% of the population (including 24% of schools and 30% of health clinics) without access to electricity (NPC, 2016, p. 212; IEA, 2019b; World Bank, 2018a). Today, Ethiopia's primary energy demand is met by bioenergy (39 MToe), oil (4 MToe) and hydroelectric power (1 MToe). Development policies such as the National Electrification Plan (2017) look to reduce the dependency on burning solid biomass for energy (IEA, 2019b). One approach to reduce this dependency is the development of around 30,000 domestic biogas systems over the course

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of the second GTP from 2015 to 2020 (NPC, 2016, p. 179). As Ethiopia's economy develops, the portion of the population with electricity access is expected to increase to full coverage in 2025 (IEA, 2019b). The roadmap in place to achieve this involves a combination of grid (60%) and off-grid (35%) expansions. These networks will supply unconnected regions with mini-hydro and solar PV in the case of off grid projects, and largely hydroelectricity (75% of energy mix) along with other state-of-the-art renewables in the case of the national grid (United Nations Framework Convention on Climate Change [UNFCCC], 2018; IEA, 2019b). Though biofuels are forecast to contribute to electricity sector expansion under stated Ethiopian policies, biodiesel from energy crops, namely Jatrofa, is the present policy focus for biofuels in the electricity sector. Biogas to power systems are not specifically mentioned in electricity-sector development plans, being discussed for domestic scales only (NPC, 2016, p. 38; IEA, 2019b).

The discourse that surrounds the biogas sector in Ethiopia is almost entirely limited to domestic scale projects. This is evidenced at the literature level, where research often fails to address the potential for larger scale biogas developments (Kamp & Forn, 2016; Mengistu et al., 2015). This focus is expected given the socioeconomic conditions in Ethiopia and policy focus on small scale projects (SNV Netherlands Development Organisation [SNV], 2020a). With Ethiopia's rapid economic growth and as policies shift towards electrification and grid-integrated renewables, larger scale biogas becomes more attractive on both an investment and research level. The National Biogas Program of Ethiopia (NBPE+) plans to develop 40 medium and large scale biodigesters by 2022 in collaboration with the Netherlands Development Organisation (DiBiCoo, 2020b; SNV, 2020b). Due to weak private sector activity, the biogas sector in Ethiopia has few core stakeholders outside of the government; a feature that manifests in low levels of market competitiveness (DiBiCoo, 2020b).

Ghana

Ghana is a country of around 30 million people bordering Togo, Côte d'Ivoire, and Burkina Faso in Western Africa. Ranking in the top three countries in Africa for freedom of speech and media, Ghana hosts a strengthening democracy and solid social capital (World Bank, 2019b).

The Ghanaian economy is one of the fastest growing in Africa, experiencing growth of around 7% since 2017 and a strong growth momentum going into the new decade. This growth is largely oil-free despite oil being a main export along with gold and cocoa which form the cornerstones of Ghana's export economy (BBC, 2018). Plans to strengthen the export economy look to develop 'strategic anchor industries' such as agro-processing, industrial starch and oil palm to maximise local value addition and support agriculture-led industrialisation (ADB, 2020, p.157; Ministry of Trade and Industry [MOTI], 2020). Agriculture accounts for 18% of GDP and employs 29% the population (World Bank, 2018b; World Bank, 2019c). This large output coupled with a policy push towards commercial agriculture indicates feedstock availability and thus opportunities for biogas production. These opportunities may be further bolstered by the Ministry of Trade and Industry's 'One District One Factory' initiative that aims to establish a factory

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in each of Ghana's 16 districts through a decentralised industrial development strategy (MOTI, 2020).

Ghana's primary energy supply is largely built on oil imports and traditional biomass which constitute 41% and 42.5% of the energy mix respectively (Energy Commission, 2016). The national grid power access coverage was 72% in 2011. With goals to gain universal coverage by 2020, reduce transmission losses and meet increasing demand due to growing industrial activity, urbanisation and population growth, Ghana's energy sector is expected to expand and diversify in the coming years (Präger et al., 2019).

Ghana sees sustainable and universal energy supply as the foundation of future economic development. The Strategic National Energy Plan (SNEP) was inaugurated in 2006 and aims to "develop a sound energy market that will provide sufficient, viable and efficient energy services for Ghana's economic development" (Energy Commission, 2006, p. 9). With overarching objectives to accelerate renewable energy contribution to the energy mix (Objective 5) and minimise the environmental impacts of energy production (Objective 7), Ghana has been ahead of the curve when thinking about sustainability (Energy Commission, 2006, p. 29). The SNEP sets out an objective of achieving 10% penetration of renewables in the energy mix by 2020. Progress towards this goal has been marginal with less than one percent of total installed electricity capacity coming from renewables in 2017 (Energy Commission, 2018). Thus, this goal has been pushed from 2020 to 2030 (Präger et al., 2019; Energy Commission, 2006).

Policies to support the development of national renewable energy supply include technology-specific FITs and a net metering code, bought in by the Ghanaian government in 2013 and 2015 respectively. Both of these policies draw upon guidelines set in the 2011 Renewable Energies Act (Energy Commission, 2006, p44; IEA, 2020c). The FIT scheme signals a strong governmental intent towards renewable energy generation. The tariffs are guaranteed for 10 years and include a biomass (including biogas) specific rate, though the scheme has been criticised on the grounds of lack of standardisation of guidelines and licensing processes (IEA, 2020c; Meyer-Renschhausen, 2013). Despite a large potential for biogas coming from Ghana's sizeable agricultural sector and existence of fiscal support schemes such as FITs, biogas technologies are uncommon in the region and do not reflect this potential (Bensah & Brew-Hammon, 2010; Präger, 2019). Barriers that have previously stood in the way of the development of Ghana's biogas market include unfavourable policies, non-availability of feed materials, poor financing arrangements, problems with social acceptance, absence of market, failure to support projects through focused energy policies, poor diffusion/dissemination strategies, poor digester design and construction, lack of project monitoring and follow up by promoters, and lack of information (Edjekumhene, 2001; Osei-Marfo, 2018).

Biogas technologies were first introduced in the 1960s to provide energy for cooking and heating on a small scale. In the 1980s a handful of Chinese dome-type plants between 10 and 30 m^3 were constructed by the Ministry of Energy, with the biogas produced also being utilised for heat. Biogas was first used to generate electricity from cow manure in 1992. A number of

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problems that surrounded the project harmed both public and governmental perceptions of biogas technologies and led to a slump in support schemes since. Since 2000 however, a number of private biogas suppliers, focussing primarily on business models providing wastewater treatment services, have entered the market despite the absence of serious government support. The Netherlands Development Organisation (SNV) have since provided a strategy for market-based growth of the household scale biogas sector though bilateral institutional support (Bensah & Brew-Hammon, 2010). Studies by Osei-Marfo et al. (2018) and Bensah and Brew-Hammon (2010) investigated the status of biogas plants, from household to industrial scale in Ghana. The results of these studies reveal that though only a small number of plants had been abandoned, most plants surveyed were not producing biogas or the biogas produced was not utilised. Overall, it is estimated that around 400 biogas plants have been constructed in Ghana, the majority of these being of household scale though a few larger scale plants (over 1000 m^3 biodigester capacity) are in operation (Osei-Marfo et al., 2018, DiBiCoo, 2020b). The Sustainable Energy for ALL (SE4ALL) country action plan has conducted feasibility studies to establish institutional biogas systems for boarding schools, hospitals and prisons and stand as the primary governmental action plan to stimulate the biogas sector in Ghana (Hanekamp & Ahiekpor, 2012).

With the majority of biogas plants operating at a suboptimal economic output, enthusiasm amongst stakeholders (namely financial actors within the sector) is low. Multilateral and bilateral support to the Ghanaian biogas sector comes largely from the Netherlands Development Organisation (SNV), German Corporation for International Cooperation (GIZ) and the United Nations DevelopmReent Programme (UNDP). Nationally, the Energy Ministry and the Ministry of Environment, Science, Technology and Innovation (MESTI) are key governmental stakeholders involved in biogas project development (DiBiCoo, 2020b). An energy crisis in 2016-17 resulted in a large number of generation licences handed out on take or pay contracts. This has since caused overproduction of electricity in the Ghanaian electricity sector. Thus, there is little to no market demand for electricity produced by biogas plants. The demand therefore comes exclusively from governmental incentives to meet the 10% renewable energy target as well as an demand for heat, digestate and waste management services from the biogas technologies (Kumi, 2017).

South Africa

The Republic of South Africa is the wealthiest country in Africa and thus an influential regional economic power for both the Southern African region and the entire continent. Economic activity in South Africa is concentrated in the finance, government, manufacturing, trade and mining sectors, most of which operate in urban centres: A characteristic which manifests in high levels of income inequality as is seen in the GINI scoring in Figure 10 (Brand South Africa, 2018). The country has been experiencing low levels of growth (around one percent) in recent years due to structural constraints (ADB, 2020, p. 180).

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With only 2.5% of GDP being gained through agricultural production, South Africa stands as somewhat of an outlier in Africa, where an average 32% of GDP is derived from agriculture. That is not to say that agriculture is not important for South Africans, with 15% of the population directly or indirectly depending on agriculture for subsistence and income (Alliance for a Green Revolution in Africa, 2013, p. 14; Brand South Africa 2018). The sector consists of both well-developed commercial farming and subsistence-level farming, a disparity that exists as a symptom of South Africa's economic inequality. With respect to feedstock acquisition for biogas production, the diversity of scale in South African agriculture presents an opportunity for biogas technologies of variable scale to be employed. Where feedstock is abundant, in commercial sugarcane farms for example, larger scale biogas to power plants are appropriate and on a subsistence level, small scale biogas digesters may be developed to a socially beneficial end.

Coal is the mainstay energy of the South African energy system, accounting for around 70% of installed capacity today though this is projected to fall to below 45% over the next decade (Department of Mineral Resources and Energy [DMRE], 2019). Energy crises since 2008 as well as commitments to decarbonising the energy sector have stimulated policy reforms to diversify the energy mix away from coal, secure domestic generation capacity and reduce carbon emissions through an emphasis on renewables. South Africa's Integrated Resources Plan (IRP) was inaugurated in 2010 and forecasts new installed capacities of 9.6 GW nuclear, 6.3 GW coal, 17.8 GW renewables and 8.9 GW for other generation sources by 2030. Of the new renewable capacity which is to reach 42% of the total energy mix by 2030, solar and wind constitute the large part and, though biomass is mentioned, no direct commitments to AD processes are made in this plan. In the most recent review of the IRP, biogas is listed as a "price competitive technology" with "huge potential" signalling an elevated governmental awareness and enthusiasm for biogas technology. Though there are no concrete commitments to adding biogas to the energy mix in the most recent IRP, biogas technologies can benefit from regulatory frameworks that promote renewable energy in general (DMRE, 2019).

Biogas technology was introduced in South Africa in 1957, but despite this early exposure has not penetrated the energy sector. This is due to price competition from cheaper fossil alternatives (notably coal), limited governmental support, and a lack of regional service providers (Mutungwazi et al., 2018). Since 1957, 700 biogas plants have been installed in South Africa, though a small portion are active today since biogas plants have a lifespan of around 20 years. Installations have been of variable scale, from DIY biobag digesters to large-scale plants with capacities above 10 MW. Mutungwazi et al. (2018) mapped the medium and large scale biogas plant installations in South Africa between 2005 and 2017 and found that, in addition to hundreds of household scale digesters, 31 digesters had been installed with capacities from 100kW to 19MW. These plants use various feedstocks including abattoir waste, energy crops, livestock manure, waste-water and agroindustrial waste. There are also four landfill waste plants in South Africa (DiBiCoo, 2020b).

Stakeholders for South African biogas at the scale explored within DiBiCoo (industrial biogas facilities) are concentrated in the private sector. Eskom, the state-owned monopolistic power utility, is vertically integrated at all levels of the electricity value chain and is therefore a major player in any national energy developments through licensing, issuing power purchasing agreements, wheeling agreements, etc. (DiBiCoo, 2020b; DMRE, 2019). Plans by the current government to unbundle Eskom into three separate entities in 2019 has slowed any new developments within this sector due to organisational needs being prioritised over issuing power purchase agreements (PPAs) (Minnaar, 2019). On a governmental level, the Department of Mineral Resource and Energy (DMRE) is a core stakeholder with direct influence on power generation, distribution and trade within South Africa, and are the primary authority for developing policy and regulatory support for the biogas sector on a governmental level. The principal drivers for regulatory changes that favour biogas technology are private project developers who influence the reputation of the biogas industry. The private sector is therefore the main mover in South Africa's biogas market and primary stakeholder throughout the development cycle (DiBiCoo, 2020b). The private sector is represented by the South African Biogas Industry Association (SABIA), a collective body that voices the needs and concerns of the sector. This includes interacting with government authorities to develop financial mechanisms to support biogas and mobilise funding to support universities and research institutions to develop technologies and skills, and financial institutions regarding biogas business cases. It is the work of the private sector, in collaboration with regulatory authorities (DMRE) and financial institutions that the biogas market in South Africa will reach its potential.

Argentina

Argentina is a vast country in South America, home to 44 million people. Stretching multiple climates from the subtropical north to sub-Antarctic south, Argentina is an ecologically diverse region and is rich in natural resources such as natural gas, agricultural lands and lithium. Argentina is a regional power in terms of industry, economy and culture and is a G20 member with a well-educated workforce. Historic volatility of economic growth and the accumulation of institutional obstacles have inhibited human development in the country, with urban poverty currently at 35.5% (World Bank 2020c).

The Argentine economy is in recession against a background of internal and external imbalances. Inflation is high, currently at 50%, and monetary policy is currently tight to counteract this trend. Following elections in 2019 the policy landscape in Argentina remains uncertain, resulting in reductions in investment. Structural reforms to restabilise the economy and encourage growth are in place though competition remains weak in many sectors, owing to domestic restrictions to market entry and barriers to entrepreneurship and trade. Reducing macroeconomic uncertainty is considered a key objective for the new government which can promote economic recovery, with positive growth projected in 2021 (OECD, 2019a).

The third largest economy in Latin America after Mexico and Brazil, Argentina possesses a developed, export-oriented agricultural sector and diversified industrial base. Argentina grows

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food for 450 million people and thus plays an important role in the global economy. The agricultural sector accounts for 40% of total exports and is based on livestock farming, cereal cultivation (wheat, corn and transgenic soy), citrus fruits, tobacco, tea and grapes (OECD, 2019b, p. 20). Sugar cane and soy are extensively cultivated for the production of biofuels, making Argentina the world largest exporter and fourth largest producer of biodiesel. The agricultural, industrial and service sectors make up 6.1%, 21.8% and 76.1% of GDP respectively. The large service sector engages in many high-tech activities through Argentina's well-educated workforce (Lloyds Bank International Trade Portal, 2020).

Argentina's total primary energy supply is dominated by oil and natural gas, which together account for 89% of total supply. Low carbon fuels make up just under 10% of total primary energy supply and renewables constitute more than a quarter of electricity generation, with the large part of this portion coming from hydropower (IEA, 2020d). In Argentina's Third Communication to the United Nations Framework Convention on Climate Change (UNFCCC), an unconditional commitment to reduce greenhouse gas emissions by 15% by 2030 was made with this goal being increased to 18% soon thereafter. This goal includes actions linked to the promotion of sustainable forest management, energy efficiency, biofuels and renewable energy (OECD, 2017). Within this Communication, biogas is referred to as a strategy to extend the environmental and social benefits of the wastewater sector (World Bank, 2016). Passed in 2015, Law 27191 on Renewable Energy sets a clear target of 20% minimum contribution from renewables to total electricity consumption. This law also establishes a special obligation for large energy users to achieve this target under a threat of penalty (Grantham Institute, 2015). Argentina's Renewable Energy Auction (RenovAr) was launched in 2016 to boost private sector renewable energy project development via an auction. This public tendering programme provides a number of fiscal incentives and financial support mechanisms along with regulatory and contractual enhancements designed to overcome the investment barriers to renewable energy developments (OECD, 2017). The projects awarded under the first two rounds of RenovAr, which included 9MW of industrial-scale biogas, issued 29, 20-year PPAs totalling 1000MW (International Finance Corporation, 2018). In 2019, 17.75 MW of biogas projects were won in round three of RenovAr alongside 400MW of other projects providing renewable capacity (IEA, 2019d). RenovAr is considered a productive step in creating favourable regulatory conditions for renewable sector development.

