Understanding the diffusion of LFGE projects in Africa

A dynamic approach through the lens of technological innovation systems

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Enjoy reading!

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Abstract

Population growth, economic development, and urbanisation are resulting in an increase in municipal solid waste. African countries dispose over 90% of their waste in landfills, even though landfills are associated with environmental pollution and contribute to global warming. Landfill gas to energy (LFGE) projects utilise methane emissions of landfills to generate energy. This could benefit African countries as it reduces waste and the associated emissions, and it improves energy supply. Although LFGE projects are already proven successful in other countries, they are not widely implemented in African countries.

This research investigated the reasons for the lacking diffusion and the conditions that will enable the emergence of LFGE projects in Africa by answering the following research question: "*What conditions enhance the diffusion of landfill gas to energy projects in Africa considering the dynamic behaviour of the landfill gas to energy innovation system?*" To answer this question, the innovation system surrounding LFGE projects, including the barriers for diffusion, was be described through the Technological Innovation System (TIS) framework. This research provides a conceptual model connecting the functional and the structural TIS approaches into a so called hybrid approach, which was then tailored to the African LFGE case.

Through a literature review and five exploratory expert interviews, 21 barriers to LFGE in Africa were identified. The barriers could be categorised into five categories: technical, institutional, organisational, social, and other. Eight barriers were incorporated into the conceptual model of the hybrid approach and converted into a system dynamics model, which was calibrated to South Africa. 41 experiments were conducted on the SD model. These experiments indicated that the wholesale price of electricity and the efficiency of the waste management system were the most important barriers to the diffusion of LFGE in Africa as they could individually cause diffusion or stagnation. Access to the national electricity grid and private ownership of the landfill, which indicates no tender processes involved, could accelerate the development if the purchase price of electricity from LFGE was considered adequate, albeit at a slower rate compared to the wholesale price and the waste management system. The worst case scenario of both barriers impedes diffusion. The development of the national electricity grid and corruption turned out to have little to no impact on the development of the LFGE TIS. In terms of policies specific for LFGE, an adequate feed-in tariff is the most impactful policy as it can create viability for LFGE. This policy is followed by the obligation to generate electricity from LFGE as this can prevent the development of LFGE if implemented under the wrong circumstances. An obligation to buy the electricity from LFGE as well as a requirement to collect the LFG accelerate the diffusion, if the most important barriers are overcome. Finally, the generation of carbon credits can partially compensate a low purchase price, which could create viability of LFGE in cases that would normally stagnate. Nevertheless, this effect is only temporary as the generation of carbon credits is not possible anymore once LFGE is considered to be the common practice in a country.

The results were synthesised into a flowchart indicating the different pathways to diffusion. This flowchart can be used by project developers to assess different countries on their LFGE potential. Additionally, the assessment of the institutional building block allows policymakers to effectively implement policies that enhance the diffusion of LFGE.

This research comes with its limitations. Firstly, this study focused on the potential of existing landfills. Moreover, the focus of this research was on the formative stage in innovation development.

Additionally, the limited number of interview participants and the limited variety within the group of interview participants might have skewed the results into an economic direction.

Future research recommendations include further exploration of the proposed hybrid approach. Additionally, different stages in the development of the TIS as well as the potential for the TIS to decline during the formation phase can be considered. Finally, future research could further explore the LFGE case by implementing the remaining barriers or the effect of the fossil fuel based regime on the development of the LFGE TIS.

Key terms: Landfill gas to energy projects, Technological Innovation Systems, System Dynamics, Africa

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List of Abbreviations

CER	Certified Emission Reductions
CLD	Causal Loop Diagram
ER	Emission Reductions
LCOE	Levelised Cost Of Energy
LFG	Landfill gas
LFGE	Landfill gas to energy
MSW	Municipal Solid Waste
PPA	Power Purchase Agreement
SD	System Dynamics
SFD	Stock Flow Diagram
SRQ	Sub Research Question
TIS	Technological Innovation System
UN	United Nations
VCM	Voluntary Carbon Market
VER	Voluntary Emission Reduction
WtE	Waste to energy

1. Introduction

Population growth, economic development and urbanisation are causing a rapid increase in municipal solid waste (MSW) (Guerrero et al., 2013). Zuberi and Ali (2015) define MSW as non-hazardous waste generated in households, markets, streets, commercial areas, and industries. Globally, two billion tonnes of MSW are produced (Wilson & Velis, 2015). Njuko et al. (2018) state that around 85% of the MSW ends up in landfills globally. This great share of MSW ending up in landfill is not surprising as landfilling is one of the cheapest methods to dispose of waste (Njoku et al., 2018; Cudjoe & Han, 2021). However, landfills are associated with soil and air pollution, and health risks, if not managed correctly (Iravanian & Ravari, 2020; Muvundika, 2015). Additionally, the methane emitted from landfills contributes substantially to global warming (Njoku et al., 2018). According to Wilson and Velis (2015) the direct methane emissions from municipal waste were estimated to be 3% of total greenhouse gas emissions in 2010.

While methane is a significant contributor to global warming if not managed properly, it can also be utilised as an energy source (Li et al., 2015). To capture this energy potential of landfill gas (LFG), landfill gas to energy (LFGE) projects have emerged. Within a LFGE project, LFG is captured and used in processes such as electricity generation, direct use, combined heat and power generation, and vehicle fuel (Njuko et al., 2018; Li et al., 2015). This change in waste management comes with both social and environmental benefits, such as improved energy supply, emission reductions, and waste reduction (Njoku et al., 2018; Li et al., 2015; Mbazima et al., 2022). Another benefit of LFGE projects is due to the potential to generate carbon revenue in the form of Emission Reductions (ER), also known as carbon credits (Bogner & Lee, 2005). While not all LFGE projects necessarily generate carbon credits, LFGE projects are recognized on both the regulatory and the voluntary carbon market (VCM) and can thus be used to offset parts of the emissions generated in a country or company, while also generating revenue for either the government or local organisations. According to Streck (2021), the VCM has a great potential to contribute to carbon mitigation action and encourage governments to implement more ambitious climate actions.

The potential of LFGE projects within the VCM becomes clear when looking at the US and Turkey. The US currently has 170 listed, registered or completed LFGE projects under one of the four major carbon standards as registered in the Berkely database (Haya et al., 2024). This database contains all carbon offset projects listed globally by four major voluntary offset project registries from 1998 until 2023. These American projects have already issued 55 million carbon credits, which is equivalent to 55 million tonne CO_2. Additionally, the database shows 58 listed, registered or completed LFGE projects for Turkey, resulting in 19 million credits being issued (Haya et al., 2024).

1.1 Policy relevance

While LFGE projects have demonstrated to be successful, their success is not guaranteed. Figure 1 illustrates the discrepancy between the USA, Turkey, and the whole African continent. Njoku et al. (2018) state that Africa has not been able to utilise their LFG. Across the entire African continent, currently only 12 LFGE projects are registered under one of the major standards, of which nine are located in South Africa (Haya et al., 2024). These projects have barely generated 1 million carbon credits (Haya et al., 2024). According to Mbazima et al. (2022), only six of these nine projects in South Africa are operational. However, during the period from 2010 to 2020, 17 LFGE projects were planned in South

Africa, underscoring the disparity between intention and implementation (Mbazima et al., 2022). This applies to both VCM-related LFGE projects and LFGE projects in general.

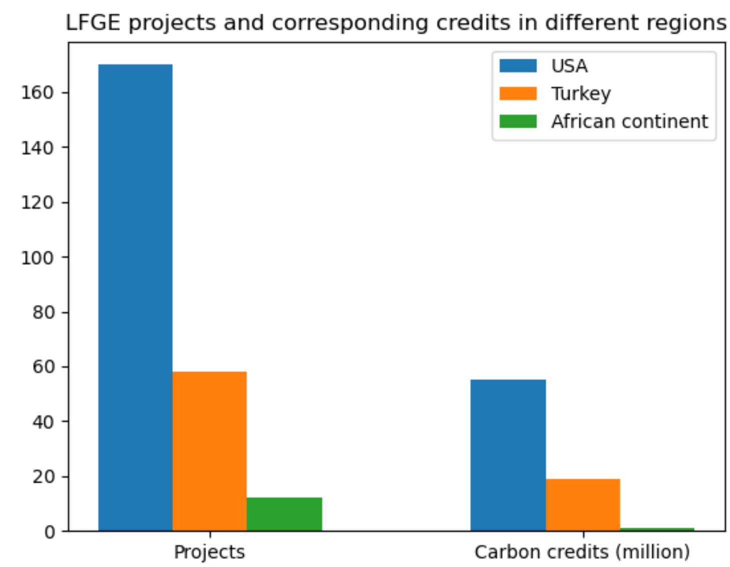

Figure 1. Comparison LFGE projects and corresponding carbon credits in different regions. Based on data from Haya et al. (2024)

However, there is potential for LFGE projects in Africa in terms of waste generation. Scarlat et al. (2015) estimate that the total methane production of the African continent is 10496 x 10^6 Nm^3 , which results in an electricity potential of 282602 TJ per year, under the assumption that all waste is landfilled. Additionally, in most African countries over 90% of their MSW is going to landfills, and the MSW generation is expected to double in the next 15 years. Nevertheless, the few LFGE projects that are implemented in this geographical area indicate that the energy potential of LFGE projects remains underutilised (Njuko et al., 2018; Wilson & Velis, 2015). Africa has approximately 1% of the global LFG utilisation technologies, and the rate at which this increases is very low (Njoku et al., 2018). However, African countries could benefit from utilising LFG through LFGE projects as access to electricity is often not sufficient (Cudjoe & Han, 2021). According to Mbazima et al. (2022) approximately 600 million people do not have access to electricity in African countries.

The anticipated rise in municipal solid waste across African countries stresses the urge for improved landfill management (Cudjoe & Han, 2021; Njuko et al., 2018). However, the cause of the scarcity of LFGE projects in Africa is still unclear. Some studies have already identified factors influencing the adoption of LFGE projects in Africa (Njuko et al., 2018; Karekezi et al., 2009). These factors do not only include technical factors, but also factors that are related to the socio-technical system surrounding LFGE projects. For example, Njoku et al. (2018) mention that poor policies on waste and lack of political will are challenges to the adoption of LFGE projects. In addition, it is expected that the VCM could affect the adoption of LFGE projects, but this effect is not widely researched yet. To include both the effect of the technical factors and the non-technical factors on the diffusion of LFGE projects in Africa, this research analyses the whole technological innovation system (TIS) surrounding those projects.

However, the relations between the drivers and barriers, and other dynamics within the innovation system, such as feedback loops or delays, remain unclear. Nevertheless, Walrave and Raven (2016) state that the growth and decline of innovation systems are dynamically complex processes and that an understanding of the interactions between innovation systems and their environment is important, as innovation systems do not emerge in a vacuum.

1.2 Scientific relevance

While efforts have been made to identify the relevant factors influencing the adoption of LFGE projects (Karekezi et al., 2009; Njoku et al., 2018; Mbazima et al., 2022), there is a lack of research on the interactions, feedbacks, and delays of LFGE projects. A more generic approach to study the emergence of technological innovation systems in the context of sustainable transitions is through the Technological Innovation System (TIS) framework (Markard, 2020). A TIS refers to a network of actors and institutions that interact in a specific technological domain and contribute to the generation, diffusion, and utilisation of a technology (Markard, 2020). Currently, two main approaches exists within the framework; the dynamic functional approach, and the more static structural approach. The static structural approach is useful for assessing the status of a TIS at a certain moment in time, whereas the dynamic TIS functions can be defined as the key processes required for a good performance of a TIS (Suurs & Hekkert, 2009; Hekkert et al., 2007; Bergek et al., 2008a; Bergek et al., 2008b). Ortt and Kamp (2022) have used the static structural TIS approach to create a framework of seven building blocks of emerging technological innovations. These building blocks include product performance and quality, production system, complementary products and services, product price, network formation and coordination, customers, and innovation-specific institutions. While the static functional approach provides a general understanding of the relevant factors of an emerging technological innovation, the dynamics within the socio-technical system surrounding a LFGE project remain unclear. Here, the dynamic functional approach comes in. There exist two sets of widely used TIS functions (Hekkert et al., 2007; Bergek et al., 2008a). Walrave and Raven (2016) have created a generic system dynamics (SD) model based on the functions of Hekkert et al. (2007) to create an understanding of the relationships between factors within a TIS, as well as potential feedback loops and delays. However, separating the functional and structural approaches prevents investigation into how structural drivers and barriers affect the diffusion of LFGE projects within the TIS over time. No research has been conducted yet on combining the two approaches into one model. This research will fill this knowledge gap by creating a conceptual model of this hybrid approach. Additionally, this conceptual model will be converted into a system dynamics (SD) model to investigate the diffusion of the LFGE TIS over time. Additionally, this research will contribute to the body of literature on the diffusion of LFGE projects by identifying the conditions required for the emergence of LFGE projects in the African context. Moreover, the role of the VCM will be investigated, which is currently not widely done.

1.3 Knowledge gaps

While the literature shows that efforts have been made to identify drivers and barriers for the adoption of LFGE projects in Africa, a dynamic understanding of the barriers and their effect on the diffusion of the LFGE innovation system is missing. Understanding the dynamic behaviour allows for an explanation of the lack of diffusion and provides an opportunity to explore conditions that enhance the emergence of LFGE projects in Africa. Another knowledge gap can be found in the omission of carbon financing, for example through the VCM, as a potential supporting factor of the LFGE innovation system. Investigating the impact of carbon financing on the diffusion of LFGE projects allows for an evaluation of the effectiveness of carbon financing in relation to LFGE projects in the African context and could potentially lead to increased utilisation of this market mechanism, if proven effective. A knowledge gap can also be found in the dynamic evaluation of drivers and barriers on the emergence of a TIS. A hybrid approach, combining the functional and structural TIS approaches, would both provide the level of detail to incorporate structural drivers and barriers, and the opportunity to assess the impact of these drivers and barriers over time.