The biogas sector in Argentina remains small despite the great potential for growth on a feedstock-availability level. In 2016, around 100 active biogas facilities were recorded in a national survey. Of this total, 53% of plants were private sector ventures, 38% belonged to public institutions and the remainder were NGO projects. With respect to scale, most plants constructed by private companies were large scale facilities while NGO and public sector facilities were primarily of small and medium scale (National Agricultural Technology Institute, 2016). The majority of plants were constructed for the purposes of waste treatment. Due to this, only 4% of plants were constructed for the sole purpose of energy generation (DiBiCoo, 2020c). CSTR reactors are the most common reactor used with 46% of plants using this design. Other reactor types include covered lagoon (19%) and UASB (16%) (INTA, 2016). Feedstocks are majorly industrial and organic wastes (D3.3). The biogas sector in Argentina has benefited from the recent fiscal support measures with the number of biogas plants producing energy for the national grid increasing 57% to a total 17 plants between 2017 and 2018, though this growth is still not reflective of Argentina's biogas potential.

Plant developers play an important role through conducting preliminary studies of potential developments as well as plant construction. On the governmental side, the Secretary of Energy is responsible for reporting, contract signing and development supervision within the sector. The Secretary of Energy, through the ENERGAS and ENRE branches, is also the central institution that connects biogas facilities to national gas and electricity markets. Research institutes: The National Institute of Industrial Technology (INTI) and the National Agricultural Technology Institute (INTA) are responsible for evaluations, research and development, environmental studies and capacity building among other research-related activities. Private companies are scarce and largely in their infancy given Argentina's relatively nascent market growth. Companies are involved with civic implementation and start-up aspects of projects and are often in communication with international, largely European suppliers (DiBiCoo, 2020b).

Indonesia

Indonesia is the largest economy in Southeast Asia, world's fourth most populous country and 10th largest economy. An archipelago nation of more than 300 ethnic groups, Indonesia is a culturally diverse region. Tectonic activity causes Indonesia to be prone to earthquakes and volcanic activity, a feature that along with Indonesia's tropical climate results in extremely fertile land and intense ecological diversity. Since the Asian financial crisis of the 1990s, Indonesia has cut poverty through the process of economic development. Though progress has been impressive, poverty rates are still at around 10%, and the improvement of public services to reduce this figure remains a priority for Indonesian decision makers. With Indonesia being a large economy and a member of G20, it is an influential regional power in Southeast Asia and holds diplomatic and trade relations with the Netherlands, USA, Japan and Australia (World Bank, 2020b).

Indonesia's economy is growing at a constant rate of 4% and is driven by declining poverty rates, low inflation, healthy employment growth and social assistance programmes. Bank loans for investments are growing strongly and export growth has slowed in recent years as a result of government policies to reduce fuel imports by diverting exports to domestic use. According to the OECD, reforms are needed to spur private investment and streamlining, and simplify business regulations should be a priority for Indonesia (Organisation for Economic Co-operation and Development [OECD], 2020).

Indonesia's Long-Term National Development Plan (RPJPN) follows a 20-year timeframe from 2005 to 2025 and is segmented into five-year medium-term plans (Ministry of National Development Planning, 2007; World Bank 2020b). Agriculture has historically been a pillar of the Indonesian export economy and provided income for local households, with agriculture

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providing 13.5% of GDP and 31.9% of employment in 2017. The sector consists of a combination of large-scale plantations under the guidance of the government, private investors and smallholders using traditional farming methods. Key agricultural products include natural rubber, cocoa, coffee, tea, cassava, rice, spices and palm oil which is by far the most important crop contributor to GDP. Indonesia provides half of the global supply of palm oil and the sector continues to grow. Around 70% of oil palm plantations are on the island of Sumatra with private, smallholder and state-owned plantations accounting for 58.5%, 33.9% and 7.6% of production respectively (Oxford Business Group, 2020).

Indonesia is one of the world's largest producers of biofuels (namely biodiesel from palm oil), fourth largest producer of coal and Southeast Asia's largest natural gas supplier. Oil exports have risen sharply in recent years to meet a growing demand due to rapid economic growth. Indonesia's energy needs are largely supplied by coal, oil and natural gas (66%) with renewables, hydro and biofuels and wastes providing the rest. Around 75% of non-fossil fuel derived energy supply comes from biofuels and wastes, 23% from wind and solar and 2% from hydropower (IEA, 2020b). Notable goals set out in Indonesia’s 2020-2025 medium-term development plan include 99.7% electrification rate and increasing new and renewable energy in primary energy supply to reach 23% by 2025. ‘New and renewable energy’ here includes renewable energies plus nuclear, hydrogen, coalbed methane, liquefied coal and gasified coal and excludes traditional use of biomass. Indonesia’s Electricity Supply Business Plan states that hydro and geothermal power account for the majority of planned new renewables capacity (IEA, 2019c).

Despite biogas being introduced in the 1980s through projects supported by the Food and Agriculture Organisation, biogas technology in Indonesia remains a novel concept in public and government discourse (DiBiCoo, 2020b; Khalil et al., 2019). Government ambitions to support the development of renewable energies considers biogas a least preferred alternative to other renewable energy technologies such as hydropower and geothermal (DiBiCoo, 2020b). Household scale biogas projects do exist in the country despite the technology’s perceived novelty. A partnership between Bali Provincial Agricultural Agency and SNV built 16,000 domestic fixed dome biogas digesters in nine provinces between 2009 and 2016. For the biogas-to-electricity pathway however, current policy is described as not supportive. Low FIT rates, no specified biogas target and uncertain policy conditions make industrial biogas an insecure and unattractive investment (DiBiCoo, 2020b; Taylor et al., 2019). The low regional technical capacity does not meet the needs of biogas plants which, coupled with a rigid 30% local involvement in all renewable development, stands as another barrier to market growth. Notwithstanding these challenges, Indonesia possesses attractive feedstock potentials, notably palm oil mill effluent (POME). In addition to being an abundant waste product in Indonesia's vast palm oil industry, POME has an attractive biogas potential of up to 0.23 $kgCH_4/kgCOD_{treated}$ when digested in a CSTR and 0.16 $kgCH_4/kgCOD_{treated}$ in a covered anaerobic pond system. Controlled systems are recommended as optimal process parameters ensure reliable performance and are therefore most appropriate for commercial biogas production (Choong et al., 2018).

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Industrial biogas developments in Indonesia are subject to a complex set of regulatory and bureaucratic hurdles. Biogas projects are closely monitored by the government, who enforce a constantly changing regulatory setting for renewable development which in turn limits the security of biogas investments, especially for financial institutions who regard biogas as a special investment case due to high risk. FITs for example are currently designed to heavily favour the national utility company, Perusahaan Listrik Negara (PLN). PLN is the only power buyer in Indonesia's electricity market. Thus, PPAs are made and managed exclusively by PLN, who are obliged to follow the national energy strategy which categorises biogas as a least preferred renewable option. Producing biogas for electricity is therefore a challenge with regard to bankability and governmental support. Business to business agreements, where electricity is utilised internally in a localised manner, may be a preferred approach for biogas to electricity developments. Other important stakeholders with high salience in the biogas sector include the Ministry of Energy and Mineral Resources who have jurisdiction over all biogas projects, the Ministry of Finance who control investment flow, and the National Planning Agency who direct long term strategic targets. From the above it is clear that the sector is dependent on the national government. Although NGOs are present in the biogas sector, they tend to stay close to the ministries by default and have a minimal impact on the industrial biogas market. The biogas sector in Indonesia is full of complexities but the National Government’s strategic goals does ultimately support biogas market growth. Governmental participation in biogas projects must be met by knowledge sharing and transparency from private stakeholders in the industry to ensure effective and mutually beneficial public-private collaboration (DiBiCoo, 2020b).

4.1.2 Biogas technology exporting countries

Where biogas sectors are mature, namely in the EU for industrial scale biogas production from agricultural waste, the USA for landfill gas capture systems, and China for small and domestic systems, technologies are well developed and proven at an operational level. Through competition and experience within each respective market, biogas companies have optimised the operational and economic performances of plants, decreased costs and found best practises for biogas production. Countries that seek to develop their biogas sectors can leapfrog the learning curves undertaken by technology-exporting countries by importing system-ready plants at high levels of technological readiness. This is a positive sum game where exporting countries are able to profit from entering new markets and importing countries are able to circumvent these often lengthy and costly learning curves. In addition to the environmental benefits associated with the growth of global biogas production, it is this positive sum nature of biogas technology diffusion that drives the social, economic benefits of DiBiCoo.

The European Union

The European Union hosts the world's largest biogas sector in terms of production capacity, technology status, and research and innovation. The market has benefitted from a favourable regulatory landscape that has allowed biogas to remain competitive despite a comparative price disadvantage in the early stages of development. Large numbers of domestic biogas firms have stimulated competition in the market and led to sectoral development through establishing a dominant design (standardisation), technological standards and in turn generating a competitive emphasis towards cost, scale and product performance (Lacerda & van den Bergh, 2014). These features make the EU a global lead market: The market in which the diffusion of a dominant design first takes place (Utterback, 1994). Within the EU, Germany is the regional market lead and can be considered an innovation centre for biogas (France, Italy, UK, and Nordic countries such as Denmark and Sweden must be considered important market actors, too). It is important to mention that the lead market status for European biogas does not include household scale biogas technology, where China is the clear lead market (IEA, 2020a).

Biogas facilities in the EU are designed to take advantage of fiscal support measures set in place by national governments. In regions where there are generous support mechanisms, like high FIT rates, biogas markets have bloomed because biogas installations have been profitable as they take advantage of these support mechanisms. Because much financial support is gained from the feeding of electricity to the grid (through the increased revenue biogas plants receive per unit of electricity fed in), the plants have evolved to maximise this metric in order to subsequently maximise profits. Thus, biogas plants in Europe are purpose-built to match specific sets of incentives and are therefore often less profitable, or viable, in regulatory environments outside the EU. The case often is: The better an importing country's incentive structure matches that of the EU, the more economically viable European technology is. When there are large regulatory differences, systems must be (technologically and organisationally) adapted to fulfil a different set of context-specific needs.

Biogas generation technologies in the EU are predominantly biodigester systems using manure, farm crop waste, green waste, food-processing industry waste and household waste, and may also use intermediate crops (crucifers, grasses, etc.) and energy crops (corn, etc.) in closed tank digesters which may be stirred or unstirred. While three quarters of EU biogas is produced using AD (CSTR-type) systems, the remainder is split between landfill gas recovery systems (17%) and municipal wastewater (sewage sludge) conversion (8%). This is a good indication of the technology that exists in the EU as well as where incentive systems are directed by national governments in the bloc. Downstream processing of biogas, via the biomethane upgradation pathway, is concentrated in Germany (201 plants) and the United Kingdom (81 plants). As mentioned, the European biogas sector is geared towards electricity and heat production to reflect current incentive structures and market demand. Electricity only and CHP plants make up 36% and 64% of EU biogas plants respectively (EurObserv'ER, 2017).

The key stakeholders in the European sector are farmers and other feedstock suppliers, national government actors, universities and other academic institutions, and the EU. Each stakeholder group performs different activities in the biogas sector with academic institutions performing research and development of novel biogas technologies, the EU driving the standards and goals and providing much financial support to all levels of the biogas value chain, and

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national governments responsible for mandating policies such as fiscal incentives and waste management directives (EurObserv'ER, 2017). Table 7 displays the roles of key stakeholders involved in the EU biogas sector. Each role within this value chain may be conducted by an individual company or a single keyturn company may take a number of roles.

Table 6. Roles of stakeholders in the four key areas of the biogas value chain. Adapted from EurObserv'ER (2017).

Development	**Finance**	**Construction**	**Operating**
Identifying sites Securing the land Feasibility studies Administrative authorizations Energy sales contracts	Financial engineering Fundraising	Engineering Sourcing suppliers Project management Insurance	Asset management Production control Operating the installations Maintenance

4.1.3 Biogas research and innovation in the European Union

Innovation and research are processes that must precede the development of a technology to commercial scale. Biogas technology, like other technologies, spends a lot of time 'incubating' in laboratories and research institutions before they're picked up by stakeholders outside of the scientific community: Developers; financiers; constructors and operators. Due to historically strong research institutions - universities and government research centres - combined with sufficient funding programmes, the European research sector for biogas is world-leading.

Biogas research involves several fields of study. A combination of wet research and dry research constitutes the body of study that forms the knowledge precursors to biogas market growth. Microbiology and process engineering form the two main groups of research activities and, because of the diversity of fields that make up biogas-related research, collaborative efforts are key to technological progress. A study by Grando et al. (2017), which looked into the biogas research landscape of Europe, identified four key areas of research: (i) Analyses of case studies in order to better meet a country's needs; (ii) research associated with technological challenges designed to meet some requirement, such as comparing the efficiency of two feedstocks, evaluating co-digestion or looking at biogas purification methods; (iii) microbiological studies and ways of optimising the degradation of the raw material; and (iv) analyses of the carbon cycle, life cycle assessment and footprint. Area (ii) and (iii) form wet research areas, and (i) and (iv) from the dry side of research.

In the same study, authors found, through analysis of articles and patents published between 1990 and 2015, that research in the European biogas sector started to take off around 2000. The leading countries in research reflect the number of biogas plants within an EU country (Table 3), with Germany and Italy leading the field. In other words, the more active a country's biogas research sector, the more active its commercial sector. Biogas market-leading countries in Europe also show a sizable amount of cross-communication and collaboration in academic work.

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Interestingly, for patents, the EU counts for only 12% of total applications. China, Japan and the US accounted for 41%, 21% and 10% respectively: A distribution that does not correlate with today's biogas production capacity. Again, most EU applications were filed in Germany. There is around a seven-year lag time between the inflection points of biogas research and patent applications, signalling a lengthy time frame between innovation and commercialisation for biogas technology. With respect to this relationship between publishing literature and patent application, Germany has a clear industrial focus when it comes to biogas with the highest patent/article ratio in Europe (Grando et al., 2017).

4.1.4 Research and development of biogas technology

Research in the context of this study must be defined to allow for effective analysis. Here, research is considered to be the process by which technological change occurs. Technological change is a process often associated with or even synonymous to innovation, another term used frequently in this study. Further, technology is a broad category and due to this there is definitional ambiguity associated with this term (Bozeman, 2000). By definition, technology is the application of scientific knowledge to the aims of human life, often through manipulation of the human environment (Encyclopedia Britannica, 2020; Sahal, 1981). A common definitional consensus for technology is that it is a 'tool' designed to make human life easier and further human *utility*. Sahal (1981) explores how vague conceptualisations of technology can defy any useful operationalisation of technology research. To address this deficiency, technology-related research must begin with regarding technology as a phenomenon inherently dependent on a subjectively determined but specifiable set of processes and products. Technology, the object, is not merely a product, but is tied to configurations of knowledge and learning of its use and application (Bozeman, 2000). Utility here denotes satisfaction/pleasure and is often quantified by the ultimate metric of utility in today's society, money.

4.1.4.1 Biogas technology and technological readiness

Building on Figure 5, the technological readiness cascade can be utilised to analyse the effect of changing the context of a technology, suggest a binary grouping of research activities and pinpoint the areas of technological development that DiBiCoo seeks to facilitate.

When technology is imported/exported, it is often already of a high TRL and has been demonstrated to a level of full operation, as is the case for biogas technology. However, due to the fact that biogas systems are embedded in their respective operational environment, technical demand of a plant must reflect specific local conditions with regard to feedstock composition, supply structure, end user requirements financing mechanisms (De Rose et al., 2017). Thus, as is seen in Figure 11, the act of importing/exporting results in biogas technology dropping

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down around three levels of technological readiness. In other words, the ‘real world’ in which the technology must be demonstrated changes causing a TRL drop. It is this drop that DiBiCoo examines, ultimately aiming to facilitate the fast-tracked transition of biogas technology back to TRL 9 within this new ‘real world’. Meeting the needs of a local setting is on the one hand an intensive process, demanding research and technical adaptation on many levels. On the other hand, it represents an opportunity for biogas plants to fit into local systems with minimal disruption, solve multiple problems at once and may involve many local actors in an empowering, capacity building manner.