1.4 Research objectives

The first aim of this research is to create a hybrid approach for assessing a TIS, combining the dynamic functional approach and the more static structural approach into one model. This links to the second research aim, which is to create an understanding of the dynamic behaviour of the LFGE innovation system to explain the reasons for the limited adoption of LFGE projects, and explore conditions within the system under which diffusion of LFGE projects could be enabled. This could guide project developers in their search for countries in Africa with high potential for LFGE and thus increase the number of successful LFGE projects. This may then stimulate further diffusion as benefits become more widely recognized and best practices are established. Additionally, this research could guide policymakers in creating an enabling institutional context for LFGE. The societal benefits of an increased number of LFGE projects in Africa will be improved waste management and the corresponding reduction in human health risks, reduction in the impact of African landfills on global warming, and a more secure energy supply in Africa.

1.5 Research questions

To fulfil the research objectives, the following research question will be answered:

What conditions within the landfill gas to energy innovation system enhance the diffusion of landfill gas to energy projects in Africa considering the dynamic behaviour of the innovation system?

This research question can be broken down into the following five sub-questions:

1. How can the TIS framework of Ortt and Kamp (2022) be connected to the TIS functions?

   As this research aims to identify the conditions necessary for LFGE to diffuse, a combination of the more general functional approach and the more detailed structural approach to investigate a TIS is required. Therefore, a connection is made between the structural framework of Ortt and Kamp (2022) and the TIS functions. Later in this study, this will be integrated into a SD model to assess the TIS of landfill gas to energy projects specifically.

2. What are the key drivers and barriers influencing the adoption of landfill gas to energy projects in Africa?

   To understand why landfill gas to energy projects are currently not emerging in Africa, a description of the innovation system in which LFGE projects operate is necessary. An important step in creating this description of the innovation system is the identification of the drivers and barriers influencing the adoption of LFGE projects. One factor that will also be included is the possibility to generate carbon credits to investigate its effect on the diffusion of LFGE projects in Africa.

3. What are the causal relations between the drivers and barriers and the TIS model as defined in SRQ1?

   Connecting the drivers and barriers to the TIS model following the hybrid approach created to answer SRQ1, will create an understanding of how these drivers and barriers influence the TIS.

4. What are the key factors or combinations of factors within the landfill gas to energy innovation system influencing the diffusion of landfill gas to energy projects in Africa?

   In SRQ3, a general overview of the structure of the system is created. SRQ4 will then identify which factors or combinations of factors within the structure are most important for the diffusion of landfill gas to energy projects in Africa.

5. Which system conditions will result in the diffusion of landfill gas to energy projects in Africa?

   Once the most impactful factors or combinations of factors have been identified, they can be used in different scenarios to determine the enhancing conditions for the diffusion of landfill gas to energy projects in Africa.

To answer these questions, a literature study is performed on TIS structures and functions to create a connection between the two, resulting in a conceptual model of the hybrid approach. Additionally, a literature study is performed to identify the drivers and barriers of LFGE projects in Africa. This is complemented by exploratory expert interviews. This information is combined into a system dynamics model, which is calibrated on South Africa. The model will then be used to investigate the conditions necessary for LFGE projects to diffuse.

1.6 Research scope

This research focusses on the formative phase of landfill gas to energy projects on country level. Edsand and Bångens (2024) argue that technologies that are relatively new to a country are often in the formative phase. During the formative stage, the TIS structures are developing and slowly taking shape, but feedback loops are still harder to establish (Bergek et al., 2008a; Edsand & Bångens, 2024). Edsand (2019) argues that the analysis of an innovation system during the formative stage will provide insights in the status and trends of processes that are considered to be important for achieving the later growth stage, in which the TIS has matured.

Additionally, as this study investigates the conditions necessary for LFGE projects to be successful and diffuse, rather than proposing policies to stimulate the adoption of LFGE projects, a project developer perspective is considered. This is different from the general body of literature on TIS, in which mainly a government perspective is taken to investigate the effect of policies. The company perspective, as also employed by Ortt & Kamp (2022) and Gruenhagen et al. (2022), could provide a more disaggregated approach compared to the governmental perspective. Nevertheless, this research remains relevant for policy makers because the institutional structure will also be explored.

Finally, it should be noted that this research is performed on country level, rather than on the individual project level because the TIS framework requires a broad, systems perspective.

1.7 Structure

The rest of the report is structured as follows. First, an introduction to landfill gas to energy projects is given in Chapter 2, followed by an introduction to the TIS framework in Chapter 3. Chapter 0 explains the methodology used in this research. Then the results of the connection between the TIS functions and the TIS building blocks are presented in Chapter 5, which is followed by an explanation of the LFGE TIS and the drivers and barriers found in Chapter 6. Chapter 7 will tailor the model to the LFGE case, provide validation of the SD model, and explain the experimental design. Chapter 8 will present the results of the experiments, followed by a discussion of the results and a reflection on the research in Chapter 0. Finally, Chapter 10 will conclude the research by answering the research questions and providing recommendations.

2. Landfill gas to energy projects

This chapter introduces landfill gas to energy projects as a waste to energy technology. Additionally, the context of carbon markets and their relation to LFGE projects will be explained.

2.1 Landfilling as waste to energy technology

Waste to energy (WtE) technologies extract energy from the organic components of municipal solid waste (MSW). According to Khan et al. (2022), there are three main processes that extract energy from waste: thermochemical, biochemical, and chemical. Thermochemical WtE processes include incineration, gasification to produce biogas, and pyrolysis, whereas physicochemical processes include transesterification (Khan et al., 2022; Agbejule et al., 2021). Finally, biochemical processes include anaerobic and aerobic digestion, fermentation and landfill gas recovery (Khan et al., 2022; Agbejule et al., 2021). Landfill gas recovery is often performed in a sanitary landfill, which is a facility used to store non-hazardous waste to limit the impact of the municipal waste on the environment (Agbejule et al., 2021). The waste stored in these landfills breaks down over time due to biological, physical, and chemical processes (Agbejule et al., 2021).

Disposal of waste in landfills is considered the least preferred method of waste management and comes with its problems, such as pungent odour, environmental pollution, and climate change (Njoku et al., 2018). The decomposition of waste within a landfill results in the emission of landfill gas, which is mixture of about 50% methane, 50% CO_2 and trace amounts of other gases (Miito & Banadda, 2016; Muvundika, 2015). Both methane and CO_2 are greenhouse gases, but methane is 28 to 34 times more potent than CO_2 over 100 years (IPCC, 2013). Additionally, landfills can produce leachate and other liquids, which could pollute the surface water and groundwater, if managed incorrectly (Amo-Asamoah et al., 2020; Agbejule et al., 2021). Moreover, a landfill can produce strong odours due to the sulphides and ammonia in the LFG, as well as litter and dust affecting their close surroundings (Njoku et al., 2018). However, landfilling is still a widely used and approved waste management practice in most African countries because of its low costs and relatively low complexity of the technology (Olodu & Erameh, 2023; Njoku et al., 2018).

To reduce the environmental impact of landfills and simultaneously tackle waste management problems, LFG could be collected. According to Mbazima et al. (2022), the amount of LFG produced depends on the amount of waste in the landfill, the type of waste, the techniques used for disposing and handling the waste, and the cover system used. Regarding the type of waste, LFG production requires a MSW stream with a high organic content, as it is the organic content in the waste that will be anaerobically digested inside the landfill to produce methane (Olodu & Erameh, 2023). Once collected, the LFG could be flared to convert the methane emissions into CO_2 emissions, directly used, used as vehicle fuel, or used in a combined heat and power plant (Olodu & Erameh, 2023; Li et al., 2015). However, due to the corrosive nature of hydrogen sulphide, one of the components of LFG, a cleaning process removing the hydrogen sulphide and other impurities is required before directly using the LFG (Solomon et al., 2021). Additionally, the LFG could be converted into electricity in landfill gas to energy (LFGE) projects. Within a LFGE project, the emitted landfill gas is collected and burned in internal combustion engines to convert it to electricity (Freeman, 2022). Figure 2 (United States Department of Energy, 1995) shows the typical landfill gas to energy process.

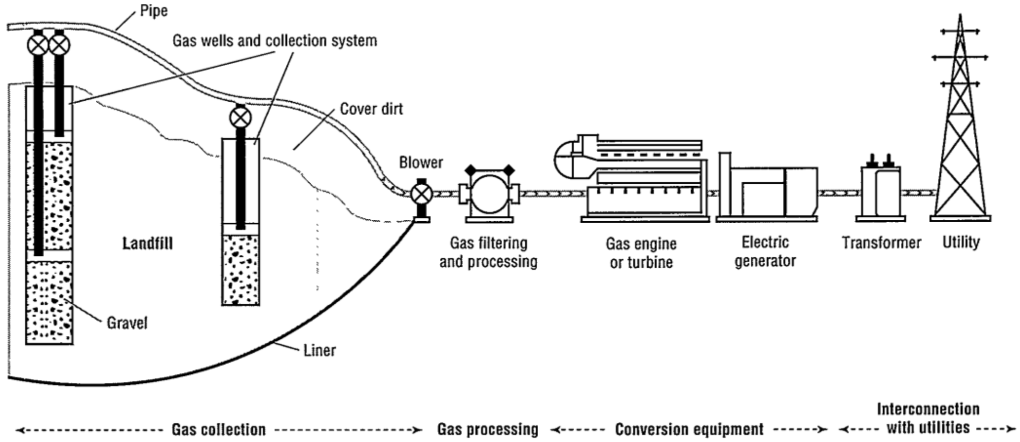

Figure 2. Typical landfill gas to energy facility (United States Department of Energy, 1995)

2.2 Landfill gas to energy projects in the context of carbon markets

The introduction of the Kyoto protocol in 1997 resulted in most industrialised countries committing to national emission targets (Cassimon et al., 2023; Couth et al., 2011). As the Kyoto protocol became binding in 2005 and put caps on national emissions, it can be seen as a cap-and-trade scheme (Cassimon et al., 2023). With the Kyoto protocol came the Clean Development Mechanism (CDM), which allowed developing countries to generate Certified Emission Reduction (CER) credits, also known as carbon credits and equivalent to one tonne of CO_2 each, by reducing their emissions in emission reduction projects (Cassimon et al., 2023; Bogner & Lee, 2005). The CERs can then be traded with industrialised countries, who can use them to partially offset their emissions (Cassimon et al., 2023). In 2015, the Paris Agreement superseded the Kyoto protocol, but CERs resulting from CDM projects continued to issue carbon credits. In addition, the Paris Agreement comes with its own mechanisms that allow the trade of carbon emissions between countries (Cassimon et al., 2023). Emissions reductions can be traded on both the regulatory carbon market, where mandatory CERs are exchanged, and the voluntary carbon market, where voluntary emission reductions (VERs) are traded outside the UN climate change regime (Lang et al., 2019).

There are two ways to use LFG to generate carbon credits. First, the LFG can be flared, which means methane will be converted into CO_2 (Muvundika, 2015). Since CO_2 is less potent than methane, this reduces the total emissions of a landfill, which can be converted into carbon credits. However, flaring does not generate co-benefits, such as electricity. Therefore, this research focuses on the second way to generating carbon credits, which involves converting the methane into electricity (Muvundika, 2015). This prevents most of the methane emissions, resulting in the generation of carbon credits. Moreover, the electricity of the national electricity grid is partially replaced by the renewable electricity from LFGE, resulting in additional emission reductions. Nevertheless, there is the requirement for carbon projects to show “additionality”, meaning that the emissions reductions would not have happened without the carbon project (Couth et al., 2011). Projects that are viable without the sale of carbon credits are not additional and therefore cannot generate carbon credits. Moreover, when there is legislation in a country that requires the collection and combustion of LFG, the project is also not considered additional (Couth et al., 2011). Finally, if a technology has already diffused in a country, and can therefore be considered the common practice, it does not meet the additionality requirement (UNFCCC, 2017; UNFCCC, 2015).

To assess the diffusion of LFGE in Africa, the TIS framework is used. According to Markard (2020), the TIS approach is widely used to study the emergence of technological innovations in the context of sustainable transitions. Chapter 3 provides an overview of the past research conducted on TIS.

3. Introduction to the TIS framework

A comprehensive literature review was conducted on the Technological Innovation System (TIS) framework. The databases Google Scholar, Scopus, and Web of Science were consulted. Search terms used were "Technological Innovation System", "Technological Innovation System functions", and "Technological Innovation System structures". The abbreviation TIS was also tried for all search terms. Both forward and backward snowballing was applied to the relevant papers. The selection of papers was based on the relevance of the title and abstract of the paper. Papers on case studies applying the TIS framework were discarded as the aim of this search was to develop a synthesis of the theory, unless the TIS framework was used on the diffusion of renewable energy technologies in Africa, or entailed a company perspective. This resulted in 15 papers being selected. An overview of the selected papers is shown in Table 1.