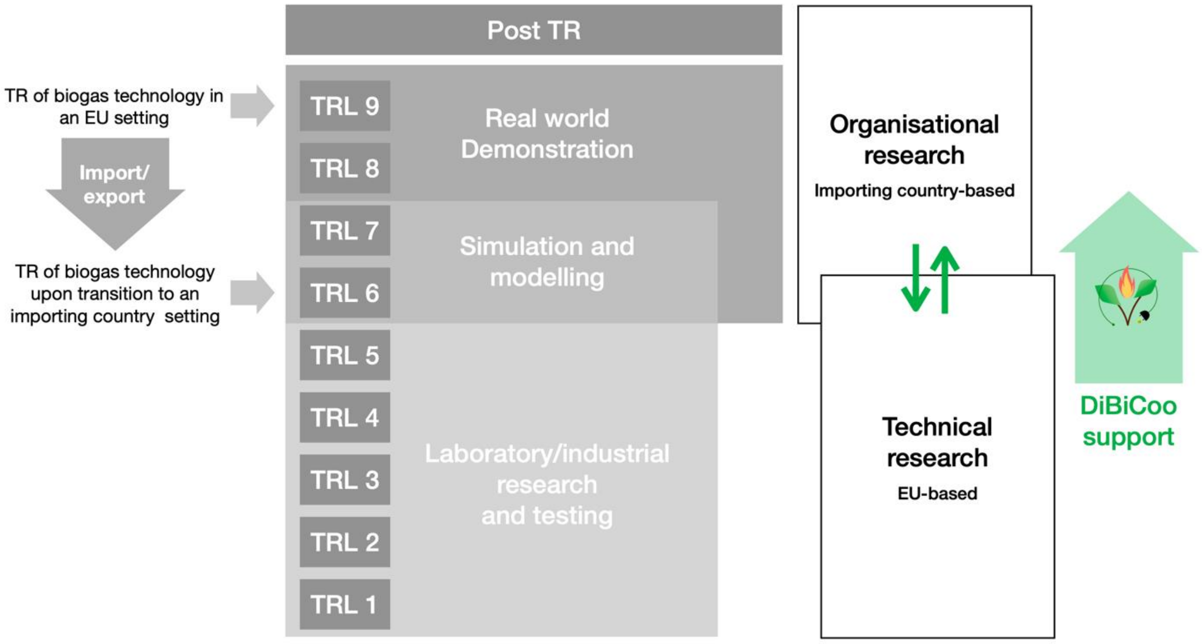

Figure 11. The relationship between technological research levels (left), technical and organisational research (right) and research context (middle). TR denotes technological readiness and items in green denote DiBiCoo-facilitated activities. Adapted from DiBCoo (2020a) and De Rose et al. (2017).

4.1.4.1.1 Organisational and technical research

For the purposes of this study, research activities will be split into two categories: Technical research and organisational research. *Technical research*, in the context of DiBiCoo and more generally biogas technology diffusion, is research carried out by companies or institutions with a high capacity for technical research, often situated in technology-rich regions. This research-type is referred to as technical adaptation within the wider DiBiCoo project and involves modification of parts, systems and unit operations to meet the needs of specific operational settings in importing countries.

Organisational research is the research and coordination required to develop a functioning and robust biogas value chain. This research is by its nature performed in large part by local actors in importing countries. While technical research is performed by researchers at an academic or industrial level, organisational research involves activities usually less associated with the term 'research'. This includes applied research such as commercialisation, the development of communication channels, capacity building and other activities related to the value chain rather than the technology itself. It should be noted that these two modes of research are not mutually exclusive and are inherently dependent on each other for successful biogas technology transfer. DiBiCoo's function within the project development pipeline involves characteristics of each category of research, as is denoted by the green arrows on Figure 11, which represent the cross flow of data, communication and intersection between these two research groupings.

The organisational and technical research commitment curves in Figure 12 display some important features of technical and organisational research in the biogas project development lifecycle. In the early stages of technology development (TRL 1 and 2), technical research is the main research activity, proving an innovation at a conceptual level in small-scale. The rise in organisational commitment comes when technical research institutions start to collaborate within their academic and industrial network to explore the commercial viability by cross validating and testing technologies with competing concepts and designs. Risk here is low and often contained within academic institutions.

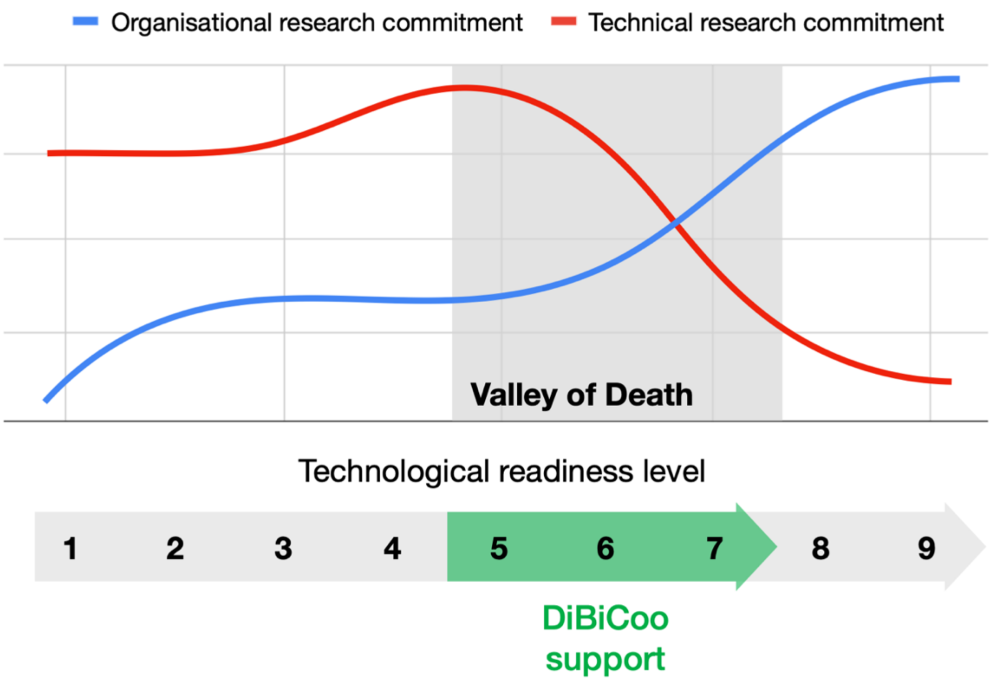

Figure 12.The contribution of technical and organisation research at different stages of the technological readiness pipeline. Adapted from National Academies of Sciences, Engineering, and Medicine, (2016). Technical research commitment curve derived from De Rose et al. (2017) and valley of death placement defined by Upadhyayula et al. (2018).

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Next, the technical research commitment increases (around TRL 3-5) due to the combined research efforts of industrial and academic research institutions. At these levels, biogas technology begins to move from the purely academic to a commercial sphere, demanding an organisational research commitment (Upadhyayula et al., 2018). This presents an issue due to academic researchers exhibiting a resistance to taking a technology or innovation outside of the laboratory and into unfamiliar, commercial territory (Huszár et al., 2016). At this stage (TRL 3-5) biogas technology undergoes significant development and technical adaptation to meet a specific context. This context can be in terms of feedstock, regulatory environment, end use requirements et cetera. Here the research load is weighted in technical areas which involves risk for those actors involved in technical research.

Afterwards, the curves converge and cross (at TRL 6 onwards) when technological adaptation is complete, and commercialisation begins. The commitment swings to organisational-type research due to a reliance on political, business and communication activities to collect relevant stakeholders for two principle reasons: (i) To collect capital to fund larger scale demonstration and eventual plant construction; and (ii) To assemble all relevant members of the value chain such as feedstock producers, plants operators, EPC firms, and end users.

At high TRL levels (8 and 9) most research is conducted in the organisational space due to the technical dimension of a project being demonstrated and validated in earlier levels and the high degree of organisational complexity involved at this stage. Risk here is shifted to commercial stakeholders, where large sums of capital are mobilised to fund construction activities (De Rose et al., 2017).

4.1.4.1.2 The valleys of death

The organisational and technical research commitments in TRL progression can be examined relative to the 'valley of death', a phenomenon that is defined as the challenge of moving a technology from concept in the laboratory to reality in use (National Academies 2016 p20).

The 'valley of death', which spans from TRL 5 to 7 in Figure 12, covers the stages of technological development where there is a shift in technical to organisational research commitment. As the commitment shifts, the risk of a project switches hands, leading to many projects collapsing at this pivotal stage. Upadhyayula et al., (2018) splits this 'valley' into two stages, the technology valley of death (TVD), at TRL 5 and 6, and the commercialisation valley of death (CVD), at TRL 7. The 'death' in the TVD levels in part originates from insufficient dialogue between academic (technical) and commercial (organisational) actors, a social phenomenon that has to be considered in any technology development process. The CVD is characterised by the difficulties associated with securing the required capital for these stages of technological readiness. Commercial viability and return on investment (ROI) are buzzwords in this valley and research such as technoeconnimc analyses through robust modelling based on pilot scale data is key to gaining financial confidence to progress past the CVD. Modelling and simulation

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research areas form a large intersection of organisational and technical research (seen in both Figure 11 and Figure 12 as the curves intersect around TRL 7). The capital required to cross TRL 7 and the CVD is often obtained through private equity or debt financing i.e. loans from banks (Jenkins & Mansur, 2011). Important factors here are financer confidence and risk minimisation, a pressing issue in developing and emerging economies with unstable financial sectors.

As displayed in Figure 12, DiBiCoo operates almost precisely within the technological and commercial valleys of death. This is a turbulent stage of technological development but essential to bring biogas systems to commercial scale. Though proving commercial viability can take five to ten years, a strong knowledge of financing mechanisms and best practises within DiBiCoo can fast track this process (Jenkins & Mansur, 2011).

4.1.5 Technology diffusion

Building on the introduction of Roger’s theory of technology diffusion in Technology diffusion models, the following section aims to frame this foundational theory in the context of DiBiCoo and its partner countries.

The study of renewable energy technology diffusion is a market-specific, multidimensional field which combines elements of many disciplines including economics, policy and governance, engineering and the social sciences (Rao & Kishore, 2010; Lacerda & van den Bergh, 2014; Kumar & Agarwala, 2016). Renewable energy technology diffusion is an emerging field becoming more prominent as social and political momentum builds in the direction of systemic sustainable transition (Lacerda & van den Bergh, 2014). Renewable energy diffusion studies seek to find the socioeconomic, technological and institutional factors that promote market acquisition within a time horizon that aligns with global and regional decarbonisation targets (2050 in the case of the Paris Climate Agreement). This field is of vital strategic importance to governments and multilateral organisations given the insufficient diffusion of renewables in the global energy system required to meet these stated targets. Diffusion theories will be employed in this study to propose the trajectory of biogas technology adoption in partner countries, examine the role of different stakeholders in effective diffusion and the influence of research and technical adoption on biogas technology diffusion.

4.1.5.1 The diffusion of biogas technologies

The application of Roger’s theory of diffusion of innovations (DOI) to industrial biogas technology is largely absent in literature. While a number of studies exist that apply elements of Roger’s theory to domestic scale biogas diffusion in developing regions (Gu et al., 2016; Mwirigi et al., 2009; Peipert et al., 2008; Putra et al., 2019; Yasmin & Grundmann, 2019), few

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studies look at industrial scale biogas technology diffusion, with these studies often being applied to European contexts (Bartolini et al., 2017; Lybæk et al., 2013). This gap - that is, the application of Roger's theory of innovations to the diffusion of industrial scale biogas in developing and emerging economies - is the focus of this section.

Biogas technology, and the nature of its diffusion, is seen to behave in accordance with Roger's theory on a national level. Figure 13 illustrates the diffusion and adoption curves for biogas plants in Germany over a 27-year period.

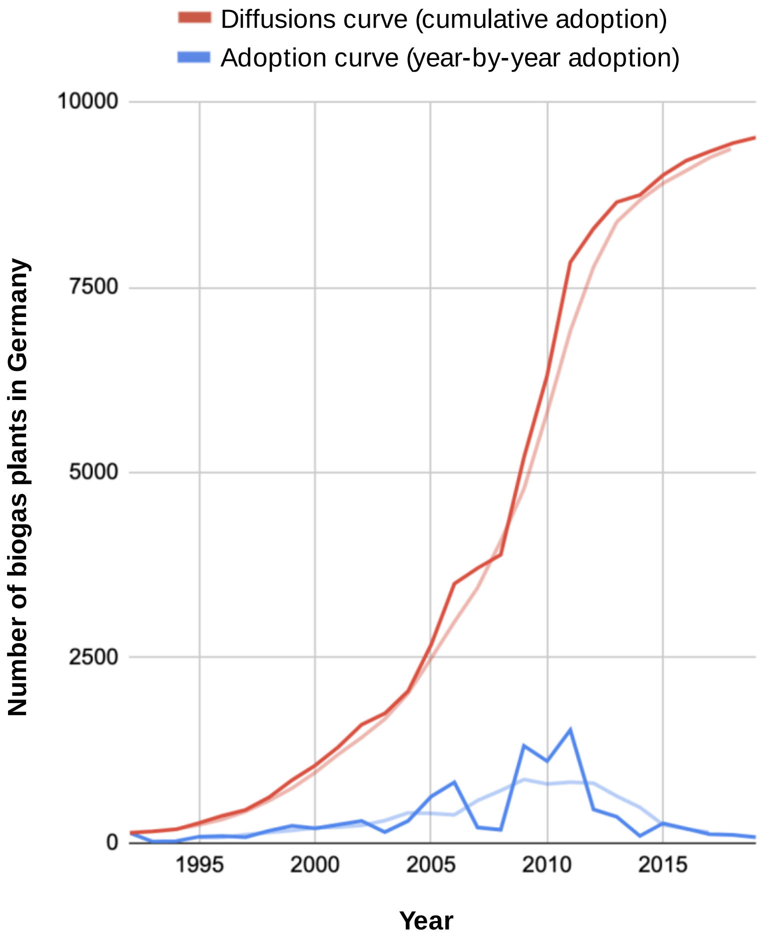

Figure 13. Diffusion curve for biogas plants in Germany, 1992-2019. Adapted from German Biogas Association (2020).

There are three characteristics of Germany's biogas diffusion curve that are important to the present discussion. First, the sigmoid and bell-shaped curves for diffusion and adoption respectively reflect those presented in Figure 6. This likeness stands as the basis for the assumption that industrial biogas technology behaves in a manner that is aligned with Roger's DOI theory and thus can be analysed using this theory. Second, the inflection point, where industry learning leads to reduced costs of technology and new user segments begin to adopt

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biogas technology, is an important point in any technology diffusion process. Here, a critical mass of adopters at a point between 10-20% market saturation presents a tipping point where technology can either reach exponential phase or slump and fail to diffuse effectively. This critical mass is an important focal point for biogas technologies in emerging markets and should not be overlooked by policy makers and other parties interested in the diffusion of biogas technology to its technical or incentivised potential (Rogers, 1995, p. 304). Third, market capacity (the asymptote to which diffusion slows towards the end of the diffusion process) is an important and complex phenomenon when it comes to biogas technology. This market capacity is determined by a number of forces which are explained below (Lybæk et al., 2013).

4.1.5.1.1 Biogas technology diffusion rate

Diffusion curves can be useful when predicting the growth of an emerging market, especially when a specific rate of diffusion is required to meet a given objective such as a decarbonisation goal. Once an endpoint (market capacity) is established, a target rate of diffusion can be set and strategies to achieve these goals can be formulated.

Diffusion rates of biogas technology through a social system are variable and determined by several factors related to both the technology itself and the social system in question. Figure 14 illustrates two scenarios (B and C) of faster and slower diffusion rates, both to the same level of market share.

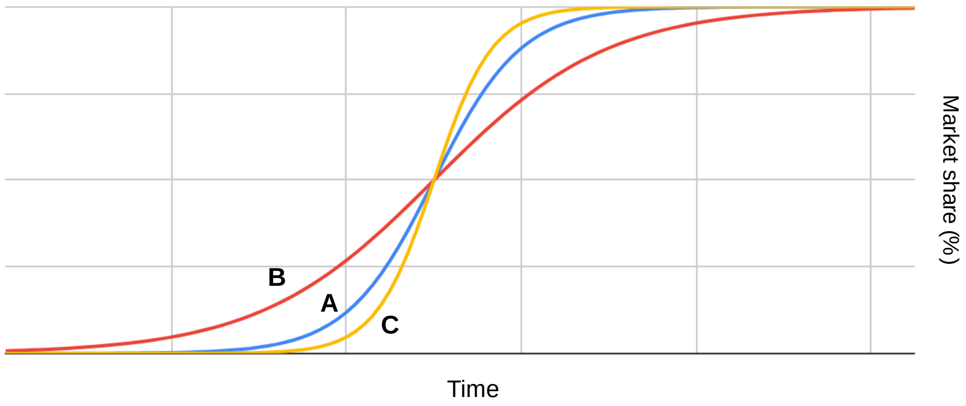

Figure 14. Diffusion curve for differential diffusion rates. A: Baseline diffusion curve; B: Slower rate of diffusion; C: Faster rate of diffusion. Adapted from Rogers (1995) p. 11.