Table 1. Overview of the selected papers

Author	TIS approach	Contributions
Bergek et al. (2008a)	Functional	They provide a practical scheme to analyse the different TIS functions. The focus of this scheme is on the analysis of the TIS functions, with limited attention given to its structures.
Bergek et al. (2008b)	Functional	They propose a functional framework to analyse the dynamics of a TIS. Their framework is similar to the one proposed by Hekkert et al. (2007), although subtle differences in interpretation exist. Additionally, they focus on the analysis of legitimation and development of positive externalities.
Carlsson & Stankiewicz (1991)	Structural	They provide an early description of the technological innovation systems framework. The focus lies on the components of a TIS. The authors also mention components that are turned into TIS functions in later research.
Edsand (2019)	Functional	Edsand complements the TIS functions defined by Hekkert et al. (2007) to fit the context of developing countries. He proposes three additions to the TIS functions as well as six landscape factors to consider.
Edsand & Bångens (2024)	Functional	They apply the extended TIS functions framework by Edsand (2019) to analyse the case of solar PV diffusion in Tanzania. They mainly focus on formal and informal institutions.
Gruenhagen et al. (2022)	Functional	They identify drivers and barriers on the firm level by taking an actor-oriented perspective when applying the functional TIS framework. They demonstrate this through a case on the Australian mining sector.
Hekkert et al. (2007)	Functional	They switch from the structural approach to the functional approach by proposing a framework that focusses on the most important processes within a TIS, which are called 'functions of innovation systems'. Their framework is similar to the one proposed by Bergek et

		al. (2008b), although small differences in interpretation exist.
Jacobsson & Bergek (2004)	Functional	They investigate the influence of inducing and blocking mechanisms on TIS functions, specifically in the case of renewable energy, taking Germany, the Netherlands, and Sweden as an example. Their analysis results in several policy challenges.
Jacobsson & Bergek (2011)	Both	They link the TIS functions as defined by Bergek et al. (2008a) to system weaknesses on the structural level in the area of environmental innovation. They also include a variety of recommendations for future research to improve the TIS framework.
Markard (2020)	Structural	Markard introduces a TIS life cycle framework considering four stage of TIS development: formation, growth, maturity, and decline, instead of focussing only on the formation and growth phase only, like in previous research. The framework is illustrated with three cases.
Ortt & Kamp (2022)	Structural	They have developed a TIS framework consisting of building blocks and influencing conditions that can be used by companies to create introduction strategies.
Raven & Walrave (2020)	Functional	They use the system dynamics model by Walrave & Raven (2016) to investigate how policy interventions influence four types of transformational failures identified by Weber and Rohracher (2012) through the dynamics with the TIS functions.
Suurs (2009)	Both	He provides an overview of the TIS framework, both in terms of structures and functions. Additionally, the TIS framework is connected to the motors of innovation, and the relation between TIS structures and TIS functions is presented. Finally, the framework is demonstrated on multiple case studies.
Suurs & Hekkert (2009)	Both	They propose a 'Succession Model of Innovation' in which they link four 'motors of innovation', which include different sequences of TIS functions, to the structural TIS elements by identifying structural drivers and barriers to each motor as well as describing the impact of each motor on the structure.
Walrave & Raven (2016)	Functional	They have created a system dynamics model of the development of a TIS based on the TIS functions by Hekkert et al. (2007) to understand the emergence of a technological innovation system in the context of a socio-technical transition pathways.

3.1 Technological Innovation System approach

When analysing the development of technological innovations it is important to take a systems approach as these innovations do not emerge on their own, but they are heavily influenced by the economical, organisational, and institutional structures surrounding them (Carlsson & Stankiewicz, 1991). Because of this, the diffusion of an innovation is not only an individual, but also a collective process (Jacobsson & Bergek, 2004). Carlsson and Stankiewicz (1991) have investigated the process in which a new technology emerges and diffuses by using the concept of technological systems, a technological-specific innovation system, which is currently known as a Technological Innovation System (TIS). The TIS approach is important for analysing the development of sustainable transitions (Markard, 2020). A TIS is defined as "a dynamic network of agents interacting in a specific economic/industrial area under particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology" (Carlsson & Stankiewicz, 1991, p.93). Therefore, a TIS does not only identify technological components, but all components relevant for the innovation process of the technology (Bergek et al., 2008a). From the definition of a TIS, the main components can be identified as technologies, actors and networks, and institutions, also known as TIS structures (Suurs & Hekkert, 2009; Markard, 2020). Following Suurs and Hekkert (2009), technologies can be defined as the products and the infrastructures in which they are integrated, while actors are the organisations that contribute to the emergence of the technology, e.g. developers, adopters, financers, and regulators. Finally, institutions include laws and regulations, as well as technology standards, and can be viewed as 'rules of the game' (Suurs & Hekkert, 2009).

The goal of the TIS framework is to create an understanding of the emergence and development of new technological innovations within their innovation system (Walrave & Raven, 2016; Markard, 2020). This can be achieved by employing a static approach to analysing the TIS structures at a certain moment in time (Suurs & Hekkert, 2009). Such analysis of the TIS structures generally results in an identification of the drivers and barriers to the diffusion of a TIS (Suurs, 2009).

Ortt and Kamp (2022) have developed a TIS framework, which identifies seven TIS building blocks and seven factors that influence these building blocks. Their framework can be used by companies to develop strategies to introduce new technologies (Ortt & Kamp, 2022). The building blocks identified are product price, production system, complementary products and services, network formation and coordination, customers, and innovation-specific institutions (Ortt & Kamp, 2022). A distinction is made between the production system and complementary products and services. The production system should be able to "deliver high quality products in large quantities" (Ortt & Kamp, 2022, p4.). The complementary products and services, on the other hand, support the development, production, distribution, adoption, use, repair, maintenance and disposal of the innovation (Ortt & Kamp, 2022). An example of a complementary product is the infrastructure supporting the distribution of a product. They argue that every building block can turn into a barrier if incomplete. Their framework is static and therefore mainly suitable for assessing the status of the TIS at a specific moment in time, rather than understanding the mechanisms of the evolution of the TIS.

3.2 Functions of a Technological Innovation System

Another approach to analysing a TIS is by outlining the TIS functions, which can be defined as the key processes that are important for the performance of a TIS (Hekkert et al., 2007; Bergek et al., 2008a; Bergek et al., 2008b). Hekkert et al. (2007) identify seven TIS functions: entrepreneurial activity, knowledge development, knowledge diffusion, guidance of search, market formation, resource mobilisation, and creation of legitimacy. Entrepreneurial activity turns the potential of new knowledge, markets, and networks into new business opportunities, which can be measured as the number of new entrants or the number of experiments with the new technology (Hekkert et al., 2007; Bergek et al., 2008a). The knowledge development and diffusion include different methods of mechanisms of learning, namely 'learning by searching', 'learning by doing', 'learning by interacting', and 'learning by using'. These functions indicate the generation and exchange of information within a network (Hekkert et al., 2007). Guidance of search refers to the activities that change the preferences in society and generate incentives or pressure for organisations to enter a TIS. These activities can include new targets set by governments or industries, as well as articles in professional journals (Hekkert et al., 2007, Bergek et al., 2008a). The market formation functions relates to the creation of a protected space for new technologies, e.g. through nice markets or favourable tax regimes, as it is often challenging for a new technology to compete with incumbent technologies (Hekkert et al., 2007). The final two functions as described by Hekkert et al. (2007) relate to the mobilisation of human and financial resources which can be used as input to the other activities, and the creation of legitimacy of the TIS by counteracting resistance to change and lobbying. Edsand (2019) has tailored the list of functions defined by Hekkert et al. (2007) to the context of developing countries by proposing three nuances. First, he proposes to add the creation of adaptive capacity to the list of functions. He defines adaptive capacity as the capability of a country to receive a new technology, which can be assessed by the status of the human, institutional, and organisational capacity of a country. The second nuance Edsand proposes regards the distinction between international and national resource mobilisation. Examples of international resources include carbon offsets and foreign direct investment (Edsand, 2019). The mobilisation of these resources could be hampered when other functions are weak (Edsand, 2019). Finally, Edsand proposes to distinguish between formal creation of legitimacy, through formal lobbying organisations, and informal creation of legitimacy, through smaller, less organised groups or individuals (Edsand, 2019).

While Hekkert et al. (2007) give a description of the most important activities within a TIS, they do not provide clear guidance on how to assess the performance of a TIS. To this end, Bergek et al. (2008a) have created a practical scheme that could be used to analyse innovation systems based on both their structures and dynamics. These steps are:

1. Defining the TIS focus.
2. Identifying the structural components of a TIS.
3. Mapping the functional patterns of the TIS.
4. Assessing the functionality of the TIS.
5. Identifying drivers and barriers.
6. Specify policy issues.

In the first step, the level of aggregation is determined, after which the structural components (actors, networks, and institutions) can be identified (Bergek et al., 2008a). During the mapping of the functional patterns, the fulfilment of the TIS functions is assessed. The functions proposed by Bergek et al. (2008a) and Bergek et al. (2008b) are slightly different compared to those identified by Hekkert et al. (2007), and include knowledge development and diffusion, entrepreneurial experimentation, influence in the direction of search, market formation, development of positive external economies, legitimisation, and resource mobilisation. Step four then helps to interpret this fulfilment of the functions in the light of the development phase of the TIS. According to Bergek et al. (2008a) it is fruitful to distinguish between two different development phases, the formative phase and the growth phase, since they both have different requirements in terms of the fulfilment of the TIS functions. They identify the formative phase as the stage in which there are large uncertainties regarding the technology and the market, there is no well-developed price or performance of the products, the demand is unarticulated, and the volume of diffusion is smaller than the expected volume, which could be due to the absence of positive feedbacks. On the other hand, they define the growth phase as system expansion and large-scale diffusion. The final two steps in the scheme of Bergek et al. (2008a) relate to the identification of the drivers and barriers enhancing or blocking the TIS functions. These drivers and barriers can be both internal and external mechanism as well as policies. However, while these steps include the identification of the structural components of the TIS, the TIS structures are not used to identify barriers and their impact on the development of the TIS over time. Rather, they provide a description of the components of the system (Bergek et al., 2008a).

Suurs and Hekkert (2009) have conducted research on the dynamics that drive technological innovation. They argue that TIS development may accelerate as a result of positive feedback loops between the TIS functions that interact over time, so-called 'motors of innovation'. These 'motors of innovation' can be considered as the different phases in the development of a TIS and refer to the interactions between the TIS functions (Walrave & Raven, 2016; Raven & Walrave, 2020). The 'motors of innovation' are: Science and Technology Push Motor, Entrepreneurial Motor, System Building Motor, and Market Motor (Suurs & Hekkert, 2009). According to Walrave & Raven (2016), the Science and Technology Push Motor concerns the development and diffusion of knowledge, leading to an increase in entrepreneurial activity, which in turn affects the political and financial support. This motor is followed by the Entrepreneurial Motor, in which they argue that an increased number of entrepreneurs working with the technology results in an increase in legitimacy and resource mobilisation, which feeds back into knowledge development. They indicate the System Building Motor to be the phase in which the TIS structures increase, for example, the formation of actors, reconfiguration of institutions, and infrastructural developments. However, due to the increasing requirement for resources for further development and the still limited internally generated resources, this phase is considered to be challenging (Walrave & Raven, 2016). Finally, after passing the System Building motor, the Market Motor is activated. During this phase, the innovation system generates enough internal resources to maintain the required processes and the innovation system is generally perceived as legitimate (Walrave & Raven, 2016).

3.3 System Dynamics and TIS

Uriona and Grobbelaar (2019) provide a literature review of fifty-four studies that use system dynamics models in the context of innovation systems. The papers they reviewed mainly included models on R&D policies, science and technology policies, agglomeration policies, and diffusion policies. Most of these papers focus only on part of the innovation system, rather than on the innovation system as a whole. Walrave and Raven (2016) bridge this gap as they have translated the TIS functions and 'the motors of innovation' into a system dynamics (SD) model to understand the emergence of a TIS over time. They base their SD model on the TIS functions as identified by Hekkert et al. (2007). Their method adds a quantitative approach of assessing the TIS functions, compared to the qualitative methods provided in literature (Bergek et al., 2008a; Edsand & Bångens, 2024). Raven and Walrave (2020) extend this model by including policy interventions to assess their effectiveness. However, the SD model by Walrave and Raven does also not consider the explicit connection between the TIS functions and TIS structures. While they do acknowledge the TIS structures within their model, the relations between the TIS structures and functions are modelled as a black box (Walrave & Raven, 2016). This creates challenges in assessing the effect of potential barriers on the diffusion of a TIS over time.

4. Research methodology

To understand why LFGE projects are currently not emerging in Africa and to evaluate the conditions necessary for these projects to diffuse in Africa, a good understanding of the innovation system is required. To gain this understanding, first the TIS functions and TIS building blocks as identified by Ortt & Kamp (2022) were conceptually linked. The TIS framework is used because it focuses on the emergence of an innovation system surrounding a technological innovation. As explained in Chapter 3, there are currently two approaches within the TIS research, the functional approach and the structural approach. The latter was extended to TIS building blocks by Ortt & Kamp (2022). Combining these two approaches allows for the dynamic assessment of the effect of the drivers and barriers, which are expected to be related to TIS structures rather than functions, on the development of a TIS.

After the conceptual link was created, a descriptive approach was taken to understand the different components of the LFGE TIS and the barriers to its diffusion. Once the components of the LFGE TIS were inventoried, a system dynamics (SD) model was constructed to deepen the understanding of the LFGE TIS and its emergence. Walrave and Raven (2016) state that the relations between innovation systems and their context are important as the potential of these systems is reliant on their environment and its dynamics. Additionally, they state that the growth and decline of Technological Innovation Systems (TIS) are dynamically complex processes. This is also acknowledged by Ortt and Kamp (2022) as they state that a dynamic model is more suitable for understanding mechanisms of the evolution in a TIS compared to a static model. Additionally, Saleh et al. (2010) state that SD has the purpose to identify the relations between system structure, policies, and problematic behaviour to identify potential solutions. Finally, Bala et al. (2013) argue that SD is an effective method for sustainability questions due to its long-term perspective and potential to include feedbacks. Therefore, SD is considered an appropriate method to identify the conditions under which LFGE projects could diffuse in Africa. As Walrave & Raven (2016) have already created a SD model on the diffusion of a TIS through a functional approach, their model was taken as a starting point to which the building blocks were added.