Though diffusion rates cannot be determined by finite criteria due to their complex and socially embedded nature, two contributing factors, or groups of factors, are assessed in this study. These two groups of factors are characteristics of technology (how technology is perceived by

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the social system) and the decision-making unit (the traits and social norms of sector actors in a social system). These are summarised in the context of industrial biogas technology in Table 7.

Table 7. Decision making and technological characteristics that influence technology diffusion rate. Adapted from Rogers (1995).

Diffusion rate contributing factors		**Definition in the context of industrial biogas technology**
Characteristics of decision making (Rogers 1995, pp. 251-263)	Socioeconomic characteristics	The age, education/technical capacity, upwards social mobility, status, affluence, commercial orientation of biogas technology adopters.
	Personality variables	The level of empathy, dogmatism (resistance to change), attitudes towards sustainability and international collaboration, political and religious beliefs etc.
	Communication networks	The social participation (through personal, commercial or institutional channels) and interconnectivity of decision-making units.
Technology characteristics (Rogers 1995, pp. 15-16)	Relative advantage	The degree to which imported biogas technology is seen as better than the technology that it succeeds (other waste management methods, fossil fuel power plants etc.). Relative advantage can be measured in different ways by different stakeholders. Subjective advantage does not differ from objective advantage.
	Compatibility	The alignment of biogas technology with the existing values, socioeconomic norms, technical infrastructure, human capacity or policies of an importing social system.
	Complexity	The degree to which biogas technology is perceived as difficult to understand, use, integrate, maintain and operate.
	Trialability	The ability to trial/pilot biogas technology in a given context - an important part of the technological readiness cascade.
	Observability	The degree to which the results and advantages of biogas technology are visible.

Characteristics of decision-making are directly related to the user segments illustrated in Figure 6. Given that the biogas markets in biogas technology importing countries are in their infancy, innovator and early adopter user segments are active social groups in these markets. The ‘decision-making units’ in the instance of industrial biogas technology are often commercial agriculture stakeholders, institutions, municipalities and private operators. These units are complex groups in and of themselves but must be thought of as possessing an emergent set of collective characteristics for the purposes of analysis here. Research suggests that these units of adoption (innovators and early adopters) possess higher levels of wealth, education, social status, commercial orientation, empathy, affinity to accept change and interconnectivity than the early and late majority and laggards (Rogers 1995, pp. 251-252). Although there is a correlation between these characteristics of decision-making units and the affinity to adopts biogas technology, this relationship is not considered causal. In the context of DiBiCoo, where technology is transferred between social systems, the personal characteristics of industrial biogas innovators are of high importance. The homophily (character likeness) between importing and exporting actors must be recognised as a strong ground for collaboration: An effect that may promote technology discrimination, especially in importing countries with high wealth inequality.

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Biogas is a complex and difficult-to-perceive technology, particularly to those without backgrounds in process engineering or biogas (groups who make up only a small portion of the stakeholders involved in the industrial biogas market). For this reason, the well/poorly understood characteristics of industrial biogas technology are vital areas of analysis and development for promoting effective technology diffusion. Research suggests that technologies and innovations that are seen to possess greater relative advantage, compatibility, trialability, observability, and less complexity will be adopted more rapidly than others (Rogers 1995).

Another technology-based factor that influences the rate of technology diffusion is experience or learning. Learning curves occur over time when a technology is better understood as experience with that technology is increased. This is especially relevant in the case of industrial biogas, where installation and technology integration into a wider system is important for effective technology diffusion. Learning curves manifest in cost reductions and process efficiency increases over time, and thus contribute to the inflection point (point where diffusion rate increases) seen in the diffusion curves (Kampman et al. 2017 p. 54). The earlier this inflection point occurs - a factor that is inherently linked with the technology push policies described below - the faster the diffusion process may proceed.

The relationship between the variable diffusion rates illustrated in Figure 14 and the decision-making and technology characteristics described in Table 7 are incorporated in the methodology (the coding approach outlined in Table 5) in the present study and form the basis for research need prioritisation discussed in

4.1.5.1.2 Biogas market capacity

Biogas markets, like other renewable energy technology markets, are controlled and determined by the level of demand-pull and supply-push policies that exist within a national market. These policies, largely established in developed regions of the world, have accelerated renewable technology markets by providing stimulus and protection from competition. With somewhat of a debate surrounding the benefits of push versus pull policies, a heterogenous set of policies exist in many nations today to promote renewable energy technologies. Supply or technology-push policies presume that the rate and direction of innovation is triggered by the supply side, i.e. through advances in technical research and development investments. Demand-pull policies on the other hand are designed under the assumption that technological change is induced by anticipated changes in market demand. Examples of demand-pull policies include FITs, fiscal incentives such as tax credits and rebates, and public finance policies such as low-interest loans. The research consensus suggests that a combination of these two angles of support must exist simultaneously for strong sector growth (Aflaki et al., 2014).

Different renewable energy technologies demand different levels of fiscal policy support due to their variable operating costs, economic viability and market demand. Albrecht et al. (2015) studied the pull/push ratio of certain renewable energy technologies in Europe and the lag time

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between supply pushes (research and development spending) and market impact or deployment. The pull/push ratio - that is, the ratio of annual spending on demand pull to demand pull efforts - elucidates important features of biogas technology incentive structures. While wind and photovoltaics (PV) possess pull/push ratios between 100 and 210, biogas possesses a pull/push ratio between 700 and 1200. This shows that biogas technology, as a renewable electricity source, demands high sums of demand-pull economic stimulus (most in the forms of FITs in the EU) to allow projects to compete under free market conditions.

The dependency of biogas technology on demand-pull policies can be seen when looking at the German biogas diffusion curve (Figure 13) and relating certain features - rapid diffusion and slowing diffusion - to certain demand-pull policies. At the time of rapid diffusion (2006-2012), Germany had a 20-year FIT guarantee and bonuses for emission reduction, utilising certain feedstocks, and heat and power generation. The point at which new biogas installations began to slow (2014) coincides with the abolition of FITs and the introduction of an overall less generous and protective tendering model (Eyl-Mazzega et al. 2019).

Two observations can be drawn here from the above: (i) Biogas markets are dependent on fiscal demand-pull incentives; and (ii) Market growth or decline correlates with the presence or absence of demand-pull policies. These relationships are true only for a European context but, given that European industrial biogas markets are the most developed globally, provides a valuable model to predict how and why biogas markets may0 grow in emerging economies.

Figure 15 illustrates several scenarios for differential market capacities on the diffusion curve. With a baseline market capacity (A), industrial biogas markets may either be greater (B), lower (C) or lost (D) as a result of two principal factors. First, as explained above, demand-pull policies have a great influence on the size of the artificial market created. Through mechanisms such as quotas and quantitative goals, governments can set a policy-mediated trajectory towards a given market size. Second, the quality, quantity and mobility of feedstock that is present and available to a biogas sector is also a determining factor for biogas market capacity. Scenario D presents a reduction in market capacity as a result of the discontinuance of industrial biogas plants. In the framing of the two aforementioned factors, discontinuance can occur through the abolition of the demand pull incentives that economic viability of plants relies on or a reduction in feedstock supply.

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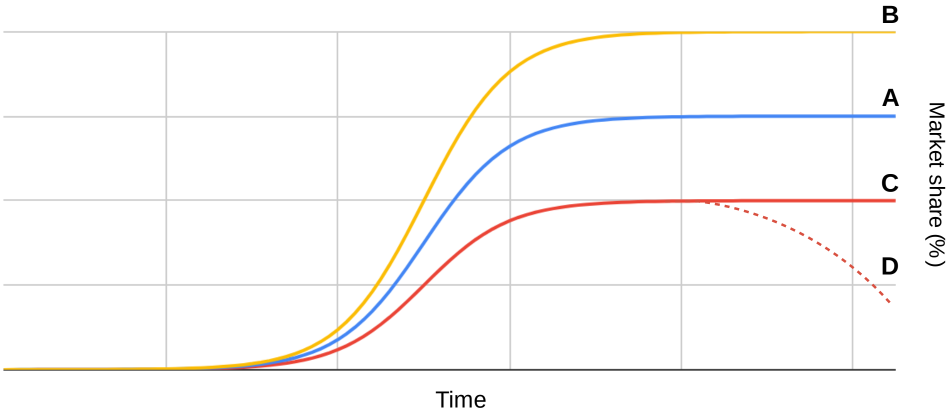

Figure 15. Diffusion curves for differential market capacities. A: Baseline diffusion curve; B: Greater market capacity; C: Lower market capacity; D: Substantial loss of market.

4.2 Results

4.2.1 Barriers matrix

The barriers matrix is an organised set of barriers to biogas market growth in Argentina, Ethiopia, Ghana, Indonesia and South Africa. These are considered for the purposes of this study to be a representative sample of the world's emerging and developing countries. General themes and recommendations of research to promote biogas sector growth in emerging economies are given below.

This matrix uses a colour coding system to express whether a specific barrier can be addressed directly, indirectly or cannot be addressed by research. Red denotes macro-barriers that are outside of the reach of research and technical adaptation; orange denotes barriers that can be influenced (indirectly addressed) by research and technical adaptation; green denotes barriers that can be directly addressed by research and technical adaptation

Description of Y-axis categorisations:

- **Decision making characteristics** include human characteristics such as personality, communication and technology/value chain-unrelated socioeconomic barriers as well as capacity building-related barriers.
- **Technology characteristics** include barriers relating to biogas technology itself: Relative advantage; compatibility; complexity; trialability; and observability.
- **Value chain** includes barriers related to aspects of the value chain: Input; output; logistics; maintenance; and operation.

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Table 8. Barriers matrix. Red denotes barriers that cannot be addressed by research and technical adaptation. Green and orange denote barriers that can be addressed directly and indirectly by research and technical adaptation respectively.

	Economic		Technical		Sociopolitical	
Decision-making characteristics	🟥	Unstable electricity price increasing risk of biogas investments	🟩	Lack of biogas technology importing country technical capacity to handle complex imported systems	🟥	Geographical distance between technology importing and exporting countries creates logistical issues for cooperation
	🟥	Biogas plants are high-risk investments	🟩	Absence of training opportunities to build regional technical capacity to meet the operational needs of imported biogas technology	🟩	Poor or unestablished regional biogas networks resulting in a lack of industry communication, knowledge sharing and common vision
	🟧	Minimal focus on business activities when establishing a project			🟧	Lack of biogas trust between private companies for information/knowledge sharing
	🟥	Normative financing systems varies between technology importing and exporting regions			🟧	Absence or lack of enforcement for governmental incentive schemes/regulatory framework supporting biogas projects
	🟥	Local currency is weak, and fluctuating compared to the Euro, increasing economic risk for imported technology			🟧	Lack of industry willingness for collaboration
	🟧	Without local technical human capacity, the first biogas plant is considerably more expensive to establish than proceeding plants			🟧	Lack of specific governmental objectives for biogas contribution to the energy mix or within decarbonisation targets
	🟧	Imported biogas parts and systems are too expensive for a developing country context			🟥	History of dependence on aid and NGO involvement with limited alignment to private sector objectives i.e. profitability and maximal returns
	🟧	Lack of funding to develop regional technical capacity for large scale biogas facilities			🟥	Human development issues are prioritised on a governmental level
	🟧	Reliance on expensive, high interest bank loans to finance large-scale projects			🟧	Perceived trade-off for private biogas companies between maintaining competitive advantage and encouraging sector growth through knowledge sharing
	🟧	There is a demand for higher returns from biogas plants in the absence of incentive scheme			🟧	Absent or underdeveloped national private sector resulting in limited market competitiveness and low industry confidence
					🟧	Lack of synchronised and centralised training policy and programmes from the government

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					🟧	Exporting country technology suppliers perceived and inflexible
					🟥	Changing skill set of workers coming into the biogas sector (new emphasis on automation, and computer science)
					🟧	Social resistance to change, inherent support to maintain well-understood, status quo technology
					🟥	Multiple national languages inhibit knowledge diffusion pathways
	Economic		**Technical**		**Sociopolitical**	
Technology characteristics	🟧	Biogas plants do not operate at a profit; generally poor economic performance from operating facilities	🟧	There is a lack of locally sourced parts and components creating dependency on imported parts	🟧	Imported technology has a poor reputation from past experiences
	🟧	Positive economic performance for imported technologies is not visible/demonstrated to private and especially government biogas stakeholders	🟥	Biogas technology must be adapted for every new project, creating a great and unmet research demand	🟧	Limited political recognition of biogas technologies
			🟩	Spare parts for imported biogas technologies are difficult to source	🟩	Lack of biogas technology demonstration and visibility to governmental stakeholders and financers
			🟩	Imported biogas technology does often not meet (importing country) consumer's needs in terms of price and operation	🟧	Biogas technology is societally perceived as complex and high risk
			🟩	The first plants to be established in biogas technology importing countries encounter many technical problems	🟥	National government lobbying against biogas technology imports, prioritising local technology
			🟩	Imported biogas technology is not adapted by suppliers to meet the needs of consumers and is therefore poorly integrated into a new context	🟥	National strategy focused on household scale biogas technology
			🟥	Competition (for imported technology) from regional plant designs		

			🟧	Biogas systems are perceived as more technically complex systems compared to competing renewable technologies		
	Economic		**Technical**		**Sociopolitical**	
Value chain features	🟧	Land fees issues for new biogas developments	🟥	Unreliable electricity supply threatens continuous plant operation	🟧	Regulatory barriers to feedstock utilisation
	🟧	Imported maintenance (for imported technology) is too costly	🟥	Poor, unreliable and low-coverage national electricity grid (for plant operation and offtake needs)	🟧	Cultural acceptance issues for using human waste as a feedstock for biogas production
	🟥	Low market demand for electricity	🟧	Complex pathway, including many stakeholders for electricity feed into the national grid	🟧	Employment guarantee for new biogas projects required for governmental support
	🟧	Cost of electricity production from biogas is too high	🟧	Inefficient and inconsistent feedstock mobilisation pathways (e.g. poor wastewater infrastructure)	🟧	Regional utility company and off takers are difficult to work with
	🟧	Digestate is underutilised as a revenue stream	🟧	Feedstock is poor in quality, varying greatly from feedstocks in exporting countries		
			🟧	Lack of technology available to utilise all biogas products (digestate, heat, gas and power)		
			🟥	Biogas plants involve more complex value chains than other renewable energy technologies, reducing their competitive advantage as power producing technologies		
			🟧	Dependency on imported technical knowledge for imported technology maintenance		
			🟧	Lack of maintenance infrastructure for imported biogas technologies		
			🟧	Lack on infrastructure to utilise gas and biogas products		
			🟧	Logistical problems for feedstock mobilisation resulting from varying scales of agricultural production (smallholder and industrial agriculture)		

The barriers matrix is a collection of stakeholder-generated barriers to industrial biogas market growth in the five aforedescribed partner countries. An extended methodology of how quantitative data was processed to arrive at these barriers is given in Appendix 6. This approach is aligned with but not synonymous to the open coding approach described in the methodology. Revisions to the methodological workflow described in Figure 8. are described in Appendix 6, which led to the barriers matrix generation process differing from the originally intended method.

The two axes of categorisation were selected so that the information contained within the matrix can be quickly selected to meet the needs of a reader. The X-axis relates to generic and well understood groupings (economic, technical and sociopolitical barriers). The Y-axis reflects categories that have emerged from the theory presented in the present study (Roger’s DOI).

After the initial collection of statements from interviews (described in Appendix 6), Argentinian, Ethiopian, Ghanaian, Indonesian and South African barrier-statements comprised 8%, 24%, 21%, 9% and 38% of total statements respectively. It must be noted that this is prior to collecting and reframing statements. Therefore, these relative contributions are only indicative of the contribution of each region to the final barrier matrix.

As expected, the large part of barriers that can be directly addressed by research (labelled green) are technical. Research often has indirect or no effects on economic and sociopolitical barriers. This is thought to be because results of research in economic and sociopolitical areas, though useful, do not manifest in a tangible or easily recognisable result (as is the case with technology-related research which will produce a new or improved piece of technology). Further, economic and sociopolitical barriers are often systemic and outside the scope of what can be influenced by research. Interestingly, value chain-related barriers are largely indirectly affected by research and technical adaptation.

4.2.2 Research needs matrix

The research needs matrix was constructed according to the methodology presented in Figure 8. While the X-axis categorisations are the same as the barriers matrix as to allow comparison between two matrices, the Y-axis uses the two research categories explored using open coding and defined in Biogas technology and technological readiness in terms of TRL. Argentinian, Ethiopian, Ghanaian, Indonesian and South African research-statements comprised 19%, 24%, 17%, 12% and 28% of total statements respectively.

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Table 9. Research needs matrix.

	Economic	Technical	Sociopolitical
Technical research	Demonstrate economic viability of biogas projects through region-specific technoeconomic analysis and feasibility studies to support financial aspects of biogas and stimulate government support	Perform specific regional research on feedstock quality and availability (as to best understand regional supply and demand)	Knowledge of plant functionality (generated through technical research) must be included in government selection criteria for incentive development
	Perform context-specific feasibility studies to support financial aspects of biogas and boost financial confidence in biogas technologies	Balance local and imported sourcing of parts by using local parts where possible	Promote regional knowledge transfer for new parts and technologies
		Promote the development of methane capture for plants focused solely on the sanitation function of biogas technology	
		Perform specific regional research on digestate processing and application (as to best meet regional demand)	
		Perform specific regional research on biogas upgrading options (as to best meet regional demand)	
Organisational research	Create programmes to improve national commercial expertise for biogas projects specifically (such as promoting economies of scale and fixing costs to mitigate risks from currency fluctuations)	Increase the observability of feedstock pretreatment options	Governmental research to build organised constitutional support in the form of fiscal and regulatory incentives
	Develop government support mechanisms to encourage low interest credits from banks for biogas investments	Prioritise the internal or localised utilisation of biogas products (biomethane, electricity, heat and/or digestate)	Research to boost the visibility of (imported) biogas technology and its economic and process-level advantages in order to improve biogas sector reputation and confidence

	Economic	**Technical**	**Sociopolitical**
Organisational research	Promote an industrial focus on multiple revenue streams to maximise economic performance of a pant	Provide technical training with a single, nationally agreed curriculum to meet technical capacity demand to operate and maintain imported biogas facilities	Create the regulatory and business conditions to incentivise private sector development
	Research to identify price-appropriate technology for a regional context	Create and promote biogas technology-related courses at national universities	Shift in the normative framing of biogas technology (to governmental stakeholders) as a waste management technology not a renewable power production technology
	Make financing resources visible by creating and promoting financial networks	Create mechanisms to enforce training by exporting firms in order to ensure the sustained operation of biogas plants	Biogas technology firms looking to export must perform customer-oriented research into regional setting
	Firms exporting biogas technology must research and gain understanding of local business conditions	Minimise the dependence on imported technical knowledge by regional training programmes and knowledge/experience sharing mechanisms	Organisational research commitment to build institutions (such as biogas associations) to support and stimulate policy reform
		Demonstrate advanced biogas technology through visibility programmes thus justifying the trade-off between reliability/performance and elevated prices for imported technology	Develop mandated policies for feedstock producers to build biogas plants for effluent treatment streams in agro-processing industries
		Ensure that warranties and guarantees are provided for imported biogas technologies as a standard practice	Develop and effectively enforce governmental mechanisms for policy adherence
		Promote national biogas firms to control the entire value chain as a best practice	
		Requirement for standardised penalties and guarantees from feedstock providers/offtakers	

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4.3 Discussion

4.3.1 Research needs prioritisation

The prioritisation process is the final stage of the methodological workflow (Figure 8). It employs the open coding approach outlined in the methodology to systematically code the transcribed interviews and in turn elucidate the relative importance of research needs to biogas importing markets. An extended methodology for data processing is described in Appendix 6. Figures 16-18 present code abundance data. This is the prioritisation of the research methodology, pointing towards research areas that are most important to emerging economy stakeholders.

Organisational and technical research needs

From Figure 16, it can be seen that when research was discussed, organisational research tended to be discussed more than technical research. This result can be seen to exist independently of interviewer bias given the even proportion of technical and organisational research suggested in the interview questions. This focus on organisational research from interviewees is consistent with the differential contribution of research types through the technological readiness levels. Due to interviews tending to cover the future of a region’s biogas market, the latter TRLs within which organisational research commitments are greater (Figure 12) was the focus of discussion. This data suggests a willingness for developing regions to engage in organisational research: An expected result considering the inherent reduction in technical demand when technology is imported.

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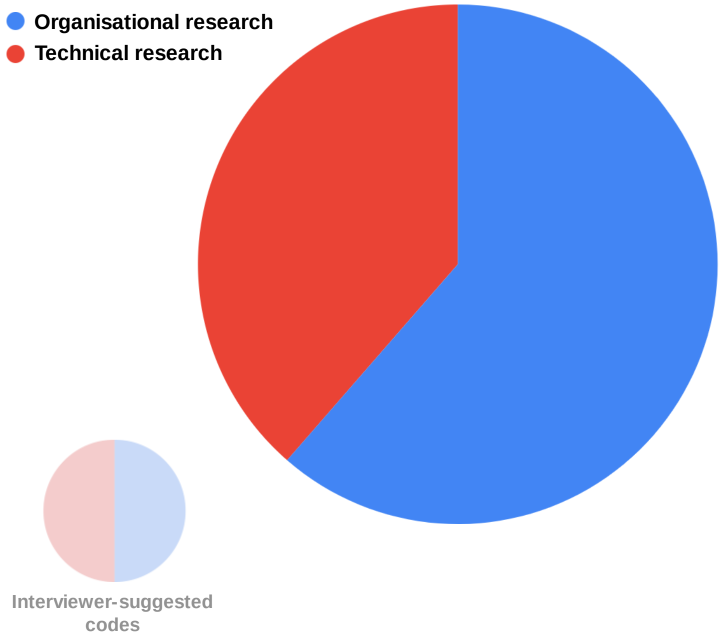

Figure 16. Code abundance for technical and organisational research codes in interview answers. Full colours in the large pie chart denote code abundance in interviews (interviewee-suggested codes). Faint colours in the small pie chart denote code abundance in the question guide (See 0 for an extended methodology for processing open coding data).

Decision-making characteristics

Decision-making characteristics are factors relating to the interpersonal features of units of adoption. As can be seen in Figure 17, communication networks were the most frequently discussed decision-making characteristic in interviews. This is especially evident in comparison with the interviewer-suggested codes (Figure 17, bottom left). These statements were in large part negative, a feature that should be expected for all codes given that barriers will introduce a negative direction to interview conversations. Though it was expected that solution-oriented conversation would ensue the barrier suggestion, the case was often that the subject of barriers tended to be the focus of discussion despite efforts to steer the interview in the ‘positive’, solution-oriented conversation. What can be used for comparison here are the relative proportions of positive codes rather than the proportion of positive to negative codes. A greater proportion of communication network statements were positive than for other decision-making characteristics. This is reflective of the enthusiasm within stakeholder networks consisting of the early adopter user segments. The early adopter user segments (the segment most involved in biogas sectors at the early stages of development) are more likely to be engaged in social networks that include both innovators and the early majority (Rogers, 1995). Communication networks were discussed in each interview and brought up independently of interviewer questions (Interview 1-5). Communication between the EU and emerging countries, especially on a technical education level was generally perceived to be underdeveloped and essential for successful biogas technology transfer (Interview 1 & 3). Internal biogas

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communication networks were also described as underdeveloped, especially between private and public biogas stakeholders (Interview 1-4).

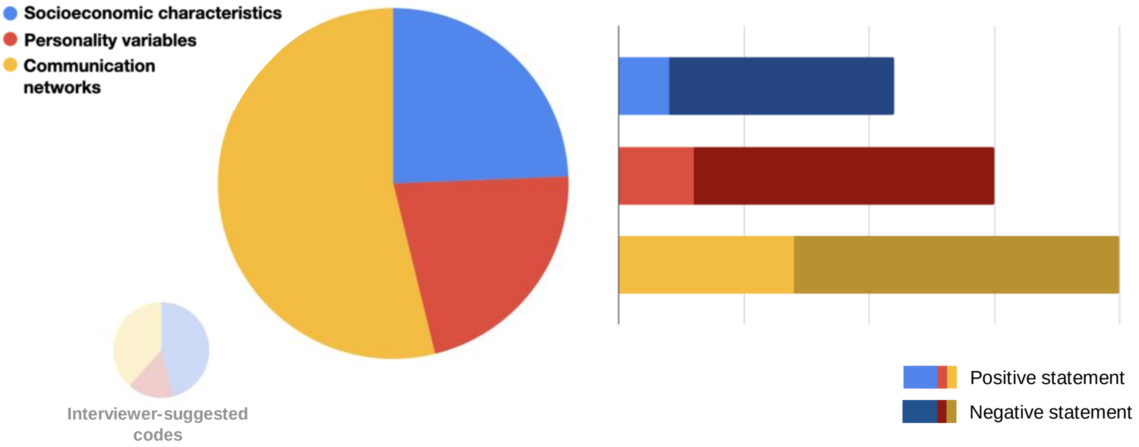

Figure 17. Code abundance of decision-making characteristics codes. Pie chart (left) displays abundance of each code in interview answers. The faint pie chart (bottom left) shows the interviewer-suggested codes (the standard for comparison). Bar chart (right) displays the distribution of positive and negative statements. It should be noted that because some comments are neutral the bar chart and pie chart will not match in terms of code proportion. See Appendix 7 for extended open coding methodology.

The remainder of codes are split fairly evenly between socioeconomic characteristics and personality variables, both of which were spoken about in a more negative manner than community networks. Again, despite all barriers being discussed with a focus on solutions (research needs), interviewees would often frame comments on aspects of their biogas sector in a barrier-context. This factor may suggest that solutions are not readily known to interviewees due to a lower technical capacity (problem solving capacity) in emerging economies, but this can only be a speculation until more research confirms this fact.

Technology characteristics

Figure 18 presents the relative abundance of technology characteristics. This is a valuable resource given its ability to elucidate the characteristics of biogas technology that regional stakeholders believe will improve technology diffusion. This information suggests the desired direction that the development of European biogas technology should take before being imported successfully.

The first important feature of Figure 18 is the relative importance of compatibility. Though this result is likely influenced by the emphasis on compatibility-related issues originating from the interview questions (bottom left), these issues can still be considered the most important

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feature of imported biogas technology from an emerging economy's standpoint. Compatibility includes the ability of EU biogas technology to meet the needs of government targets and policies, as well as technical aspects of technology in a developing region. This results in a priority need for research that can increase compatibility in two principle ways: One is to create and export more appropriate biogas technology. The other is to raise an emerging region's technical capacity so that their biogas market can uptake a wider array of technology.

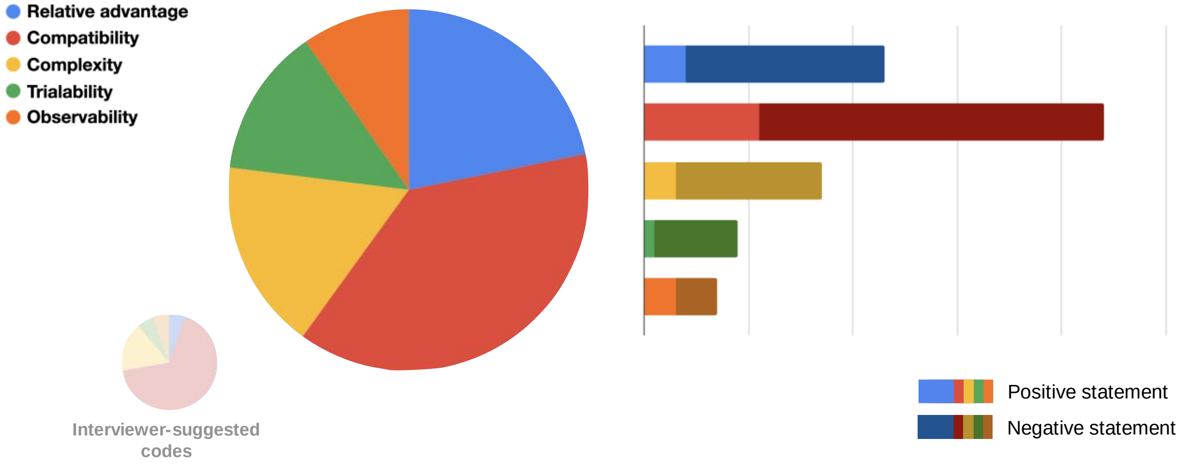

Figure 18. Code abundance of technology characteristics codes. Pie chart (left) displays abundance of each code in interviews. The faint pie chart (bottom left) shows the interviewer-suggested codes. Bar chart (right) displays the distribution of positive and negative statements. It should be noted that because some comments are neutral the bar chart and pie chart will not match in terms of code proportion. See Appendix 7 for extended open coding methodology.

More export appropriate technology can be developed through EU biogas suppliers (technical researchers) working with reliable databases and independent reviews of market conditions in developing regions (organisational research). Specifically, this may take the form of developing plants that at more focused on the sanitation function or digestate side of biogas production to match demand (Interview 1 & 3). The second compatibility-raising mechanism is the need for increasing regional technical capacity to create a regional labour force that can maintain and operate European biogas technology (Interview 1-5). This can increase the compatibility of EU technology without adaptation of the technology itself, while improving local conditions in emerging economies. Of the two aforementioned ways of increasing compatibility, the latter is preferred on a social level.

The sanitation function of biogas plants can be seen to have been overlooked by the EU biogas market because of a market dependence on FITs (promoting electricity production rather than sanitation performance). This is perhaps reflective of an EU demand setting, where ample sanitation systems are already established. For emerging economies however, sanitation systems are often not developed and are in high demand. This is the case in Ghana, where biogas is often not utilised because sanitation is the primary function of the plants, and Indonesia, where the palm oil industry creates a high demand for sanitation of palm oil mill effluent streams (Interview 1 & 4).

The relative advantage of imported biogas is the second most abundant code, with the majority of statements being negative. Codes were often logged when an interviewee was describing European biogas technology relative to local technology, with failures making more of an impression than success stories (Interview 5a). European technology was at times not successful due to a lack of adaptation to fit a local setting. Biogas stakeholders in Ghana for example have begun to develop a regional design that resembles septic tanks that are ubiquitous, locally sourced and well understood by local engineers and technicians (Interview 1). Competition can be seen as a positive force in any market as it increases the functionality of a technology while decreasing price as competitors try to gain an advantage. Though it may be reflected in the 'negatives' in this research, competition is a welcome and productive driver of adaptation and research. In countries where there is no competition for industrial biogas facilities, such as Ethiopia where there is currently only one private biogas company, there is a great risk of biogas investors overspending on inappropriate technology due to the fact that there is no industry standard (Interview 2a & 2b). This must not be overlooked by regional decision makers looking to develop a nascent or non-existent industrial biogas sector.

Trialability and observability are two features of technology that are interrelated in the case of industrial biogas. In early stages of sector development, where many decisions are being made by potential adopters, trialability and observability are invaluable mechanisms to increase awareness and trust in the performance of technology. This highlights the importance of successful pilot projects and first movers in the sector to create a positive image for imported technology (Interview 1-5).

Complexity is another important factor for the diffusion of a technology. For interviewees, the inability of local technicians to maintain complex European technology presented a significant barrier (a factor that ties in with compatibility). Suggested research needs for this issue again come from two forms, one from the importing region and one from the exporting region. In importing regions, education and training can improve local capacity, allowing regional stakeholders to successfully adopt, maintain and operate more complex technology. From the exporting market side, exporting labour is an option. Perhaps the nexus of these two approaches is for exporting firms to engage in training activities in importing regions: A practise that must be carefully regulated to ensure a socially beneficial outcome (Interview 2 & 3). Another suggestion made by an importing region stakeholder was the remote control and operation of biogas plants. This can mean that high-level engineering work can be outsourced where appropriate (Interview 3).

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Value chain research needs

Value chain aspects of research needs were not analysed using the code abundance approach. Interesting value chain features elucidated by the interviews was the lack of alignment with European literature stating the abundance of feedstock potential with the reality on the ground (Interview 1 & 2b). In Ghana for example, feedstock was recognised as a principle barrier in the way of biogas sector growth, with improvements in quality and quantity required. This view is contrary to a recent feedstock analysis by the German development agency (a review that the interviewee was unaware of) that suggests a high biogas potential for agricultural, agro-industrial and municipal sectors in Ghana (Daniel, 2014). This could be a result of lack of a distribution network for biogas research in Ghana or through European institutions trying to raise investment interest.

It is important to recognise the potential imperialist issues associated with technology transfer and the history of regions involved in renewable energy technology transfer. Social science study may be beneficial to ensure the mutual benefit, though this was not suggested by importing country interviewees, who suggested capacity building as the principle mechanism to ensure equitable sector growth.