The research design of this study is shown in Figure 3. The yellow blocks represent inputs required for a specific step in the model cycle, while the blue blocks show the sub-research questions answered in a certain step. First, a conceptual connection between the TIS functions and the TIS building blocks was created. This general conceptual model was then used as a starting point for the conceptualisation phase of the modelling the cycle. The modelling cycle used in this research is based on the SD modelling cycle as identified by Auping et al. (2023). They identify five steps in the modelling cycle. During the first phase, problem articulation, the research scope is determined. It is recommended that the focus is on the problem rather than on the whole system, meaning that only the part of the system that is causing the problematic behaviour is modelled (Auping et al., 2023). In this case, this means only modelling the parts of the system in detail that are related to the barriers. The second phase they identify is the conceptualisation phase. During this phase, a conceptual model is formulated that can be converted into the SD model in the formulation phase. Additionally, conceptual models can be used to communicate the core structure of a model to the public. During the formulation phase, the conceptual model was formalized by specifying the equations and parameter values. The model was then verified and validated during the model evaluation phase, after which it was used for analysis. It should be noted that the modelling cycle is a highly iterative process that requires moving back and forth between different steps.

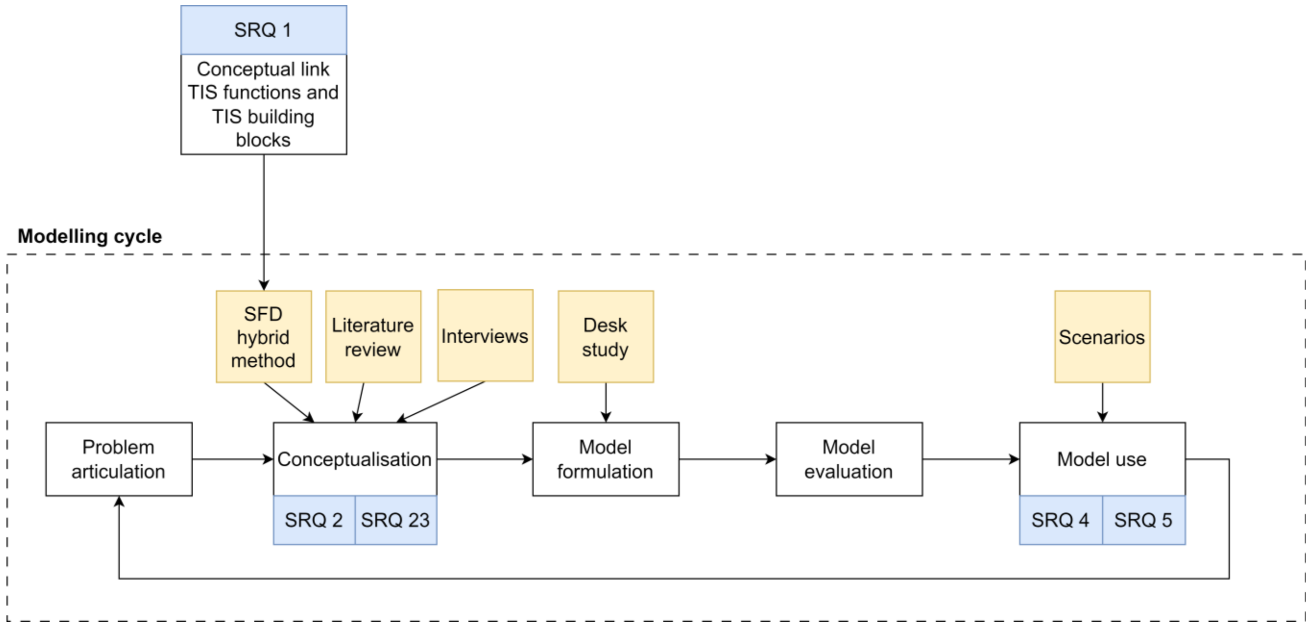

Figure 3. Simplified research flow.
The yellow blocks represent inputs required for a specific step in the model cycle, while the blue blocks show the sub-research questions answered in a certain step.

4.1 Conceptual link TIS approaches

First, the TIS functions and the TIS building blocks were conceptually linked to answer SRQ1. The TIS functions as identified by Edsand (2019) were used. Edsand extends the functions identified by Hekkert et al. (2007) to adapt them to the context of developing countries. The TIS functions were first linked to the three TIS structures, to reduce the complexity of the model. Once these relations were established, the conceptual model was extended to incorporate the TIS building blocks. The resulting, more detailed model, was then used converted into a Causal Loop Diagram (CLD), which not only included the causal relations between the TIS functions and TIS building blocks, but also the relations between the TIS functions themselves. To accomplish the latter, the relations identified by Walrave & Raven (2016) were taken as a starting point and added to the CLD. Finally, the CLD was converted into a stock flow diagram (SFD), which could then be turned into a SD model.

4.2 Problem articulation

As stated in Section 1.6, this research focuses on the formative phase of landfill gas to energy projects in Africa. During the formative stage, the TIS structures are developing and slowly taking shape, but feedback loops are still harder to establish (Bergek et al., 2008a; Edsand & Bångens, 2024). This results in the expectation that the TIS will slowly increase at first, but will grow exponentially after this first period of slow growth.

Moreover, only the existing landfills of a reasonable size are considered as potential LFGE projects. According to Olodu & Erameh (2023), WtE technologies that are carried out in a controlled environment are preferred over landfilling. Additionally, they argue that WtE technologies should not compete with waste reduction strategies. Moreover, Mbazima et al. (2022) raise the challenge of limited space to develop landfill sites, which is exacerbated by the competition of land with housing and urban development. These arguments increase the uncertainty surrounding the opening of new landfills, provided countries act on them, making it worthwhile to investigate this conservative scenario to see whether LFGE could be viable with the existing number of landfills and waste production in a country. Additionally, potential projects should be of a reasonable size as very small landfills do not produce much methane and are not likely to be converted into a LFGE project.

Finally, the focus of the research will be on the generation of electricity from LFG in a country. Other forms of energy generation from LFG, such as direct use, vehicle fuel, and combined heat and power generation are considered to be out of scope. Emissions reductions resulting from flaring, rather than electricity generation are also not considered in detail.

4.3 Conceptualisation

During the system conceptualisation, the stock-flow diagram of the hybrid approach was extended to fit the LFGE context. To this end, the drivers and barriers to LFGE in Africa were identified.

4.3.1 Literature review on LFGE projects

First, the drivers and barriers of LFGE projects had to be identified (SRQ2). The drivers and barriers were determined by a literature review, which was complemented with exploratory expert interviews. During the literature review, a general idea of drivers and barriers was formed. To this end, the Google Scholar, Scopus, and Web of Science databases were used. First, the search terms ‘landfill gas to energy projects’ and ‘landfill gas to energy utilisation’ were used in combination with ‘drivers’ or ‘barriers’. During a second round, these search queries were complemented with the terms ‘Africa’, ‘clean development mechanism’ and ‘voluntary carbon market’ to analyse the carbon context as well as the chosen geographical scope. The relevance of the resulting papers was determined based on the titles and abstracts. Papers about landfill gas to energy in African countries were considered relevant and were therefore selected. Papers with the wrong geographical or technological scope (e.g. other waste to energy technologies) were discarded, as well as papers that had a scope that was too technical, such as papers determining the energy potential of LFGE projects in a specific country. Finally, papers that were about waste to energy technologies in general, without specifically investigating landfill gas to energy were discarded. This resulted in 6 papers being selected (Table 2).

Table 2. Papers selected for LFGE literature review

Author	Geographical focus	Technological focus
Adeleke et al. (2021)	South Africa	Anaerobic digestion, landfill gas recovery, and incineration
Dlamini et al. (2019)	South Africa	Landfill gas recovery, incineration, and anaerobic digestion
Agbejule et al. (2021)	Ghana	Landfill biogas, incineration, anaerobic digestion, and aerobic composting
Karekezi et al. (2009)	Africa	Anaerobic digestion, incineration, and landfill gas production
Njoku et al. (2018)	South Africa	Landfill gas utilisation
Mbazima et al. (2022)	South Africa	Landfill gas

4.3.2 Expert interviews

In addition to the literature review, five expert interviews were conducted to complement the literature review. The interviews comply with the TU Delft regulations on human research and ethics as the interview process was approved by the TU Delft Human Research and Ethics Committee (HREC number 4170). The main objective of the interviews was to deepen the understanding of the drivers and barriers found in literature, as well as to extend the list of drivers and barriers found. Additionally, the aim was to obtain an understanding of the building blocks of the LFGE TIS and the role of carbon financing within LFGE projects. Although interviews are a time consuming data collection method and therefore only possible at a smaller scale, and might result in subjective perspectives rather than objective representations of reality, they are considered to be a valuable source of information. The interactive nature of interviews allows asking for clarification and probing into emerging topics, which is expected to broaden the understanding of the phenomena of interest (Alshenqeeti, 2014). During this research, key informant sampling was used, meaning that people who are knowledgeable on the topic of landfill gas to energy projects were targeted (Young et al., 2014). Potential respondents were recommended by Anthesis – Climate Neutral Group. Consequently, four of the five respondents currently work for Anthesis – Climate Neutral Group. They have all been involved in the development in landfill gas to energy projects in the Middle East, Africa and the Caribbean, and other regions in either their current work or in the past. They can therefore be considered experts on LFGE project development. Additionally, four of the respondents also have experience on carbon markets, making them valuable assets in creating an understanding of both LFGE project development in general and the opportunities provided by carbon markets. Most respondents were based in the Netherlands. Nevertheless, a respondent based in South Africa was included to incorporate an African perspective. Finally, one respondent outside of Anthesis – Climate Neutral Group was selected to create additional variety. This respondent has worked for Veluwse Afval Recycling, now Aterro, which is a waste processing company based in the Netherlands. To ensure the privacy of the respondents, no job titles or additional information is shared.

Most interviews were conducted online, however, there was also an interview that was conducted face-to-face. Each interview took around 60 minutes and was of a semi-structured nature. The interviews were conducted in either Dutch or English depending on the participant's preference. During the interviews, questions were asked about the drivers and barriers, as well as about the technology, actor, and institutions relevant to LFGE projects to obtain an understanding of the TIS structures. The interview guide is provided in Appendix A. Interview . Semi-structured interviews were chosen over unstructured and structured interviews because they allow the flexibility to further investigate topics emerging during the interview, while maintaining structure, which makes comparison between interviews easier (Eppich et al., 2019).

Before every interview, informed consent was acquired for participation in the research, and for recording the interview. The interviews were recorded and transcribed through Microsoft Teams, after which the transcript was manually checked to correct any mistakes made by the software, and converted into a more readable transcript using intelligent verbatim transcription. Within an intelligent verbatim transcription, filler words are removed to make the transcript more readable, while preserving the main message (Eppich et al., 2019). Because of the exploratory nature of the interviews, the interviews were not coded, which increased the importance of a readable transcript. Each transcript was then sent to the corresponding respondent to provide the opportunity to correct any mistakes. To guarantee anonymity and protect the privacy of the participants, the transcriptions are not included in this report. Quotations from the participants are cited in this research as “personal communication”. Finally, the drivers and barriers were extracted from the interview data, as well as the insights on the TIS structures. The findings are presented in an anonymised manner in Section 6.2.

4.3.3 Conceptual model of LFGE TIS

Once the drivers and barriers were identified, a selection of them was incorporated into the conceptual model of the hybrid approach to create a model tailored to the LFGE TIS, which provides an answer to SRQ3. The aggregated conceptualisation of the hybrid approach was complemented by two submodels. Each of the submodels zooms in on a specific part of the aggregated model. Submodel 1 focuses on the institutions, market formation, including the product price and demand, and the carbon credit structures. Submodel 2 zooms in on the funding processes, more specifically on domestic and foreign investment, required for the implementation of LFGE projects.

4.4 Model formation

During the model formation phase, the conceptualisations were translated into a SD model by assigning values to the variables. To this end the software tool Vensim Pro 10.2.0 was used. The model was calibrated to South Africa. Calibration to a specific case makes evaluation of the model more straightforward. There are three ways to estimate the variables within a SD model: 1) estimation from unaggregated data, 2) estimation from an equation, and 3) estimation from the knowledge of the entire model structure (Bala et al., 2017). For the constants in the model, the first method for variable estimation was preferred. Data was collected from scientific literature, World Bank indicators, and documentation of existing projects, which is freely available in the registries of carbon standards, such as Verra and Gold Standard. When no unaggregated data was available, an estimation was made based on the expected behaviour of the model. The other variables in the model were estimated by an equation, which was either based on literature or on assumptions about the model behaviour. Dimensional consistency tests were regularly conducted throughout the model formation to ensure correctness of the equations.

4.5 Model evaluation

To build confidence in the model, the model was verified, tested and validated. Verification is done to ensure the model was built correctly and was converted correctly from the conceptualisation (Balci, 1994). Testing compares the model to the descriptive knowledge of the real world, while validation examines the plausibility of the results and therefore its usefulness (Forrester & Senge, 1980). As there is no single test that validates a model, a variety of tests were performed. The model was tested and validated by performing a structure verification test, extreme conditions test, behaviour reproduction test, and a behavioural sensitivity test. A more elaborate description of the tests, as well as their results are presented in Section 7.3.

4.6 Model use

Once the model was verified and validated, it was used to answer SRQ4 and SRQ5. The sensitivity analysis performed during model validation provided preliminary insights into the relative importance of the model barriers. To explore this in more detail and determine the most important barriers (SRQ4) 41 experiments were conducted. The experimental design is included in Appendix H. Experimental design The experiments also provided insights into the conditions required for diffusion (SRQ5). The experiments were conducted on best case and worse case scenarios for each of the modelled barriers. The results were compared to a base case scenario.