4.3.2 The Renewable Energy Multiplier Paradox

The open coding approach yielded three headline observations that can be viewed in conjunction to define an interesting observation that will be referred to as The Renewable Energy Multiplier Paradox (REM Paradox, Figure 19). The three headline observations drawn from interviews are:

a) Successful and operational biogas plants are required as a prerequisite to building regional expertise
b) Regional expertise and knowhow is required to gain the confidence from financiers (of the same region)
c) Confidence from financers is required to establish successful and operational biogas plants

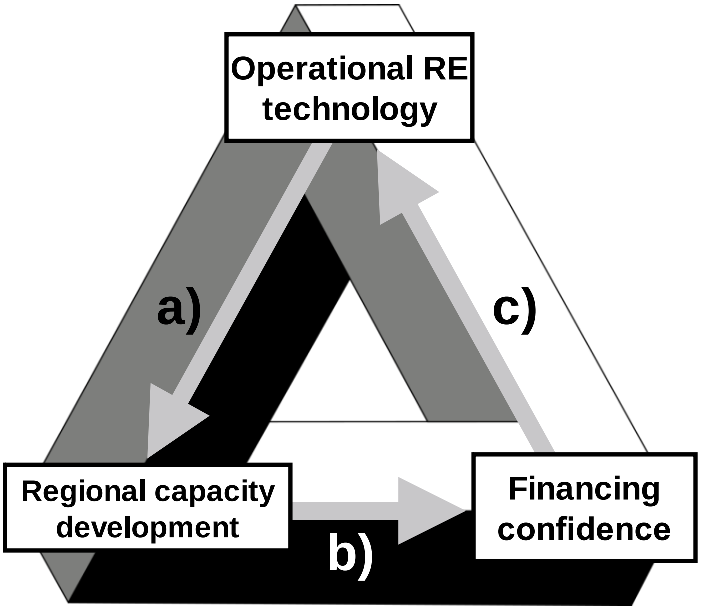

Figure 19. The Renewable Energy Multiplier Paradox for developing and emerging economies.

The REM Paradox can be easily defined by dissecting its name. The REM Paradox is first a paradox because each integral feature to a biogas market is dependent on its preceding condition. If a), b) and c) above describe the processes of development as one node (black box) stimulates the growth of the next, the paradox maintains that this cycle is in deadlock until one node is stimulated by an external force (be it research or import).

The REM paradox is a multiplier because of its likeness with the well-known multiplier effect (which posits that an injection of spending into a circular cash flow will lead to an increase in final spending). This foundational concept is applied here to several currencies as well as fiscal: a) Human capital (technical capacity); b) Network capital (communication network and trust between stakeholders); c) Financial capital. The central idea here is that the system gets out more of what is put in because currency increases with each iteration of the cycle (through spillovers, learning/experience curves etc.).

The REM paradox is not limited to biogas markets. Other renewable energy technologies may also benefit from using this paradox as a heuristic for approaching research needs to kickstart a sector. Figure 19 shows a generalised REM paradox, with nodes and arrows as described above.

Though the causal cycle can be seen as a limitation, establishing one node via external forces can trigger a cascade leading to market growth through a multiplier. Figure 20 illustrates how certain mechanisms can interact with the components of the REM paradox to promote one node. In reality it is often many mechanisms acting in aggregate that stimulates biogas market growth. There are however some mechanisms, such as generous demand-pull policies, that can single-handedly trigger RE multipliers. The figure below uses concepts and primary research needs found in this study to add mechanisms of change to the REM Paradox.

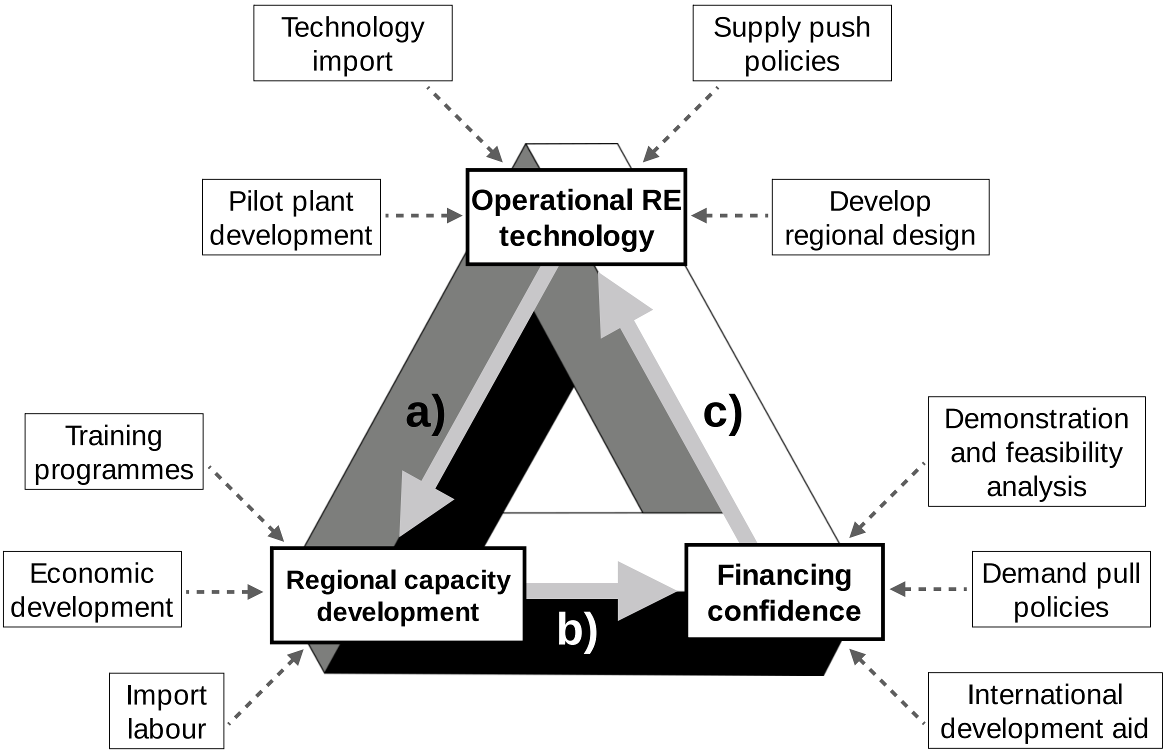

Figure 20. The Renewable Energy Multiplier Paradox with suggested mechanisms to stimulate nodes.

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5 Conclusion and recommendations

This study was conducted to answer the task-derived research questions presented at the beginning of this work. These questions are:

- **Research Question 1:** What are the primary barriers inhibiting biogas sector development in developing economies?
- **Research Question 2**: How can research and technical adaptation address these barriers to enable biogas market growth in the developing economies?

Research Questions 1 and Research Question 2 are answered directly through the Barriers matrix (Table 8) and Research needs matrix (Table 9) respectively. These matrices function as stand-alone results that may be isolated and utilised further to identify the research needs voiced by stakeholders in partner countries. A hands-off methodology was employed to create matrices with minimal researcher bias.

Further, a prioritisation approach (using the technological readiness levels and diffusion of innovations theory) was taken to analyse interview data using open coding. Headline recommendations drawn from this approach are:

- Research efforts are multidimensional, with a focus on organisational research needs over technical research in emerging and developing countries. When technology is diffused, it undergoes a context shift. This results in the need for human infrastructural development (capacity building) in importing regions so that: (i) Technology can be adopted sustainably; and (ii) So that importing societies and markets can benefit from the learning effects of imported technology.
- Emerging and developing economies can often not afford the incentive structures (demand-pull policies) that are available in the EU. This is especially unrealistic in the 10-year/30-year time-frame set for economies to make steps towards decarbonisation. Thus, private-sector biogas market growth, which focuses on and tailors imported biogas systems to meet a regional demand, be this for digestate, heat and power, waste management services or employment is a priority. The intention here is to grow a biogas market using market forces alone, largely independent of development aid, leading to multipliers, competition and sectoral learning that is retained in the importing region.
- The development of compatible, appropriate technology is a research need. This combines organisational research efforts from importing regions (in the form of communication networks and independently created, reliable databases for local market and feedstock conditions) with technical research from exporting regions (in the form of technical adaptation) to meet market needs. The wider DiBiCoo project addresses many of these priority concerns.

The REM Paradox model seeks to express the experience gained through interviews and interview analysis. The take-home from this model is that there are many research-derived, research-influenced and research-independent mechanisms that may boost a biogas market –

creating positive emergent benefits for the entire sector. It is important to recognise which of these mechanisms best match local demand conditions, solve barriers on the regional level and produce the most positive outcome for both the market and wider society.

This study forms the theoretical basis for development of research on the ground in emerging regions. Though the research needs and prioritisations are made in general terms here, this work should be used to develop region specific research needs for importing region stakeholders by local researchers.

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Appendices

Appendix 1 - Figure 10: Sources and method

Figure 10 employs various popular socioeconomic indices, tabulated below, to illustrate each DiBiCoo partner country's performance in these indices in a visually comparative manner. Online mapping software, mapchart.net, was used to create the map shown in the figure.

Table 10. Indices used in Figure 10, sources of data and data processing methods.

Index name	Index reference	Data processing
The Human Development Index (HDI)	United Nations Development Programme [UNDP] (2019)	HDI scores were normalised by dividing by the global average HDI.
Gini coefficient of wealth inequality (GINI)	Central Intelligence Agency (2020)	Gini scores were normalised by dividing by the global average and inverted to reflect other indicators (so that low scores denote poor performance). Due to low variability, normalised Gini scores were multiplied by a factor of 1.5 to allow variation to be detected by inspection.
Gross domestic product per capita (GDP)	World Bank (2020d)	GDP scores were normalised by dividing by the global average GDP. Due to high variability, normalised GDP scores were multiplied by a factor of 0.5 to allow variation of other indices seen clearly by inspection.
Sustainable Development Index (SDG Index)	Sachs et al. (2019), Sustainable Development Report 2019	SDG Index scores were normalised by dividing by the global average score.
Corruption Perceptions Index (CDI)	Transparency International (2019)	CDI scores were normalised by dividing by the global average score.

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Appendix 2 - Overview of survey questions and answer type

Table 11. Overview of survey questions and answer type.

Section	Questions	Anwer-type
General information and disclosure agreement	Name/Country/Associated organisation/Email address/Disclosure agreement and data protection information	Written response/tick-box
Status of national research and identification of research stakeholders	What degree of technical support does your country require from foreign institutions/organisations for strong biogas sector development?	Likert scale
	Please indicate these stakeholders' importance to biogas research and technical advance on a national level? (Note that the term 'biogas' here denotes only larger scale biogas with power generation capacity)	Likert scale matrix
	Who are the most important research stakeholders in your country's biogas sector? Please use this section to also indicate any stakeholders you feel were not included on the above list and the specific names of stakeholder organisations.	Written response
	What are the barriers to fulfilling the research needs within your country required for strong sector development? (E.g. technical expertise, funding)	Written response
	Is there much collaboration between research institutions in your country and EU-based research? If yes, please provide details of these partnerships and channels through which research collaboration occurs.	Written response
Technical capacity	In which stakeholders is technical capacity lacking most? I.e. Where in the value chain is technical capacity building best placed?	Written response
	Which organisations, national or abroad, can best address this lack of technical capacity?	Written response
Biogas technologies	On a broad level, what are the most common/important challenges in the way for successful implementation of foreign biogas technologies? (Economic/environmental/social challenges)	Written response
	On a technical level, why have biogas plants implemented by foreign organisations failed in the past? Please give details of the reasons and stakeholders involved with any unsuccessful projects.	Written response
	Which EU or other foreign components/systems cause the biggest problems when they're implemented? I.e which require the most modification or must be thought about the most in a foreign collaboration project.	Written response
	How can the components/systems be adapted better to get around these problems? And who are the important stakeholders (national or foreign) in adapting components and systems to suit your country's needs?	Written response
	What would you like to see done by EU biogas companies to create a more enabling environment for implementation of foreign biogas systems?	Written response
	Is there research needed for data to support licencing and permits (e.g. air emissions licence)? Please provide details of the primary stakeholders involved in this research.	Written response
	Is process modelling, techno economic analysis and other computer simulation work done nationally or by foreign stakeholders?	Written response
Feedstock	What is the national status of feedstock analysis?	Likert scale
	Is this status suitable to support biogas projects and development in the biogas sector?	Tick-box
	Please suggest what feedstock research and analysis would be most beneficial to the biogas sector in your country.	Written response
Revenue	What research could impact the financing mechanisms for biogas projects in your country? For example, research to support government tariffs and subsidies for biogas.	Written response
	Name the strategies most important to maximising the value out of biogas end products in your country? (Value upgrading through biogas upgrading, liquid biofertiliser etc.)	Written response

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Appendix 3 - Overview of interview questions

Table 12. Semi-structured interview question guide.

Section	Question	
Part 1 - General Questions	What functions do you personally have in the national biogas sector?	
	How strong/wide-reaching is the biogas network in your country?	
	What is the status of research for biogas within your country?	
	Who are the main stakeholders involved in research for biogas in your country?	
	Which of these stakeholders can best boost your country's biogas sector through research? And how would they do this?	
Part 2 - Addressing Barriers	Barrier	
	Economic barriers	Lack of governmental financial support mechanisms (feed-in-tariffs, subsidies, tax breaks, carbon)
		Lack of project financing and low interest bank loans
		Electricity produced by biogas technologies is not very profitable when sold to the grid in your country.
		High initial investment
	Social barriers	Lack of stakeholder network between EU and companies in your country
		Is there a cultural or language barrier between national and international biogas stakeholders?
		Lack of technical knowledge, know-how and institutional capacity in importing countries
		Lack of ability to maintain organisational structures
		Lack of insight in the local market
	Political barriers	Lack of biogas-related goals, targets etc.
		Difficult regulation concerning treatment of organic residues
		Biogas is recognised as unreliable and not bankable
	Technical barriers	Other types of waste compared to Europe
		Difference in technical requirements
		Lack of local key experts for technical and commercial assistance
		Dependency on changes in incentive schemes
		The fact that European technology is perceived as expensive
		Cheap pathways to treat certain types of waste in a non-sustainable way - for POME in particular
		Lack of grid connection
Part 3 - Concluding questions	Do you have any other suggestions of barriers?	
	Are there any that jump out as extremely important or especially unimportant barriers?	
	In what ways do you think that DiBiCoo could fail as a project?	
	What three things need to happen in your country for more European technology to be taken up in the biogas market in your country?	
	What three things need to happen in the EU for more European technology to be taken up in the biogas market in your country?	

The three parts of the interview are as follows:

- **Personal introduction and general questions:** The interviewer and interviewee may introduce themselves. The project and intentions/objectives for the interview are

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discussed. Questions here are asked to gain an understanding of the interviewees salience which may influence the analysis of responses.

- **Addressing barriers**: Here, a number of economic, social, political and technical barriers are described and discussed. The discussion is led with an emphasis on the research-related solutions to each barrier. This is achieved by asking: “Are there ways in which research and technical adaptation can help overcome this barrier?” after describing a given barrier. Part two forms the main body of the interview, with around 60 minutes being dedicated to this part.
- **Concluding questions**: The final part is used here for the interviewee to suggest additional barriers and solutions and make some general remarks about the DiBiCoo project.

Appendix 4 - Overview of interviews

Table 13. Overview of interviews conducted.

Interview in-text reference	Associated country	Associated organisation and role	Details of interview	Notes
Interview 1	Ghana/West Africa	Senior Research Scientist, Council for Scientific and Industrial Research – Institute of Industrial Research	Interview conducted: 12 May 2020 Interview length: 90 minutes	The organization has been the main driver of biogas development in Ghana with the installation of a number of institutional biogas digesters
Interview2a	Ethiopia	CEO and owner, Bioflame Biogas Co.	Interview conducted: 13 May 2020 Interview length: 93 minutes	Bioflame Biogas is the only private biogas developer in Ethiopia
Interview 2b	Ethiopia	Researcher and lecturer at Addis Ababa University	Interview conducted: 07 May 2020 Interview length: 93 minutes	Open coding was not performed on this interview
Interview 3	South Africa	Manager, Green Create Africa	Interview conducted: 19 May 2020 Interview length: 81 minutes	Greencape is a private biogas developer with a number of operating plants in South Africa
Interview 4	Indonesia	Mill and engineering head, First Resources Group	Interview conducted: 14 May 2020	
Interview 5a	Argentina	Argentine Chamber of Renewable Energies, Head biomass committee, the Argentina Renewable Energy Chamber (CADER)	Interviews conducted between November 2019 and May 2020	Ten years experience in the biogas sector
Interview 5b	Argentina	President, TECNORED		TECNORED is a biogenergy company who build the first industrial biogas plant in Argentina
Interview 5c	Argentina	Dean of the chemistry and engineering, University of Rosario/Owner, SOLAM		SOLAM are a biogas company with two operational plants in San Lorenzo
Interview 5c	Argentina	Bioelectrica		Bioelectrica is a biogas company owned by farmers with four active plants in Argentina
Interview 5d	Argentina	Seeds energy group		Argentinian biogas company with plants totalling 4 MW capacity using a mix of European and local technology
Interview 5e	Argentina	Grupo Roggio Ambiental and TECSAN		Key players in the area of landfill gas use

*Interview conducted by DiBiCoo partners, RDI using the question guide.

**Interviews were conducted prior to research. DiBiCoo partners at INTA collected sections of each interview deemed relevant to the question outlined in the question guide.

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Appendix 5 - Limitations of stated methods

Due to time restrictions and communication errors between DiBiCoo partners, the surveys created for the purpose of generating the barriers to be used for the interviews and barriers matrix were largely not completed. The minimum survey number to be included in this study is 25 and, because this number was not reached, the literature generated barriers were used to write the interviews (dotted arrow, Figure 8). In addition to this diversion in the methodological workflow, interviews were then used to generate both the barriers and the research needs matrix using the method defined in the figure and following text below.

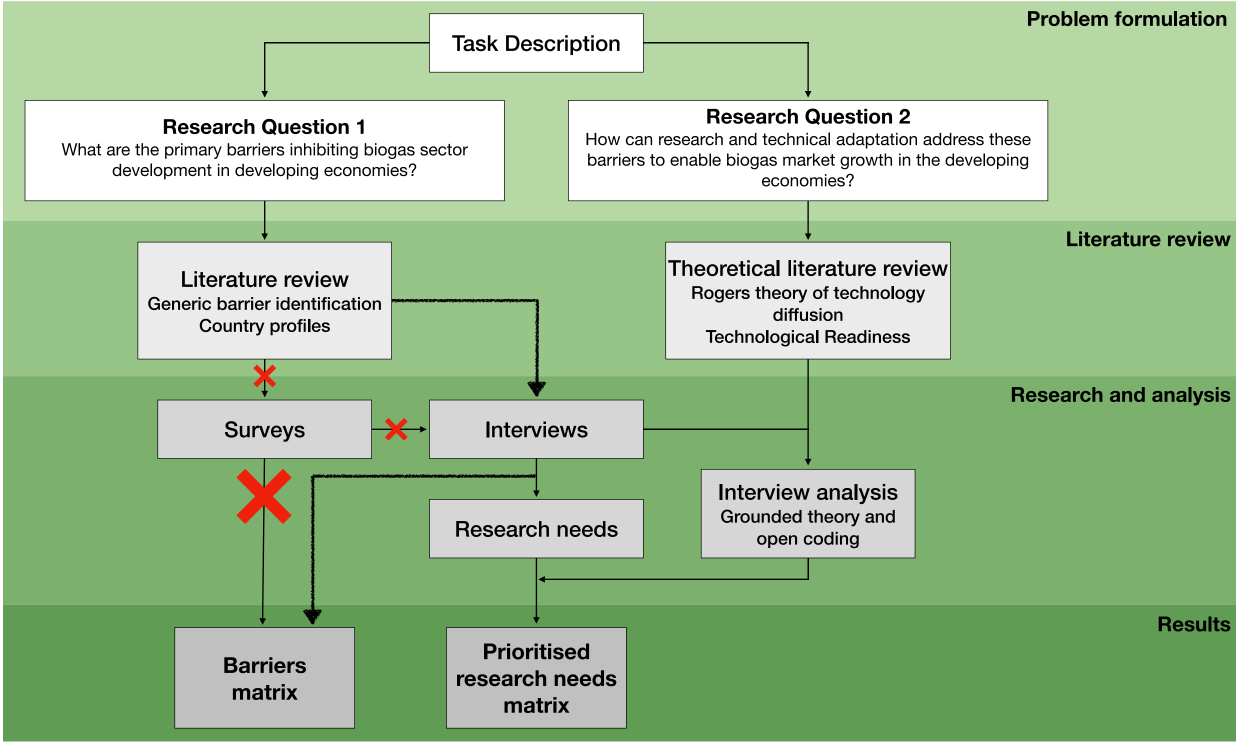

Figure 21. Diversions and revisions of the methodological overview and workflow initially presented in Figure 8.

Appendix 6 - Extended methodology for matrix generation

The research needs barriers matrices were constructed using an identical methodology listed below. This process was performed after open coding, and used the coding methods, memoing and the QDA approach to arrive at the barriers and research needs matrices. The step by step workflow is given below:

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1. Interview transcripts were screened for statements relating to or suggesting barriers and research.
2. Statements were isolated, collected and reframed to create a more generic, less context-specific date-type. For example, “an unwillingness to participate in something new” was reframed to “social resistance to change.”
3. Now that the statements could be interpreted outside a country context, barriers and research needs were grouped into economic, technical, and sociopolitical columns.
4. Within these three columns, related phrases were grouped into sentences that would incorporate up to four statements.
5. Y-axis categorisations, based on the code groupings in Table 5, were then added. These codes are decision-making/technology/value chain and technical/organisation for barriers and research needs matrices respectively.
6. Finally, for the barriers matrix only, each cell of the matrix was coded to indicate the extent to which barriers can be addressed by research and technical adaptation.

Appendix 7 - Open coding data processing extended methodology

The data obtained from the open coding process was processed in silico to provide (indirectly) quantitative data to support the prioritisation process. The abundance of each code was catalogued in addition to whether the code was a positive (optimistic, presented an opportunity) or negative statement (pessimistic, presented a problem). A standard for comparison was created by performing the open coding method to the interview question guide. The abundances are shown alongside the abundances of codes in interviews as a standard for comparison i.e. these are the results if respondents raised single points for each question. This is considered a method to reduce the interviewer bias in the (indirectly) quantitative analysis of open coding data.

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6 References

Adedeji, A. (1995). An African Perspective on Bretton Woods. In *The UN and the Bretton Woods institutions* (pp. 60-82). Palgrave Macmillan, London.

Aflaki, S., Basher, S. A., & Masini, A. (2014). Does economic growth matter? Technology-push, demand-pull and endogenous drivers of innovation in the renewable energy industry. *HEC Paris Research Paper No. MOSI-2015-1070*.

Africa Energy. (2019). Ghana Power Report – 2019/20. Retrieved 6 May 2020, from https://www.africa-energy.com/sites/default/files/Ghana%20BrochureR2.pdf

African Development Bank. (2020). African Economic Outlook 2020. Retrieved 10 June 2020, from https://www.afdb.org/en/documents/african-economic-outlook-2020

Albrecht, J., Laleman, R., & Vulsteke, E. (2015). Balancing demand-pull and supply-push measures to support renewable electricity in Europe. *Renewable and Sustainable Energy Reviews*, *49*, 267-277.

Alliance for a Green Revolution in Africa. (2020). Africa agriculture status report: Focus on staple crops. Retrieved 10 June 2020, from https://reliefweb.int/sites/reliefweb.int/files/resources/agrafinalaugust20akim.pdf

Ayres, L. (2008). Semi-structured interview. *The SAGE encyclopedia of qualitative research methods*, 811-813.

Bachmann, N., la Cour Jansen, J., Bochmann, G., & Montpart, N. (2015). Sustainable biogas production in municipal wastewater treatment plants. Massongex, Switzerland: *IEA Bioenergy*.

Bartolini, F., Gava, O., & Brunori, G. (2017). Biogas and EU's 2020 targets: Evidence from a regional case study in Italy. *Energy Policy*, *109*, 510-519.

Basu, P. (2010). Biomass gasification and pyrolysis: practical design and theory. *Academic press.*

Benaquisto, L. (2008). Codes and coding. *The Sage encyclopedia of qualitative research methods*, *1*, 85-88.

Bensah, E. C., & Brew-Hammond, A. (2010). Biogas technology dissemination in Ghana: history, current status, future prospects, and policy significance. *International Journal of Energy and Environment*, *1*(2), 277-294.

Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Praveenkumar, R., Chozhavendhan, S., & Iyyan, J. (2018). Biogas production–A review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renewable and Sustainable Energy Reviews*, *90*(C), 570-582.

Bozeman, B. (2000). Technology transfer and public policy: a review of research and theory. *Research policy*, *29*(4-5), 627-655.

Brand South Africa. (2018). South Africa's key economic sectors. Retrieved 10 June 2020, from https://www.brandsouthafrica.com/investments-immigration/business/investing/economic-sectors-agricultural

British Broadcasting Corporation. (2019). Ethiopia country profile. Retrieved 10 June 2020, from https://www.bbc.com/news/world-africa-13349398

British Broadcasting Corporation. (2018). Ghana country profile. Retrieved 10 June 2020, from https://www.bbc.com/news/world-africa-13433790

Bryant, A., & Charmaz, K. (2007). Grounded theory research: Methods and practices. *The Sage handbook of grounded theory*, *1*, 29.

Charmaz, K. (1983). The grounded theory method: An explication and interpretation. *Contemporary field research*, 109-126.

Central Intelligence Agency. (2020). The World Factbook. Country comparison, Gini Index. Retrieved 5 June 2020, from https://www.cia.gov/library/publications/the-world-factbook/rankorder/2172rank.html

Choong, Y. Y., Chou, K. W., & Norli, I. (2018). Strategies for improving biogas production of palm oil mill effluent (POME) anaerobic digestion: A critical review. *Renewable and Sustainable Energy Reviews*, *82*, 2993-3006.

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

Comparetti, A., Febo, P., Greco, C., & Orlando, S. (2013). Current state and future of biogas and digestate production. *Bulgarian Journal of Agricultural Science*, *19*(1), 1-14.

Cornet, C., & Euverink, G. J. W. (2017). Inhibiting factors in the anaerobic digestion process for biogas production (*Doctoral dissertation, Faculty of Science and Engineering*).

Daniel, U., Pasch, K. H., & Nayina, G. S. (2014). Biogas in Ghana: sub-sector analysis of potential and framework conditions. *GIZ, Berlin, Germany*.

De Rose, A., Buna, M., Strazza, C., Olivieri, N., Stevens, T., Peeters, L., & Tawil-Jamault, D. (2017). Technology Readiness Level: Guidance Principles for Renewable Energy Technologies. *European Commission: Petten, The Netherlands*.

Department of Mineral Resources and Energy. (2019). Integrated Resource Plan (IRP 2019). Retrieved 10 June 2020, from http://www.energy.gov.za/IRP/2019/IRP-2019.pdf

Deublein, D., & Steinhauser, A. (2011). Biogas from waste and renewable resources: an introduction. *John Wiley & Sons.*

Digital Global Biogas Cooperation. (2020a). Grant Agreement. Horizon 2020 Call: Building a low-carbon, climate resilient future: Secure, clean and efficient energy.

Digital Global Biogas Cooperation. (2020b). Deliverable 3.1. Report on the Stakeholder Mapping for Importing

Countries

Digital Global Biogas Cooperation. (2020c). Deliverable 3.3.Biogas Markets and Frameworks in Argentina, Ethiopia, Ghana, Indonesia, and South Africa.

European Biogas Association (EBA) (2019): EBA Statistical report 2019: European Overview. https://www.europeanbiogas.eu/eba-statistical-report-2019-european-overview/

European Biogas Association EBA (2020a): Biogas: a powerful and safe enabler of decarbonisation & complementing the zero-pollution ambition of the Green Deal. https://www.europeanbiogas.eu/wp-content/uploads/2020/05/FINAL-position-paper_agriculture.pdf

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

European Biogas Association (EBA) (2020b): The contribution of the biogas and biomethane industries to medium-term greenhouse gas reduction targets and climate-neutrality by 2050. https://www.europeanbiogas.eu/wp-content/uploads/2020/04/20200419-Background-paper_final.pdf

European Biogas Association (EBA) (2020c): Acknowledging the full potential of biomethane as transport fuel. https://www.europeanbiogas.eu/wp-content/uploads/2020/07/EBA-Transport-position-paper_FINAL.pdf

Edjekumhene, I., Atakora, S. B., Atta-Konadu, R., & Brew-Hammond, A. (2001). Implementation of renewable energy technologies–opportunities and barriers: Ghana Country Study. *UNEP Collaborating Centre on Energy and Environment, Roskilde*, *146*.

ElMekawy, A., Mohanakrishna, G., Srikanth, S., & Pant, D. (2016). The Role of Bioreactors in Industrial Wastewater Treatment. *Environmental Waste Management*, 157.

Emmann, C. H., Guenther-Lübbers, W., & Theuvsen, L. (2013). Impacts of biogas production on the production factors land and labour–current effects, possible consequences and further research needs (No. 1021-2016-81783, pp. 550-566).

Encyclopedia Britannica. (2020). Technology | Definition & Examples. Retrieved 11 June 2020, from https://www.britannica.com/technology/technology

Energy Commission. (2006). Strategic National Energy Plan 2006 – 2020. Retrieved 10 June 2020, from http://energycom.gov.gh/files/snep/MAIN%20REPORT%20final%20PD.pdf

Energy Commission. (2016). Energy Outlook for Ghana. Retrieved 10 June 2020, from http://www.energycom.gov.gh/planning/data-center/energy-outlook-for-ghana#

Energy Commission. (2018). National Energy Statistics, 2008 - 2017.Retrieved 10 June 2020, from http://energycom.gov.gh/files/ENERGY_STATISTICS_2018_FINAL.pdf

EurObserv'ER. (2017). Biogas Barometer 2017. *EurObserv'ER, Ed*

European Biogas Association. (2018). Statistical Report 2018. Retrieved 6 May 2020, from https://www.europeanbiogas.eu/wp-content/uploads/2019/05/EBA_Statistical-Report-2018_AbrigedPublic_web.pdf

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

European Biomass Association. (2012). EU Handbook - Biogas Markets. Retrieved 28 April 2020, from http://www.crossborderbioenergy.eu/fileadmin/crossborder/Biogas_MarketHandbook.pdf

European Biomass Industry Association. (2020). Gasification – WikiBiomass. Retrieved 28 April 2020, from https://www.eubia.org/cms/wiki-biomass/pyrolysis-and-gasification/gasification/.

European Commission. (2020a). A European Green Deal. Retrieved 6 May 2020, from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#timeline

European Commission. (2020b). What is Horizon 2020?. Retrieved 6 May 2020, from https://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020

Eyl-Mazzega, M. A. and Mathieu, C. (2019) Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy. *Études de l'Ifri*, Ifri.

Frischmann, P. (2012). Enhancement and treatment of digestates from anaerobic digestion. Desk top study on digestate enhancement and treatment. *WRAP.*

German Biogas Association. (2020). Slide 1, Biogas market data in Germany 2018/2019. Retrieved 8 June 2020, from https://www.biogas.org/edcom/webfvb.nsf/id/DE_Branchenzahlen/$file/19-07-12_Biogasindustryfigures-2018-2019_english.002.pdf

Glaser B. G., & Strauss A. L. (1967). The discovery of grounded theory: strategies for qualitative research. *New York, Adline de Gruyter*.

Global Syngas Technologies Council. (2020). The Gasification Industry. Retrieved 28 April 2020, from https://www.globalsyngas.org/resources/the-gasification-industry/.

González-González, L. M., Correa, D. F., Ryan, S., Jensen, P. D., Pratt, S., & Schenk, P. M. (2018). Integrated biodiesel and biogas production from microalgae: towards a sustainable closed loop through nutrient recycling. *Renewable and Sustainable Energy Reviews*, *82*, 1137-1148.

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

Grando, R. L., de Souza Antune, A. M., Da Fonseca, F. V., Sánchez, A., Barrena, R., & Font, X. (2017). Technology overview of biogas production in anaerobic digestion plants: A European evaluation of research and development. *Renewable and Sustainable Energy Reviews*, *80*, 44-53.

Grantham Institute. (2020). Climate Change Laws of the World, Argentina. Retrieved 4 May 2020, from https://climate-laws.org/cclow/geographies/argentina/laws/law-27191-on-renewable-energy

Gu, L., Zhang, Y. X., Wang, J. Z., Chen, G., & Battye, H. (2016). Where is the future of China's biogas? Review, forecast, and policy implications. *Petroleum Science*, *13*(3), 604-624.

Hanekamp, E., & Ahiekpor, J. C. (2012). Technical assistance to the Ghana Energy Commission to develop a dedicated programme to establish institutional biogas systems in 200 boarding schools, hospitals and prisons, and to prepare for CDM application Feasibility Study. Retrieved 10 June 2020, from https://www.partnersforinnovation.com/wp-content/uploads/2019/05/Feasibility-study-of-Ghana-Institutional-Biogas-Programme.pdf

Hinchliffe, D., Frommann, J., & Gunsilius, E. (2017). Waste to energy options in municipal solid waste management. *Eschborn: GIZ*.

Huszár, S., Prónay, S., & Buzás, N. (2016). Examining the differences between the motivations of traditional and entrepreneurial scientists. *Journal of Innovation and Entrepreneurship*, *5*(1), 25.