5. Linking TIS functions and TIS building blocks

As mentioned in Chapter 2.2, there are currently two main approaches within TIS research; the functional approach and the structural approach. The structural approach, which is of a more static nature, assesses the status of a TIS at a specific moment in time and typically results in the identification of drivers and barriers to this development. The more dynamic functional approach on the other hand assesses the fulfilment of the key activities, the TIS functions, and results in an understanding of the diffusion of a TIS over time. Nevertheless, discerning between these two approaches impedes the exploration of how specific drivers and barriers, such as poor infrastructure or lack of supporting institutions, affect the long-term diffusion of a TIS. Therefore, a combination of the structural and functional approach, a so called hybrid approach, is proposed. Currently, this hybrid approach has not been applied in other studies. Bergek et al. (2008a) have proposed to identify the structures, while also assessing the TIS functions. However, they do not explicitly connect the structures to the functions. Suurs (2009) provides a high-level explanation of the relation between TIS structures and TIS functions. He states that TIS structures gradually develop over time and are subject to changes over time. These changes are represented by the TIS functions as they represent more rapid changes (Suurs, 2009). However, the explanation of this relation remains at a high-level. Jacobsson & Bergek (2011) explain the causes of weak TIS functions by linking them to system weaknesses on the structural level. However, the exact impact of the weak TIS structures remains unclear. Finally, Walrave and Raven (2016) have tried to capture the relation in their model by adding a 'TIS structures' stock to their SD model of TIS development. Nevertheless, they have aggregated the three TIS structures into this one stock, which creates a black box of the exact relations between the TIS functions and the specific TIS structures (Walrave & Raven, 2016).

5.1 TIS functions and structures within this research

To combine the functional and structural approach, and thus to analyse the diffusion of a TIS over time in a more disaggregated way, the TIS functions are linked to the TIS building blocks defined by Ortt and Kamp (2022). Although Hekkert et al. (2007) and Bergek et al. (2008a) have defined two sets of TIS functions that are most widely used in TIS research, this research follows the TIS functions proposed by Edsand (2019). While his list of functions is largely in line with the functions defined by Hekkert et al. (2007), Edsand has proposed three additional functions that adapt the TIS functions to the context developing countries. The TIS functions considered in this research are: entrepreneurial activity, knowledge development, knowledge diffusion, creation of adaptive capacity, guidance of search, market formation, national resource mobilisation, international resource mobilisation, and creation of legitimacy. Table 3 presents a description of the functions as used in this research. It should be noted that Edsand (2019) argues that the relevance of distinguishing between formal and informal creation of legitimacy depends on the accessibility of internet within a country. He argues that access to internet eases the share and access of information, which accelerates the formation of public opinion. Therefore, he argues that the distinction between formal and informal creation of legitimation could lose its relevance when the access to internet is very low. Nevertheless, the differentiation in the creation of legitimation will be employed in this research because sharing information through social media is only one way through which the public opinion is shaped. Finally, it is important to note that in this research, guidance of search is related to the supply-side of a new technology. Guidance of search is often fulfilled through industries and governments by selecting which technology to invest their limited resources in (Suurs, 2009; Hekkert et al., 2007). These investments result in the production and improvement of the new technology. To enhance the demand for the new technology, governmental resources could be employed, for example by implementing subsidy programs.

Table 3. TIS functions

TIS function		Description	Indicator	Source
F1.	Entrepreneurial activities	Activities concerning the new technology.	Started and planned projects.	Edsand & Bångens (2024)
F2.a	Knowledge development	Knowledge created regarding the new technology.	Number of publications regarding new technology.	Bergek et al. (2008a)
F2.b	Creation of adaptive capacity	The capability of a country to receive a new technology.	Level of human (e.g. level of higher education), institutional, and organizational adaptive capacity.	Edsand (2019)
F3.	Knowledge diffusion	Distribution of knowledge regarding the new technology through an actor network.	Number of conferences about the new technology.	Edsand (2019); Hekkert et al. (2007)
F4.	Guidance of Search	Activities that shape the needs, requirements and expectations of actors regarding support of the new technology.	Expectations about the technology.	Bergek et al. (2008a); Suurs (2009)
F5.	Market formation	Market entry assistance for the new technology to encourage supply.	Pricing policies, e.g. feed-in tariffs, tax exemptions etc.	Edsand & Bångens (2024); Edsand (2019)
F6.a	Resource mobilisation (national)	Resources allocated by the national government or industry to the new technology.	Funds to R&D. Subsidies for the new technology.	Edsand & Bångens (2024); Edsand (2019)
F6.b	Resource mobilisation (international)	International resources allocated to the new technology.	Availability, size, and type of international resources allocated to the new technology.	Edsand & Bångens (2024); Edsand (2019)
F7.a	Creation of legitimacy (formal)	Formal support for the new technology.	Formal advocacy groups.	Adapted from Edsand & Bångens (2024) and Edsand (2019)
F7.b	Creation of legitimacy (informal)	Support for the new technology by the general public.	Public opinion, support for and acceptance of new technology	Edsand & Bångens (2024); Edsand (2019)

The conceptual model linking the TIS structures with the TIS functions is combined with the disaggregated structural framework of Ortt and Kamp (2022). The building blocks can be considered a specification of the TIS structures. This is useful when creating an understanding of the conditions necessary for the successful adoption of a technology since this requires, for example, an understanding of the demand-side, and the different components of a technology, such as the infrastructure and price.

Integrating these two approaches is done in two steps. First, a high-level conceptual model is created in which the TIS structures, technology, actors and networks, and institutions, are connected with the TIS functions (Figure 4). Then this high-level conceptual model is specified by integrating the building blocks as identified by Ortt and Kamp (2022). A description of the building blocks, and the link to the TIS structures is shown in Table 4. Although Ortt and Kamp (2022) also considered a demand structure, it was decided not to incorporate demand as an explicit structure in this research, as this would confine only one building block, customers, within this category. Therefore, customers are categorised in the actors and networks structure. Price is considered to be directly linked to the product and is therefore considered to be part of the technology structure. Finally, an important note regarding the innovation-specific institutions is that fulfilment of this building block is achieved when an enabling institutional environment for the new technology has been created. Therefore, supporting institutions build up the building block, while obstructing institutions block the fulfilment of this building block. Another important note concerns the product performance and quality building block. In this research, product performance and quality relates to the theoretical performance achieved by the new technology, independent of the execution. When the knowledge required to achieve high performance is present, this building block is considered fulfilled. Low performance due to inadequate execution is addressed by the production system building block.

Table 4. TIS building blocks and their corresponding TIS structure.
Source: adapted from Ortt & Kamp (2022)

Building block	Description	Corresponding TIS structure
Product performance and quality	A new technology with a good potential performance and quality compared to competing technology.	Technology
Production system	A production system delivering a high quality product at a large scale.	Technology
Complementary products and services	Products and services supporting the development, productions, distribution, adoption, use, repair, maintenance, and disposal of the new technology.	Technology
Product price	The financial purchase price of the new technology.	Technology
Network formation and coordination	The networks of actors in the supply chain.	Actors and networks
Customers	Customers that are aware of the innovations, see its benefits, and have the knowledge and the means to acquire the new technology.	Actors and networks
Innovation-specific institutions	Formal rules surrounding the new technology.	Institutions

5.2 Linking the TIS building blocks to the TIS functions

Figure 4 shows a high-level conceptual link between the TIS structures and the TIS functions. Replacing the TIS structures by the TIS building blocks results in the more detailed conceptual link in Figure 5. Note that in both Figure 4 and Figure 5, the relations between the TIS functions and the TIS structures/building blocks themselves are not shown to prevent cluttering of the model.

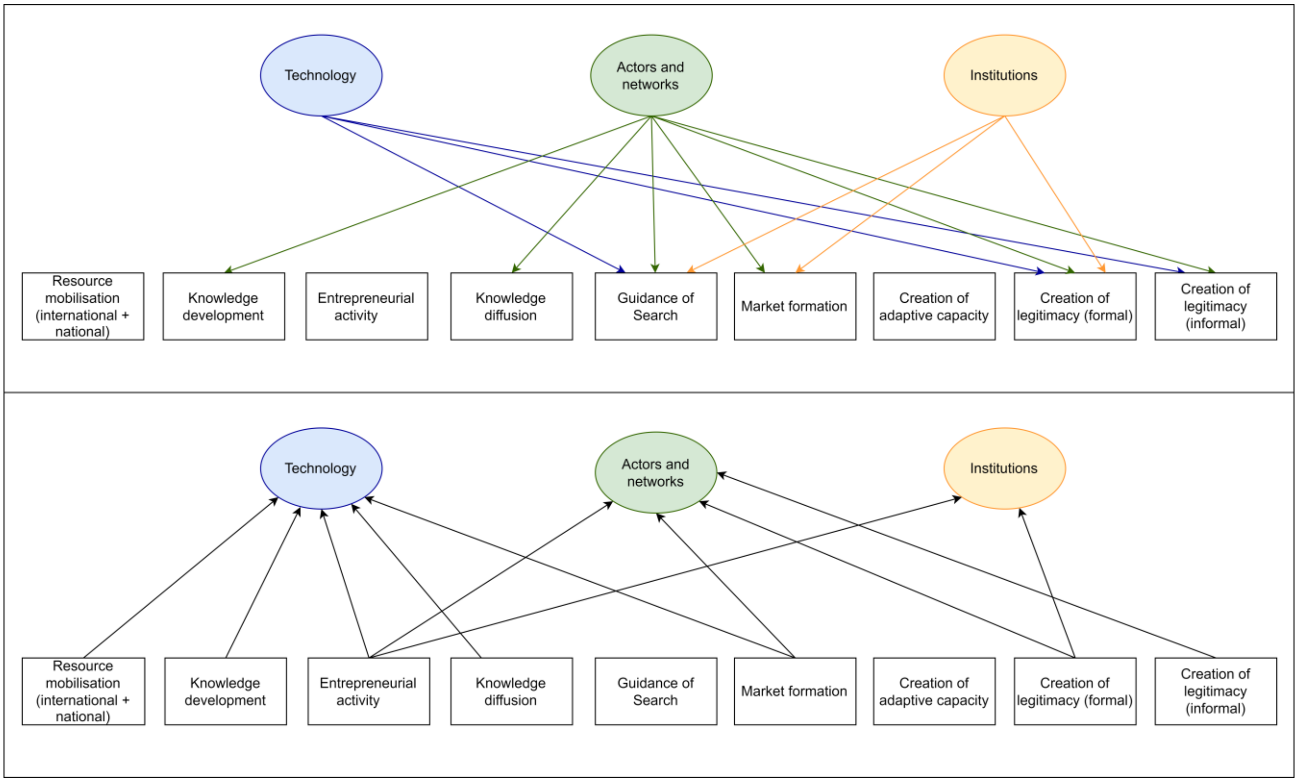

Figure 4. High-level conceptualisation connection the TIS structures and TIS functions.
Source: Own work

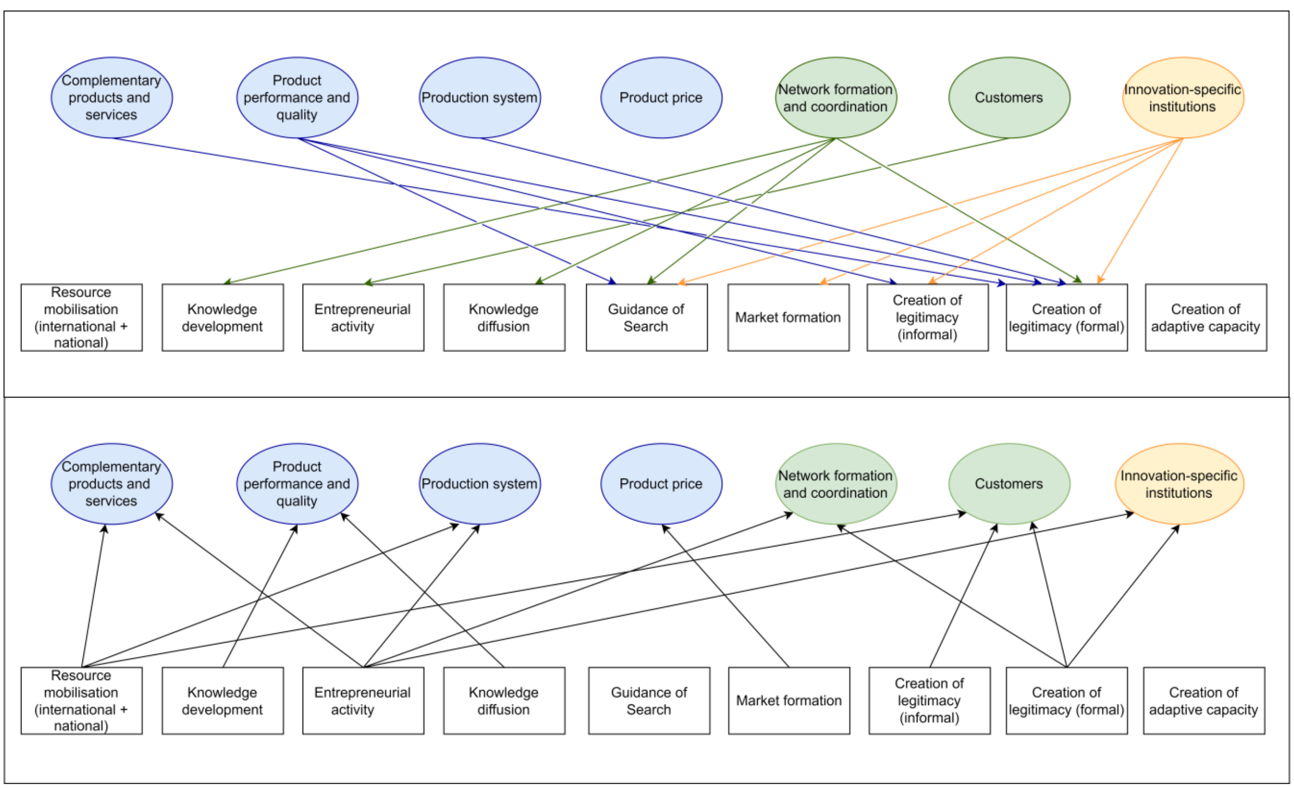

Figure 5. Detailed conceptualisation connecting the building blocks as identified by Ortt & Kamp (2022) to the TIS functions.
Source: Own work

As mentioned in Section 0, the TIS structure technology consists of the technologies within the TIS and the technological infrastructure in which they are implemented (Suurs & Hekkert, 2009). Technology is influenced by the technological knowledge developed and diffused. Suurs (2009) states that knowledge development is an important condition for the emergence of a technology as it affects the reliability, and thus performance, of a technology. The developed knowledge is then diffused through a network of actors (Edsand, 2019), improving the product performance even more as more actors now possess the knowledge resulting in the quality of the product becoming more homogeneously. Additionally, technology is influenced by entrepreneurial activity because increased implementation of the technology could result in an improvement of the required infrastructure (Walrave & Raven, 2016). Finally, resource mobilisation influences the production system and complementary products and services. These elements require human, natural, and financial resources to be build, (Ortt & Kamp, 2022). To acquire these resources, the available resources need to be allocated to the technology structure through the resource mobilisation function.