Intergovernmental Panel on Climate Change. (2020). Climate Change 2014 Synthesis Report. Retrieved 14 June 2020, from https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

International Energy Agency. (2019a). Africa Energy Outlook 2019. Retrieved 10 June 2020, from https://www.iea.org/reports/africa-energy-outlook-2019

International Energy Agency. (2019b). Ethiopia Energy Outlook. Retrieved 10 June 2020, from https://www.iea.org/articles/ethiopia-energy-outlook

International Energy Agency. (2019c). Southeast Asia Energy Outlook 2019. Retrieved 29 April 2020, from https://webstore.iea.org/download/direct/2887?fileName=Southeast_Asia_Energy_Outlook_2019.pdf

International Energy Agency. (2019d). Argentina Renewable Energy Auctions - RenovAr Program (Round 3). Retrieved 4 May 2020, from https://www.iea.org/policies/6562-argentina-renewable-energy-auctions-renovar-program-round-3-miniren-round

International Energy Agency. (2020a). Outlook for biogas and biomethane: Prospects for organic growth. Retrieved 2 April 2020, from https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth

International Energy Agency. (2020b). Sustainable Development Scenario - World Energy Model. Retrieved 10 June 2020, from https://www.iea.org/reports/world-energy-model/sustainable-development-scenario

International Energy Agency. (2020c). Policy Database, Ghana. Retrieved 10 June 2020, from https://www.iea.org/policies?country=Ghana

International Energy Agency. (2020d). Argentina - Countries & Regions. Retrieved 4 May 2020, from https://www.iea.org/countries/Argentina

International Finance Corporation. (2018). RenovAr (Argentina): Scaling 'Express Edition'. Retrieved 4 May 2020, from https://www.ifc.org/wps/wcm/connect/987eeec6-6259-4c00-8e21-fbf49813a47b/scaling-infra-argentina-08.pdf?MOD=AJPERES&CVID=mSCMXzz

Jędrzejczyk, M., Soszka, E., Czapnik, M., Ruppert, A. M., & Grams, J. (2019). Physical and chemical pretreatment of lignocellulosic biomass. In *Second and Third Generation of Feedstocks* (pp. 143-196). Elsevier.

Jenkins, J., and Mansur, S. (2011). Bridging the Clean Energy Valleys of Death: Helping American Entrepreneurs to Meet the Energy Innovation Imperative. *The Breakthrough Institute, Oakland, CA, US*A. 1–22.

Kamp, L. M., & Forn, E. B. (2016). Ethiopia′ s emerging domestic biogas sector: Current status, bottlenecks and drivers. *Renewable and Sustainable Energy Reviews*, *60*, 475-488.

Kampman, B., Leguijt, C., Scholten, T., Tallat-Kelpsaite, J., Brückmann, R., Maroulis, G., & Elbersen, B. (2017). Optimal use of biogas from waste streams: an assessment of the potential

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

of biogas from digestion in the EU beyond 2020. Retrieved 8 June 2020, from https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf

Khalil, M., Berawi, M. A., Heryanto, R., & Rizalie, A. (2019). Waste to energy technology: The potential of sustainable biogas production from animal waste in Indonesia. *Renewable and Sustainable Energy Reviews*, *105*, 323-331.

Khandkar, S. H. (2009). Open coding. *University of Calgary*, *23*.

Kumar, R., & Agarwala, A. (2016). Renewable energy technology diffusion model for techno-economics feasibility. *Renewable and Sustainable Energy Reviews*, *54*, 1515-1524.

Kumi, E. N. (2017). The electricity situation in Ghana: Challenges and opportunities. *Washington, DC: Center for Global Development*.

Lacerda, J. S., & Van den Bergh, J. C. (2014). International diffusion of renewable energy innovations: Lessons from the lead markets for wind power in China, Germany and USA. *Energies*, *7*(12), 8236-8263.

Lauer, M., & Thrän, D. (2018). Flexible biogas in future energy systems—Sleeping beauty for a cheaper power generation. *Energies*, *11*(4), 761.

Lloyds Bank International Trade Portal. (2020). The economic context of Argentina - Economic and Political Overview. Retrieved 4 May 2020, from https://www.lloydsbanktrade.com/en/market-potential/argentina/economical-context

Lybæk, R., Christensen, T. B., & Kjær, T. (2013). Governing innovation for sustainable development in the Danish biogas sector–a historical overview and analysis of innovation. *Sustainable Development*, *21*(3), 171-182.

Mankins, J. C. (1995). Technology readiness levels: A white paper. Retrieved 10 June 2020, from http://www.artemisinnovation.com/images/TRL_White_Paper_2004-Edited.pdf.

Mengistu, M. G., Simane, B., Eshete, G., & Workneh, T. S. (2015). A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia. *Renewable and Sustainable Energy Reviews*, *48*, 306-316.

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

Meyer-Renschhausen, M. (2013). Evaluation of feed-in tariff-schemes in African countries. *Journal of Energy in Southern Africa*, *24*(1), 00-00.

Ministry of National Development Planning. (2007). Long Term National Development Plan of 2005-2025. Retrieved 10 June 2020, from https://www.bappenas.go.id/files/6715/3173/4665/RPJPN_2005-2025.pdf

Ministry of Trade and Industry. (2020). The 10 Point Agenda. Retrieved 10 June 2020, from http://www.moti.gov.gh/10pointagenda.php

Minnaar, U. (2019). OP-ED: Unbundling Eskom — the good, the bad and the ugly. Retrieved 10 June 2020, from https://www.dailymaverick.co.za/article/2019-02-11-unbundling-eskom-the-good-the-bad-and-the-ugly/#gsc.tab=0

Molino, A., Larocca, V., Chianese, S., & Musmarra, D. (2018). Biofuels production by biomass gasification: A review. *Energies*, *11*(4), 811.

Montgomery, L. F., & Bochmann, G. (2014). Pretreatment of feedstock for enhanced biogas production. *Ireland: IEA Bioenergy,* 1-20.

Mutungwazi, A., Mukumba, P., & Makaka, G. (2018). Biogas digester types installed in South Africa: A review. *Renewable and Sustainable Energy Reviews, 81*, 172-180.

Mwirigi, J. W., Makenzi, P. M., & Ochola, W. O. (2009). Socio-economic constraints to adoption and sustainability of biogas technology by farmers in Nakuru Districts, Kenya. *Energy for Sustainable Development*, *13*(2), 106-115.

National Academies of Sciences, Engineering, and Medicine. (2016). The role of experimentation campaigns in the Air Force innovation life cycle. *National Academies Press*.

National Agricultural Technology Institute. (2016). Relevamiento Nacional de Plantas de Biogas. Retrieved 5 May 2020, from https://inta.gob.ar/sites/default/files/inta_-33-relevamiento_nacional_de_plantas_de_biogas_-_goicoas_v.pdf

National Planning Commission. (2016). Growth and Transformation Plan II (GTP II) (2015/16-2019/20). Retrieved 10 June 2020, from https://ethiopia.un.org/sites/default/files/2019-08/GTPII%20%20English%20Translation%20%20Final%20%20June%2021%202016.pdf

Navaratnasamy, M., Jones, J., & Parkington, B. (2008). Biogas: Cleaning and uses*. Alberta Agriculture and Rural Development.*

Organisation for Economic Co-operation and Development. (2017). Growth, investment and the low carbon transition. Retrieved 4 May 2020, from http://www.oecd.org/env/cc/g20-climate/collapsecontents/Fiel-argentina-growth-and-low-carbon-transition.pdf

Organisation for Economic Co-operation and Development. (2019a). Argentina Economic Snapshot - Economic Forecast Summary November 2019. Retrieved 4 May 2020, from http://www.oecd.org/economy/argentina-economic-snapshot/

Organisation for Economic Co-operation and Development. (2019b). Economic Surveys Argentina Overview. Retrieved 4 May 2020, from http://www.oecd.org/economy/surveys/Argentina-2019-OECD-economic-survey-overview.pdf

Organisation for Economic Co-operation and Development (2020). Indonesia Economic Snapshot. Retrieved 29 April 2020, from http://www.oecd.org/economy/indonesia-economic-snapshot/

Osei-Marfo, M., Awuah, E., & de Vries, N. K. (2018). Biogas technology diffusion and shortfalls in the central and greater Accra regions of Ghana. *Water Practice & Technology*, *13*(4), 932-946.

Oxford Business Group. (2020). New areas for growth in Indonesia's agriculture sector. Retrieved 29 April 2020, from https://oxfordbusinessgroup.com/overview/breaking-new-ground-small-scale-farming-and-mechanised-production-set-unlock-sector%E2%80%99s-economic

Patinvoh, R. J., & Taherzadeh, M. J. (2019). Challenges of biogas implementation in developing countries. *Current Opinion in Environmental Science & Health*.

Peipert, J., Severyn, T., Hovmand, P. S., & Yadama, G. N. (2008). Modeling the dynamics of the energy, environment, & poverty nexus: A study of biogas unit diffusion in Andhra Pradesh, India. *Washington University in St. Louis, USA: 13*.

Präger, F., Paczkowski, S., Sailer, G., Derkyi, N. S. A., & Pelz, S. (2019). Biomass sources for a sustainable energy supply in Ghana–A case study for Sunyani. *Renewable and Sustainable Energy Reviews*, *107*, 413-424.

Putra, A. R. S., Pedersen, S. M., & Liu, Z. (2019). Biogas diffusion among small scale farmers in Indonesia: An application of duration analysis. *Land Use Policy*, *86*, 399-405.

Raja, I. A., & Wazir, S. (2017). Biogas Production: The Fundamental Processes. *PakistanCattlekit, Mohlin Lal, Pakistan: COMSATS Institute of Information Technology*.

Rao, K. U., & Kishore, V. V. N. (2010). A review of technology diffusion models with special reference to renewable energy technologies. *Renewable and sustainable energy reviews*, *14*(3), 1070-1078.

Robinson, L. (2009). A summary of diffusion of innovations. Enabling Change. *New York: Simon & Schuster*.

Roessner, J. D. (2000). Technology transfer. *Science and technology policy in the US. A time of change. Longman, London*.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., ... & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 C. *Nature*, *534*(7609), 631-639.

Rogers, E.M. (1995). Diffusion of innovations. 4th ed. *Free Press: New York.*

Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G., & Fuller, G. (2019). Sustainable Development Report 2019. Transformations to Achieve the Sustainable Development Goals. New York: Bertelsmann Stiftung. *Sustainable Development Solutions Network (SDSN).* Retrieved 5 June 2020, from https://www.sdgindex.org

Sahal, D. (1981). Alternative conceptions of technology. *Research policy*, *10*(1), 2-24.

Sauser, B., Verma, D., Ramirez-Marquez, J., & Gove, R. (2006). From TRL to SRL: The concept of systems readiness levels. In *Conference on Systems Engineering Research, Los Angeles, CA* (pp. 1-10).

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

Scarlat, N., Dallemand, J.F. and Fahl, F. (2018). Biogas: Developments and perspectives in Europe. *Renewable energy*, *129*, 457-472.

Schnurer, A., & Jarvis, A. (2010). Microbiological handbook for biogas plants. *Swedish Waste Management U*, *2009*, 1-74.

Seidel, J. V. (1998). Qualitative data analysis: Ethnograph 5.0. *Qualis Research, Colorado Springs*.

SNV Netherlands Development Organisation. (2020a). National Biogas Programme - Ethiopia. Retrieved 10 June 2020, from https://snv.org/project/national-biogas-programme-ethiopia

SNV Netherlands Development Organisation. (2020b). Biogas Dissemination Scale-Up Programme (NBPE+). Retrieved 10 June 2020, from https://snv.org/project/biogas-dissemination-scale-programme-nbpe

Straub, E. T. (2009). Understanding technology adoption: Theory and future directions for informal learning. *Review of educational research*, *79*(2), 625-649.

Taylor, R., Devisscher, T., Silaen, M., Yuwono, Y., Ismail, C., Thamrin, S., & Takam, T. (2019). Risks, barriers and responses to Indonesia's biogas development. Stockholm Environment Institute.

Trachuk, A., & Linder, N. (2019). Knowledge Spillover Effects: Impact of Export Learning Effects on Companies' Innovative Activities. In *Current Issues in Knowledge Management*. IntechOpen.

Transparency International. (2019). Corruption Perceptions Index 2019. Retrieved 5 June 2020, from https://images.transparencycdn.org/images/2019_CPI_Report_EN_200331_141425.pdf

United Nations. (2010). World Population Prospects The 2010 Revision Volume I: Comprehensive Tables. Retrieved 10 June 2020, from https://www.un.org/en/development/desa/population/publications/pdf/trends/WPP2010/WPP2010_Volume-I_Comprehensive-Tables.pdf

United Nations Conference on Trade and Development. (2019). Country classification. Economic groups and composition. Retrieved 19 March 2020, from

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

https://unctadstat.unctad.org/en/Classifications/DimCountries_EconomicsGroupings_Hierarchy.pdf

United Nations Development Programme. (2019). Human Development Report 2019. p. 307. ISBN 978-92-1-126439-5.

United Nations Framework Convention on Climate Change. (2018). Ethiopia Off-Grid Renewable Energy Program. Retrieved 10 June 2020, from https://cdm.unfccc.int/ProgrammeOfActivities/poa_db/3M69I0RNTCWLHSPJE24BKDXVYQ5Z7F/view

United States Environmental Protection Agency. (2020). Overview of Greenhouse Gasses. Retrieved 9 June 2020, from https://www.epa.gov/ghgemissions/overview-greenhouse-gases

United States Energy Information Administration. (2020). Frequently Asked Questions (FAQs), How much carbon dioxide is produced per kilowatt hour of U.S. electricity generation?

Retrieved 9 June 2020, from https://www.eia.gov/tools/faqs/faq.php?id=74&t=11

Upadhyayula, V. K., Gadhamshetty, V., Shanmugam, K., Souihi, N., & Tysklind, M. (2018). Advancing game changing academic research concepts to commercialization: A Life Cycle Assessment (LCA) based sustainability framework for making informed decisions in Technology Valley of Death (TVD). *Resources, Conservation and Recycling*, *133*, 404-416.

Utterback, J. M. (1994). Mastering the dynamics of innovation Harvard Business School Press. *Boston, MA*.

World Bank. (2016). Third National Communication to the United Nations Framework Convention on Climate Change Projects. Retrieved 4 May 2020, from http://documents.worldbank.org/curated/en/226761467992493219/pdf/ICR3536-P116974-Box394857B-PUBLIC-disclosed-2-8-16.pdf

World Bank. (2018a). Ethiopia's Transformational Approach to Universal Electrification. Retrieved 10 June 2020, from https://www.worldbank.org/en/news/feature/2018/03/08/ethiopias-transformational-approach-to-universal-electrification

World Bank. (2018b). Agriculture, forestry, and fishing, value added (% of GDP). Retrieved 10 June 2020, from

https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?locations=GH

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

World Bank. (2019a). Ethiopia Overview. Retrieved 10 June 2020, from https://www.worldbank.org/en/country/ethiopia/overview

World Bank. (2019b). Ghana Overview. Retrieved 10 June 2020, from https://www.worldbank.org/en/country/ghana/overview

World Bank. (2019c). Employment in agriculture (% of total employment) - Ghana. Retrieved 10 June 2020, from https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?locations=GH

World Bank. (2020a). Ethiopia Poverty Assessment. Retrieved 10 June 2020, from http://documents.worldbank.org/curated/en/992661585805283077/pdf/Ethiopia-Poverty-Assessment-Harnessing-Continued-Growth-for-Accelerated-Poverty-Reduction.pdf

World Bank. (2020b). Indonesia Overview. Retrieved 29 April 2020, from https://www.worldbank.org/en/country/indonesia/overview

World Bank. (2020c). Argentina Overview. Retrieved 4 May 2020, from https://www.worldbank.org/en/country/argentina/overview#1

World Bank. (2020d). GDP per capita (current US$) | Data. Retrieved 5 June 2020, from https://data.worldbank.org/indicator/NY.GDP.PCAP.CD

World Commission on Environment and Development. (1987). Report of the World Commission on Environment and Development: Our Common Future. *UN Documents: Gathering a Body of Global Agreements*.

Yang, L., & Li, Y. (2014). Biogas Cleaning and Upgrading Technologies. *Agricultural and Natural Resources*.

Yasmin, N., & Grundmann, P. (2019). Adoption and diffusion of renewable energy–The case of biogas as alternative fuel for cooking in Pakistan. *Renewable and Sustainable Energy Reviews*, *101*, 255-264.

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under grant agreement N° 857804. The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the EU.

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Munich, 2020