Technology, in its turn, influences the formal perceived legitimacy of the TIS. More specifically, an increase in the technology structure, such as the development of the necessary infrastructure, increases market legitimacy (Walrave & Raven, 2016). Additionally, a high expected performance of a technology could increase the formal legitimacy of the technology (Bergek et al., 2008b). Besides, a good product could also increase the support of the general public, which increases the informal legitimacy. The same goes for the actors and institutions structures. An increase in, for example, network formation (actors) or supporting regulations (institutions) increases the formal market legitimacy of a TIS (Walrave & Raven, 2016). It is important to note that networks are not required for the informal creation of legitimacy, as the creation of public support can also be carried out by individuals (Edsand, 2019).

The state of the technology and its fit to existing institutions both influence the guidance of search as these could result in higher expectations of the technology (Suurs, 2009). Finally, the product price can be influenced by the market formation function through pricing policies, such as feed-in tariffs.

Actors and their networks play an important role in the development and diffusion of knowledge within the TIS (Hekkert et al., 2007; Suurs, 2009). Actors, such as universities or entrepreneurs, develop knowledge regarding the new technology, which is then spread through a network of actors (Suurs, 2009). Additionally, actors influence the guidance of search, as guidance of search can be considered the process of exchanging expectations regarding the new technology between different actors (Suurs, 2009; Hekkert et al., 2007). Actors and networks are also influenced by the legitimacy of a TIS and entrepreneurial activity. When a TIS gains legitimacy, it could attract more actors that are willing to work in it because the risks associated with the TIS decrease (Walrave & Raven, 2016). A specific actor group that could be attracted due to the increased legitimacy are the customers. Bergek et al. (2008b) argue that legitimacy is a requirement for the formation of demand. Additionally, formal lobbying could result in institutional changes when authorities are urged to adjust the institutional configuration (Suurs, 2009). Another influence on actors and networks is an increase in entrepreneurial activity, which results in the formation of entrepreneurial networks and networks of interest groups (Walrave & Raven, 2016). This increase in entrepreneurial activity could also create the need for institutional changes, influencing the institutional structure (Walrave & Raven, 2016). When institutional changes include changes resulting in a protected market, through favourable tax regimes or the creation of niche markets, it enhances the formation of a market (Jacobsson & Bergek, 2011; Hekkert et al, 2007).

Figure 5 emphasises the importance of networks, institutions, and product performance and quality as these building blocks influence most TIS functions. On the other hand, entrepreneurial activity is the function with the greatest influence over the building blocks, making it an important function in building up the TIS.

5.3 Conceptualisation of the hybrid approach

The conceptual link between the TIS functions and building blocks in Figure 5 is extended by adding the relations between the TIS functions and the building blocks themselves. The subsystem model shown in Figure 6 illustrates the main relations within the hybrid model, while Figure 7 shows the SFD of the hybrid approach. The corresponding CLD is presented in Appendix B. Conceptual models 'hybrid approach'

The building blocks in the general SFD model are modelled in an abstract way. They should be build up over time, meaning they will have a value of 1 when complete and 0 when non-existent. Zooming into a specific aspect of the model changes the level of abstraction, providing the opportunity to model that part of the system with real-world values. This section elaborates on the relations that are not yet explained in Section 5.2. Walrave & Raven (2016) have already indicated various relations between the TIS functions themselves. In Figure 7 these relations are depicted in red. These relations are taken as a starting point and extended with the relations between the TIS functions and the building blocks.

Adaptive capacity has a positive impact on the development of technological knowledge. As indicated by Esmailzadeh et al. (2020), the ability of a developing country to receive a new technology and absorb external knowledge is important for the development of knowledge within that country. Actors and their networks also play an important role in the development and diffusion of knowledge within the TIS (Hekkert et al., 2007; Suurs, 2009).

Another function influencing knowledge development, as well as knowledge diffusion, is domestic resource mobilisation (Walrave & Raven, 2016). An increase in resources, often financial, results in more research activities, as well as more conferences on the topic (Suurs & Hekkert, 2009). The amount of domestic resources available is influenced by the guidance of search (Walrave & Raven, 2016). High expectations about the technology, as well as targets to which the technology is related could allocate more resources, e.g. in the form of investments, towards the technology (Suurs & Hekkert, 2009). With these resources the production system and the necessary infrastructure can be build. Investment into the development of the production system can also come from foreign direct investment through international resource mobilisation. Investment decisions are often based on the perceived profitability of a project, which is associated with the risk on the investment. Liu & Zeng (2017) have identified three main risks in renewable energy investment; market risk, policy risk, and technological risk. They argue that technology risk is related to technology maturity, progressiveness and applicability. Additionally, they associate policy risk with uncertainties regarding access policy, price policy, and industry regulation. Finally, they distinguish between two forms of market risk; external and internal. External market risk, they argue, has to do with market access barriers, market competitiveness, and market growth potential. On the other hand, they argue that internal risk is associated with a company's financial risk, service quality and marketing capabilities. Within the context of the TIS functions and building blocks, the external market risk can be related to the market formation function, while the risk and the product maturity are related to the innovation-specific institutions and product performance and quality, respectively. The assumption is made that only financial healthy companies, that are actually able to invest in these large projects, will invest in LFGE projects, making the internal market risk negligible.

According to Walrave and Raven (2016), knowledge development has a negative influence on the current state of the knowledge diffused in the TIS, meaning that if more knowledge is developed, this new knowledge needs to be diffused, reducing the amount of knowledge being diffused at that specific moment in time.

Knowledge development and knowledge diffusion influence the expectations of a technology, shaping the guidance of search (Walrave & Raven, 2016). Additionally, knowledge development and diffusion result in more formal support for the technology (Walrave & Raven, 2016). This higher level of formal legitimacy implies that entrepreneurs become more interested to work within the TIS because the risks associated with the technology decrease when formal legitimacy is increasing (Walrave & Raven, 2016). This strengthens the actor structure since more entrepreneurial activity could result in the formation of entrepreneurial networks, as well as networks of interest groups (Walrave & Raven, 2016). Informal legitimacy, on the other hand, partially determines the growth in entrepreneurial activities. Informal institutions, which are incorporated under informal legitimacy, such as the believe that certain products should be free, could result in less entrepreneurial activities as they increase the risks of working within the TIS. A high acceptance of the new technology, on the other hand, reduces this risk and could result in more entrepreneurial activity (Edsand & Bångens, 2024).

Increased entrepreneurial activity results in the development of actor networks, improvement of the required infrastructure, and institutions (Walrave & Raven, 2016). These institutions could affect the market formation function as this function consists of the pricing policies that enhance supply, such as feed-in tariffs or tax exemptions, resulting in lower risks for entrepreneurs and therefore increasing entrepreneurial activity. These pricing policies require financial resources, which need to be mobilised toward the TIS. Additionally, the articulation of demand, resulting in customers, can be enhanced by specific policies, such as subsidies for consumers. However, this also requires resources, which need to be mobilised. Moreover, demand is influenced by the product price through market forces.

Guidance of search is influenced by all TIS structures. Actors play an important role in shaping the guidance of search as this function can be considered a process of exchanging expectations regarding the new technology between different actors (Suurs, 2009; Hekkert et al., 2007). Additionally, the state of the technology and its fit to the current institutions could increase or decrease the expectations and thus the guidance of search (Suurs, 2009). A high product performance increases the expectations, while a good fit to the current institutions reduces perceived barriers to the technology, also raising expectations. Guidance of search could increase the resources being allocated to the new technology, contributing to resource mobilisation (Suurs & Hekkert, 2009).

The TIS structures are modelled as stocks, as these need to be formalised to develop the TIS. Their flows, the changes in these structures, are influenced by the TIS functions, as well as the drivers and barriers corresponding to the structure. It is expected that most drivers and barriers are related to process that only change slowly, and are therefore of a structural nature (e.g. lack of institutions, poor quality of the technology). The TIS structures will then affect the performance of the TIS functions. However, it is possible that drivers and barriers directly influence a TIS function. Therefore, these direct relations should be considered when applying the conceptualisation to a specific case.

The TIS functions are modelled as factors. As they are needed to build up the building blocks, they are influencing the inflows of the stocks. The TIS functions change based on changes in other TIS functions or changes in the TIS structures. Each of the TIS functions can also be considered a stock-flow structure. However, to prevent cluttering and to keep the focus on the building blocks, they are shown as factors in Figure 7. Additionally, both the TIS functions and the TIS building blocks can be modelled in more detail by zooming in on the stock-flow structure, when this is required.

It should be noted that the building blocks do not have any outflows. The assumption was made that mainly the inflows are relevant as the scope of the model is the formation phase of a TIS, in which the TIS starts taking shape. This means that the TIS is growing. The outflows become more important in models that include the decline phase of an innovation system (e.g. Markard, 2020). However, there might be building blocks that decline during the formation phase, for example network formation and coordination. Nevertheless, to limit the complexity of the model, these outflows are not considered.

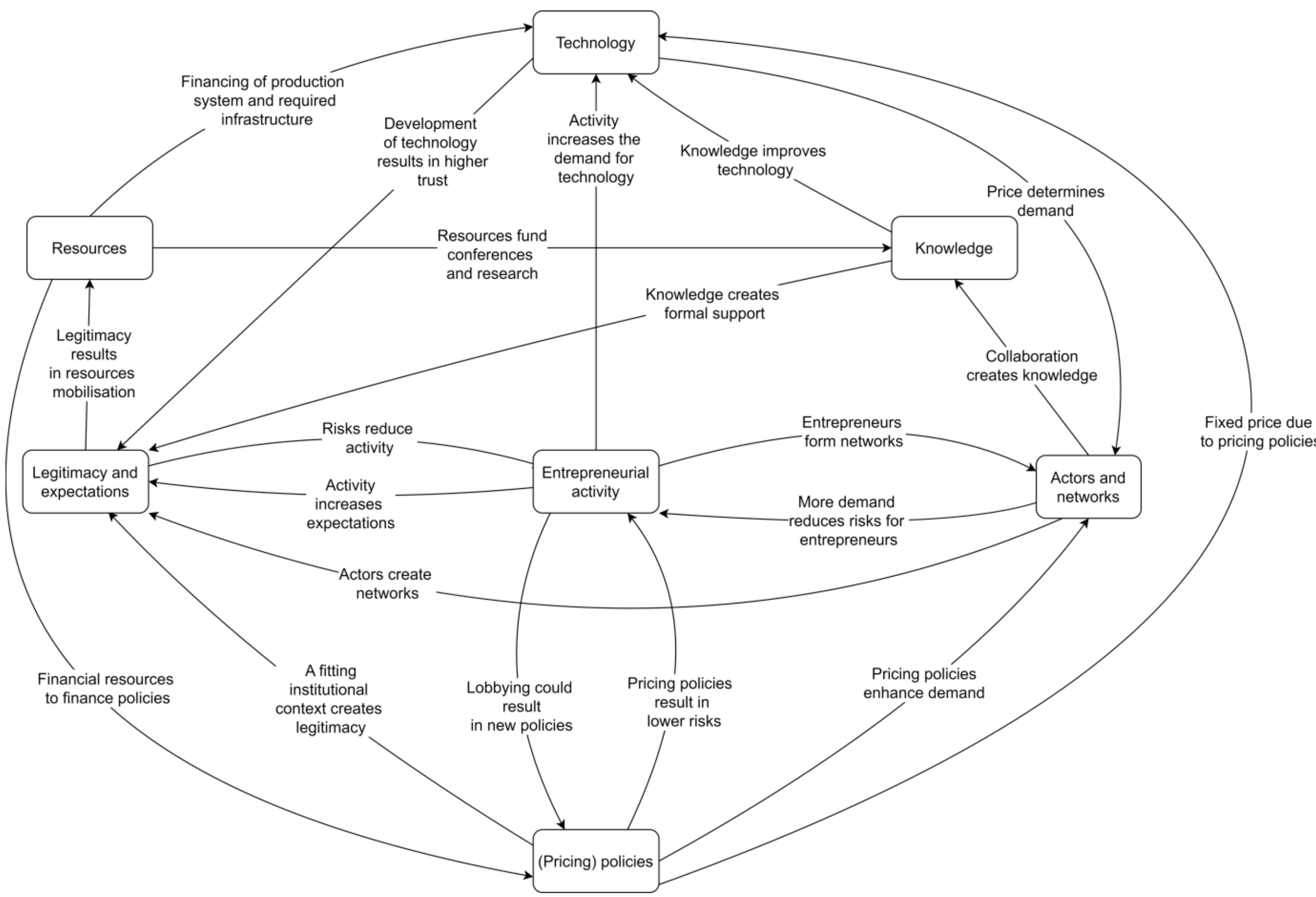

Figure 6. Subsystem diagram of the hybrid approach

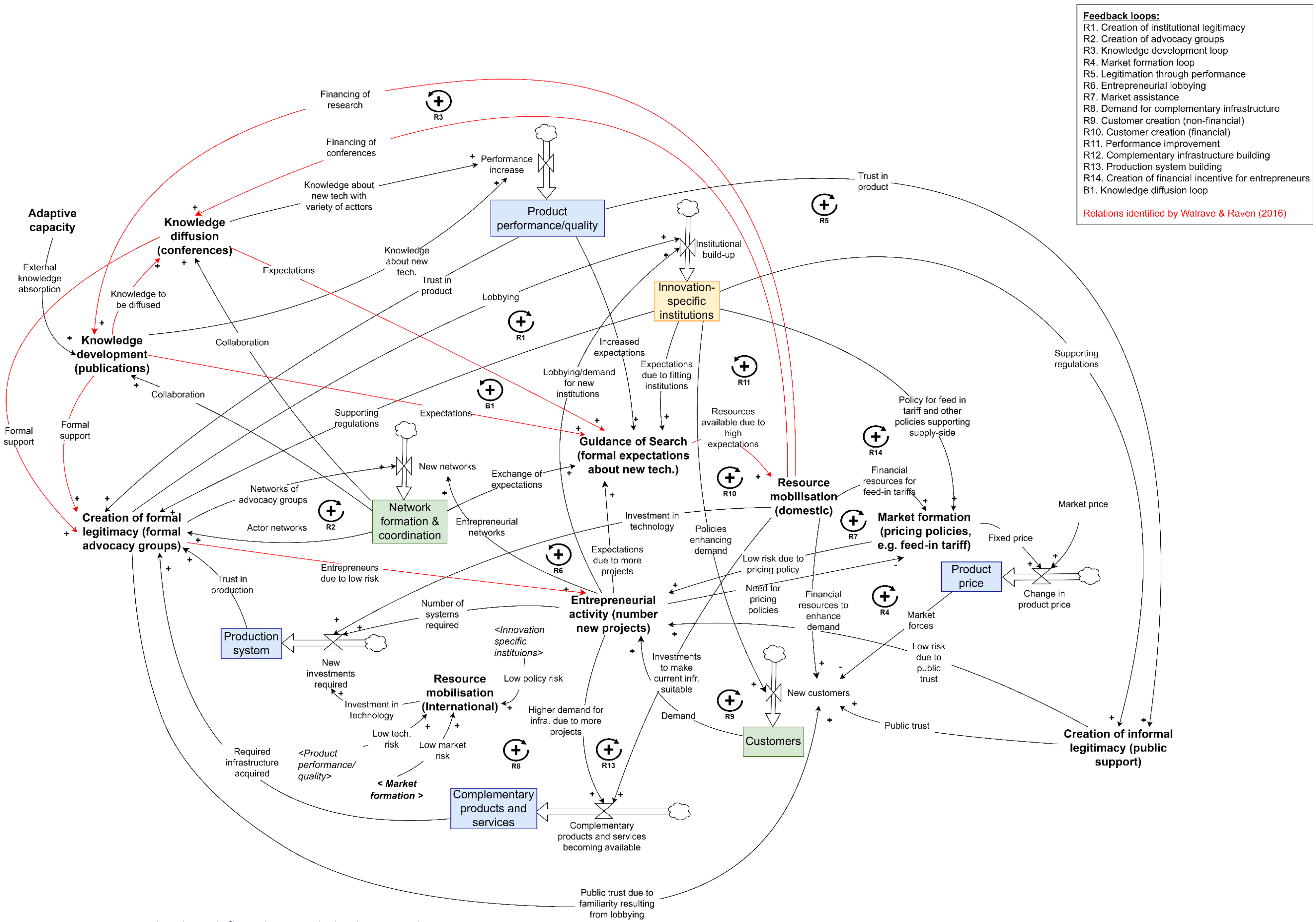

Figure 7. Stylised stock flow diagram hybrid approach.
Source: Own work

6. The landfill gas to energy technological innovation system

This chapter explains the building blocks of the technological innovation system surrounding LFGE projects. Additionally, the drivers and barriers to these projects will be identified. To this end, a literature review was performed and expert interviews were conducted.

6.1 Building blocks of LFGE projects

From the literature review and the interviews a synthesis of the building blocks of the LFGE TIS can be created.

6.1.1 Product performance and quality

The product of LFGE is electricity. To generate electricity, a sufficient flow of LFG needs to be produced within a landfill. The interviews indicated that this flow is not constant because of the intermittency of the biological process required for the decay of organic waste and therefore the production of LFG. Bogner & Lee (2005) also mention temperature and drought as factors influencing the LFG production in South Africa. They state that, while high temperatures enhance LFG production, low precipitation rates reduce it. Njoku et al. (2018) also mention the quality and the duration of the LFG generation as an important factor that needs to be considered before the implementation of a LFGE project. During the interviews it was mentioned that the LFG production can be enhanced by good landfill design: "if it does not have proper landfill design and drainage et cetera, it is unlikely to produce very good gas" (personal communication, 2024).

Within this research, this building block is fulfilled when the knowledge to create high quality electricity from LFG is present within the country. This means that theoretically, a high quality product could be produced. To avoid double counting, any deviation from this theoretical performance due to an incomplete production system is considered in the corresponding building block, as the production system building block is defined as "a production system delivering a high quality product at a large scale". Therefore, when the production system building block is complete, the theoretical performance is met.

6.1.2 Production system

As sufficient LFG production is required for the generation of electricity, the production system of LFGE projects does not only include the engines converting the LFG to electricity, but also the infrastructure required for LFG production. This includes the landfill and its design. During the interviews it was mentioned that the landfill should have enough waste to be digested to produce LFG, as well as pipes transporting the produced LFG. Additionally, a drainage system and a cover enhance the production and capture of LFG as they prevent the waste from containing too much moisture, which would impede the production of LFG, and reduce the amount of LFG that is leaked into the atmosphere because "the only way out for the LFG would be the pipes" (personal communication, 2024).

Since this research investigates the diffusion of LFGE projects on country level, fulfilling the production system building block means that the production system for all implemented projects should be in place.

6.1.3 Complementary products and services

Complementary products and services that are important for the production of LFG and electricity from LFGE projects are the waste management system and the national electricity grid. Inappropriate waste management is problematic for the implementation of LFGE projects. An insufficient, unreliable flow of waste to a landfill can impede LFGE projects as a minimum amount of waste is required for a sufficient amount of LFG to be produced (Karekezi et al. 2009; Njoku et al. 201; Adeleke et al., 2021). Additionally, the generated electricity needs to be connected to its end-users. The most well-known way to do is through the national electricity grid. The electricity could also be directly connected to the end-user through a direct cable or used on-site. However, the latter means no revenue is generated.

6.1.4 Product price

The product price in the LFGE TIS is the purchase price for the electricity generated during the project, which means it is the price paid on the demand side. The purchase price can either be the wholesale market price for renewable electricity to be paid by the electricity distributors, or a specific price negotiated with the electricity offtaker. In the latter case, the electricity often does not flow through the national grid but directly to the offtaker. For this, the offtaker needs to be relatively close to the landfill where the electricity is produced. Finally, the price can be determined through pricing policies. Some countries have implemented feed-in tariffs to reduce the risk for investors. According to Couture and Gagnon (2009), feed-in tariffs are considered to be an effective policy for incentivising the development of renewable energy sources. They identify two general feed-in design options: market independent feed-in tariffs and market-dependent feed-in tariffs. The most common feed-in tariff design is the fixed-price feed-in. This is a market independent design in which a fixed-price is agreed on for a specific time period, and often includes a purchase guarantee (Couture & Gangnon, 2009). The importance of adequate feed-in tariffs was also acknowledged by three of the participants. One of the participants expected to find a significant correlation between the feed-in tariffs and the implementation of LFGE projects as feed-in tariffs help making the project economically viable.

Finally, carbon credits play a role in the revenue created from LFGE projects. However, carbon credits are a separate flow of income, which is rewarded for the emission reduction achieved by the project rather than for the electricity that is generated during the project. Therefore, the price of carbon credits is not included in the purchase price and does therefore not belong to the product price building block.

6.1.5 Network formation and coordination

The relevant actors related to LFGE project that were mentioned during the interviews are shown in Table 5.

Table 5. Most important actors related to LFGE projects

Actor	Role
Municipalities/local authorities	Decision-makers, potential owners of the landfill and the project.
Landfill owner	They own the landfill. This can be either a public organisation, such as a municipality, or a private party.
Project operator	They operate the LFG extraction system and its conversion to electricity.
Financial institutions (e.g. banks)	The provide funding in the form of loans for the investment in a LFGE project.
Private investors	They invest in the project. This category includes investments to create the carbon layer of the project.
Neighbouring communities	They feel the environmental and social impact of a landfill and therefore also the improvements made through a LFGE project.
Scavengers	They earn their livelihood from the landfill. Sometimes they even live on the landfill.
Electricity offtakers	The customers of the project. They buy the electricity. They can be distributor companies or parties buying the electricity directly.
Waste companies	The collect the waste and deliver it to the landfill.

6.1.6 Customers

The customers of a LFGE project are the parties buying the generated electricity. These can either be electricity distributors that sell the electricity on the national grid, or parties that buy the electricity directly, without using the national grid. To reduce complexity, any customers that do use the national electricity grid, but do not buy it through an electricity distributor are not considered separately.

6.1.7 Innovation-specific institutions

Although one participant stated that "most of the policy is not restrictive in Africa" (personal communication, 2024), it is still important to create an overview of the relevant policies to allow the assessment of the building block. Even if policies do not act as a barrier, there could still be potential for improvement by transforming the institutional framework into a driver. Mbazima et al. (2022) state that there is a lack of policies promoting LFGE projects in South Africa. They propose implementing a policy that mandates generating electricity from the captured LFGE. Additionally, they state that the existing policies and regulations should be reviewed to ensure maximising the benefits from LFGE projects. Before an obligation to generate electricity is implemented, a policy mandating the collection of LFG could be implemented. It was mentioned during the interviews that that there are countries that mandate the collection of LFG. However, this does not necessarily mean that generating electricity is also mandatory. Using the collected LFG for flaring could also be an option depending on the implementation of the policy.

Additionally, Mbazima et al. (2022) mention that there currently is a lack of policies on WtE in South Africa, while these are required in solving the MSW management and energy crisis in the country. Adeleke et al. (2021) also mention the waste management system in South Africa could be improved by legislation, as well as enforcement of the legislation, on waste management. Although regulations on improving the waste management sector are not directly related to LFG production, they are still important to consider because LFG production is linked to the amount and quality of waste entering a landfill. The same goes for environmental policies. One participant stated that "without any environmental law a LFGE project could be installed and operated" (personal communication, 2024). Nevertheless, it would be helpful to have policies that provide guidance on how a landfill should be designed and operated to reduce its environmental impacts. Another participant mentioned that the carbon tax that has been implemented in South Africa as a policy increases the incentive for reducing and offsetting emissions. However, since policies on waste management and environmental goals are not directly linked to LFG and electricity production, they are not considered as innovation-specific institutions, but rather as either guidance of search (environmental policies) or general factors affecting the complementary products and services building block.

Finally, policies that reduce the risks for investors, such as feed-in tariffs or other pricing policies and purchase obligations are important for the implementation of LFGE projects. One participant noted that in high-risk countries, e.g. due to corruption, require a higher rate of return. This means that the price that is received on the supply side should be higher in these higher risk countries, which could result in the need for higher feed-in tariffs.

6.2 Drivers and barriers to LFGE projects in Africa

Three participants named factors related to combating climate change as one of the main drivers for LFGE projects. These factors included mitigating the greenhouse effect and complying with the Paris Agreement. Additionally, two participants mentioned tackling the environmental problems related to landfills, such as emissions and pollution, as a driver, whereas one participant mentioned social problems related to health and safety to be a driver. The reduction of greenhouse gas emissions and the reduction of environmental pollution were also acknowledged as a driver by Karekezi et al. (2009). Another driver that was mentioned by four participants was the possibility to generate energy. However, a remark that was made, was that the ability to actually sell the electricity is crucial for it to become a driver. To this end, three participants mentioned the importance of adequate feed-in tariffs. Carbon financing was also mentioned by multiple participants as something that could be a driver as it makes the project more lucrative. This driver that is corroborated in literature (Njoku et al., 2018; Adeleke et al., 2021). However, one participant remarked that when other (financial) incentives are in place, carbon financing will not act as a driver, because the project would be economically feasible without the carbon financing. Two drivers that were found in literature, but that were not mentioned by any of the participants were the depletion of fossil fuels and their increasing prices, and the increasing energy demand that needs to be accommodated (Karekezi et al., 2009; Adeleke et al., 2021).

The literature review and interviews resulted in 27 obstructing factors (Appendix C. Drivers and barriers to LFGE projects) that are aggregated into the 21 barriers shown in Table 13. These barriers are divided into four categories: economic, technical, organisational, and social. The barriers that did not fit into one of those categories were combined in a category called 'other'.

Table 6. Overview of the barriers impeding LFGE projects

Economic		Technical		Institutional		Organisational		Social		Other	
E1.	Viability of the project	T1.	Scale of the landfill	I1.	Access to the electricity grid	O1.	Public landownership	S1.	Limited awareness of benefits	X1.	Corruption
E2.	Funding	T2.	Uncertainty of quantity of electricity generation	I2.	Lack of regulations on LFG handling	O2.	Human capacity			X2.	Public support
		T3.	Waste management	I3.	Lengthy carbon processes	O3.	Monopolised energy sector			X3.	Availability of end-users
		T4.	Low efficiency of the project	I4.	Complexity of PPAs					X4.	Dependency on cheap fossil fuels
		T5.	Distance to the electricity grid								
		T6.	Availability and accessibility of land								
		T7.	Technical solutions								

The interviews made it evident that the economic barriers are very important in LFGE projects in Africa. It was indicated that it can be challenging to create a viable business case. On the one hand the investment and operational costs of LFGE projects are relatively high, as was indicated by multiple participants, as well as in literature (Karekezi et al., 2009; Njoku et al., 2018; Mbazima et al., 2022). On the other hand, the price of electricity generated by the LFGE project is not always sufficient to cover the costs. Karekezi et al. (2009) also mention the absence of standard price for generated power as one of the barriers to LFGE projects. This results in the need for pricing policies to ensure a price that makes the project viable to develop and invest in. An example of a pricing policy, as indicated by multiple participants, are feed-in tariffs. Feed-in tariffs guarantee a price over a fixed period of time for electricity produced by renewable energy sources, which attracts a greater number of investors (Couture & Gagnon, 2010). However, when feed-in tariffs are too low, it is challenging to create a viable business case, which in turn creates a challenge in finding funding for the project. As indicated by one participant, carbon credits can give the final push to make the project viable. However, several participants indicated that the price of carbon credits for LFGE projects has been fluctuating a lot, being very low after 2012, right after the Kyoto Protocol ended. This uncertainty regarding the financial benefits of a LFGE project could result in investors worrying about the recovery of their costs, which is a barrier to waste to energy projects identified by Adeleke et al. (2021).

A related barrier is the challenge of securing funding for projects. When project risks are high, both in terms of financial returns and the internal context within a country, attracting investors in LFGE projects becomes difficult. Additionally, one participant indicated that attracting private investment is difficult when the only income flow of a project are the carbon credits because the processes for obtaining carbon credits take a long time. This is an institutional barrier that was corroborated by literature (Njoku et al., 2018; Couth et al, 2011). If electricity is not generated immediately after the start of the project and sold at a suitable price, the project will have no income during this time of going through the necessary processes to obtain carbon credits. This emphasises the need for revenue from electricity. Additionally, one participant mentioned there could exist regulations that discourage international investment. Some countries aim to stop the capital flight, which also results in less capital coming into the country because of the risk of not being able to recuperate the investment (personal communication, 2024). Nevertheless, this risk could be mitigated by carbon financing as carbon credits are traded internationally. Within the existing body of literature, funding is also identified as one of the barriers to LFGE projects (Karekezi et al., 2009; Njoku et al., 2018; Dlamini et al., 2019; Adeleke et al., 2021).

The economic barriers are related to the technical barriers, as the landfill has to meet certain requirements to be able to generate a sufficient amount of energy to become economically viable. Three participants identified the scale of a landfill as a barrier. When a landfill is too small, it will simply not produce enough electricity to be economically viable. Another important factor mentioned is the waste management system in a country. An unreliable flow of waste to the landfill, or a flow that is too small, as well as an incorrect composition of the waste could prevent the landfill to produce enough energy (Karekezi, 2009; Njoku et al., 2018; Adeleke et al., 2021). As stated in Section 2.1, the waste needs to contain a high organic content, as this will be digested and converted into methane. However, the data on waste production is often of poor quality, posing difficulties for designing an effective waste management system (Njoku et al., 2018; Mbazima et al., 2022). Also, the management of the landfill can cause problems. One participant mentioned the low efficiency of some LFGE plants due to the leakage of methane through the landfill cap, which was caused by poor management. Another hindering factor is the intermittency of the electricity generated by the landfill, which was identified by one participant. Since the digestion of the organic content of the waste is a biological process, which is dependent on natural factors, such as temperature, rain (moisture), and the composition of the waste, the generation of methane from the landfill is not constant, but follows a curve that decreases over time (Karekezi et al., 2009; Njoku et al., 2018). This directly impacts the amount of electricity that can be generated. Finally, the distance of the landfill from the electricity grid is a technical factor that is highly related to the investments costs of a project. When the landfill is located at a great distance from the electricity grid, a long and expensive cable needs to be implemented to transport the electricity generated on the landfill to the grid. This barrier could be overcome by selling the electricity to nearby industry, or other local energy offtakers. However, these are often not available, as was indicated by the participants.

One of the institutional barriers mentioned is also related to the electricity grid. Three of the participants mentioned that it can be challenging in some countries to get access to the electricity grid. Adeleke et al. (2021) corroborates the challenge of accessing the electricity grid for WtE projects. As reported, this implies that a local offtaker of the electricity needs to be available, or the electricity should be used for on-site processes. However, the latter means that no revenue can be generated. Additionally, the literature identifies an unsupportive institutional framework as a barrier to LFGE projects (Karekezi et al., 2009; Njoku et al., 2018; Mbazima et al., 2022; Adeleke et al., 2021). Often, policies incentivising the development of LFGE projects are lacking. One participant mentioned that some countries have implemented policies that require at least flaring of the captured LFG, which could be extended to mandating the generation of electricity from the LFG. This would create incentive to develop a LFGE project. Mbazima et al. (2022) report lack of promotion of the adoption of LFGE and the lack of institutional frameworks on WtE as a challenge to the implementation of LFGE projects. They offer recommendations on how to improve the institutional framework. However, they do not specify the policies that make the institutional framework conflicting with the framework required for LFGE projects. Additionally, Karekezi et al. (2009) state that without enforceable regulations on waste management, waste to energy technologies cannot compete with conventional technologies.

An organisational barrier that was mentioned by almost all participants is public ownership of a landfill. It was mentioned that a landfill is often owned by the local government. This means that to start a LFGE project, a tender is created. However, the participants reported the tender processes to be slow and frequently lack transparency, paving the way for cronyism and corruption. The complexity of tender processes is corroborated by Mbazima et al. (2022). Additionally, one participant reported governments to have hidden agendas and to be too focused on profit resulting from the project, especially from carbon credits. However, it was reported that these skewed expectations can often not be met, which could result in a damaged relationship, or even the retraction of permits.

Another organisational barrier mentioned is the lack of skilled personnel to operate and implement the project (Adeleke et al., 2021; Agbejule et al., 2021). This was corroborated by one participant, indicating that municipalities often lack the capacity to operate a LFGE project themselves. Finally, Njoku et al. (2018) mention monopolisation within the energy sector to act as a barrier as this makes investors lose interest.

The main social barrier identified by the participants is related to the awareness of the benefits of the project. The participants did not only mention the lack of awareness of the local community, but also the lack of awareness of (local) governments and landfill operators. Njoku et al. (2018) also identified the limited awareness of the benefits of a LFGE project among decision-makers as one of the barriers.

The other barriers mentioned during the interviews are corruption and the lack of public support. One participants stated that large (public) organisations could slow down the process, or even block the project. Two participants mentioned that once organisations noticed that a LFGE project could create profit, they would try to block the project to try to implement it themselves, which did not always turn out to be successful. The lack of government support is also mentioned in the body of literature (Adeleke et al., 2021; Njoku et al., 2018; Mutezo, 2015). Finally, the lack of end-users and the dependency on the still cheap fossil alternatives were identified as barriers (Njoku et al., 2018; Adeleke et al., 2021).

7. Modelling LFGE projects

This chapter describes the LFGE TIS in more detail. First, the three submodels that have been created to investigate the diffusion of the LFGE TIS in Africa are explained. The first two submodels are related to the institutional alignment and the funding processes of LFGE projects. The third submodel shows the aggregated TIS model, which is modelled more generically. Then, the settings of the running model are provided, and the model is evaluated to build confidence that it is fit for purpose.

7.1 Conceptualisation

To tailor the general model in Figure 7 to the case of LFGE projects, a number of barriers found in Section 6.2 are integrated. To do this, two submodels were created: the institutional alignment submodel, and the funding submodel. The submodels were connected to the aggregated TIS model, making this aggregated model the third submodel. By creating these three submodels, most barriers from the economic, institutional and 'other' categories are modelled explicitly. The interviews indicated these categories to be of high importance. The technical barriers where not modelled as this would result in a misalignment in the level of aggregation. The technical barriers require the model to be on project level, while the rest of the model is modelled on country level to align with the scope of the research and the TIS framework. Traditional SD modelling does not allow for modelling different levels of aggregation. Therefore, the model assumes the technological barriers to be overcome when the production system building block is complete. Moreover, barriers I3, I4, O2, O3, S1, and X4 are not included in the model as these barriers did not fit in one of three submodels. To keep the model manageable and to meet the time constraints of the research, no submodels beyond the three mentioned before were created, and therefore these barriers were excluded from the model. The full implementation of the three submodels, as well as an overview of the main model assumptions can be found in Appendix E. Model variables and their implementation

7.1.1 Submodel 1: Institutional alignment

Submodel 1 focusses on the innovation-specific institutions building block. The conceptual link in Figure 5 highlights the importance of this building block, as it affects multiple TIS functions. Moreover policies could have a great impact on the diffusion of LFGE projects as they can create incentive to develop such a project. Additionally, the process regarding the generation of carbon credits from LFGE projects is modelled in this submodel. Since one of the research objectives is to determine the effect of carbon credits on the diffusion of LFGE projects, it important to investigate this in more detail. Finally, as carbon credits and feed-in tariffs, one of the innovation-specific policies, are closely related to the income generated during the project, the income aspect is also included in this first submodel.

Figure 8 shows the stock flow diagram of the submodel on institutional alignment. The effects of the policies are depicted by a dotted line because the implementation of a policy does not change the system numerically, but requires changes in the model structure. The feed-in, however, is not modelled as a structural change as the level of the feed-in tariff actually does change the model numerically.

As explained in Table 4, the building block innovation-specific institutions is defined as the formal rules surrounding the new technology. According to Ortt & Kamp (2022), stable and supporting innovation-specific institutions can facilitate the diffusion of innovations. Therefore, the building block is operationalised as the institutional fit of the existing policies to LFGE projects. This institutional fit needs to be built up, meaning that it can either be complete, partially complete, or incomplete. A complete

institutional fit means that all relevant supporting innovation-specific institutions are in place. Therefore, to have a complete institutional fit, there should be a policy mandating the collection of LFG, a policy mandating the generation of electricity from LFG should, the feed-in tariffs should be adequate, and there should be a purchasing obligation to guarantee the sale of the electricity. If these four boxes are ticked, the fit of the innovation-specific institutions can be considered complete. A complete institutional fit will remove barrier I2 lack of regulations on LFG handling, and it will partially remove barrier E1 as feed-in tariffs will improve the viability of LFGE projects. Nevertheless, as it is possible to implement LFGE projects without these four policies, the institutional fit is modelled as an incentive rather than a barrier to the implementation of LFGE projects.
The creation of an institutional fit can be achieved, with a delay, by entrepreneurs and formal advocacy groups putting pressure on the government to change the institutional framework to a more fitting one. The increased institutional fit in turn results in more support from the general public, as well as more formal support for LFGE projects, which results in a reinforcing loop. The reinforcing power of the loop will naturally stop once the institutional fit is complete. It is expected that the policies, once implemented, will not be removed during the formative phase.
Lobbying for adequate feed-in tariffs by entrepreneurs, among others, also results in a reinforcing loop as the increase in financial incentive could result in more entrepreneurs being active in the LFGE TIS. Although there are many different ways to implement a feed-in tariff, this research only considers the fixed price model. The costs of the feed-in tariff can either be covered by the government or by the consumers (Del Río & Gual, 2007). This research only investigates the scenario in which consumers pay for the costs of the feed-in tariff as it is expected that there is a greater chance African governments will implement this scenario. Feed-in tariffs are generally designed to make efficiently designed installations cost-effective (Couture & Gagnon, 2010). This research therefore assumes that the feed-in tariffs are higher than the wholesale market price of electricity in case of a low market price, but do not exceed the levelised costs of energy (LCOE). The LCOE is the minimum required price that is required for the project to breakeven over the total project life and therefore indicates the economic viability of a project (Cudjoe & Han, 2021). Nevertheless, the feed-in tariff can still be too low to make LFGE economically attractive.

The market formation variable is defined as the ratio feed-in price and minimum required price for LFGE projects to be an attractive opportunity. As it is assumed that the feed-in tariff will not exceed the LCOE of LFGE projects, this ratio will be a value between 0 and 1. This range allows for the integration of this variable into the aggregated model. Additionally, when the wholesale market price is higher than the minimum required price for a project to be viable, there is no need for the implementation of a feed-in tariff, and the market formation function is assumed to be 1. The minimum required price is determined by the LCOE from LFGE, which can be adjusted to include potential carbon revenues per kWh. The LCOE is calculated by Equation 1 (Ogunjuyigbe, 2017).

$$LCOE = \frac{Life\ cycle\ costs}{Electricity\ potential} * Capital\ recovery\ factor \tag{1}$$

In this equation, a discount rate is included in both the life cycle costs and the capital recovery value. However, in the model it is assumed that the interest rates are low, so the discount rate is excluded from the model calculation.

Finally, entrepreneurs lobbying for purchase obligations results in a reinforcing loop that attracts new customers, which reduces the risk for entrepreneurs, resulting in more entrepreneurs joining the TIS. The demand also depends on whether there is access to the national electricity grid (barrier I1) as this would increase the pool of potential customers (barrier X3). When a project is not connected to the national electricity grid, the pool of potential customers only consists of customers that directly buy the electricity. This type of customers is harder to find, as they need to be close enough to the project for a direct cable to be installed. The demand is also affected by the purchase price of the electricity from LFGE compared to the price of electricity from other sources. When the wholesale market price of electricity is lower than the price of electricity from LFGE, the demand will shift to the cheaper source, negatively impacting the demand for electricity from LFGE.

The demand for LFGE projects and the purchase price of electricity from LFG are both modelled as auxiliary values rather than as stocks. Because both demand and purchase price are only used in submodel 1, and not in the aggregated model, they can be modelled using real world values. As they do not have to be integrated directly into the aggregated model, they do not have to have a value between 0 and 1. Additionally, only the yearly demand, rather than the total demand, is of interest in this model. Furthermore, in the LFGE case, legitimacy does not affect demand as the end-user is not expected to be concerned about the source of their electricity. Moreover, it is expected that the distribution companies will buy electricity from any source, basing their decision solely on the price.

The entrepreneurial activity is determined by the number of LFGE projects within a country as a ratio of the number of potential projects, and is measured by the saturation of LFGE projects, which ranges between 0 and 1. This range allows for integrating the variable into the aggregated TIS model. Although one interviewee indicated that "every landfill could be a landfill gas project" (personal communication, 2024), the number of potential projects was considered to be less than the total number of landfills in a country because this research only considers the landfills of a reasonable size that have a high potential of being or becoming viable in the near future. This approach excludes the smaller landfills from the analysis. Additionally, it is assumed that no new landfills will be opened because alternative WtE technologies are preferred when opening waste facilities (Olodu & Erameh, 2023). Any additional waste being collected due to a higher efficiency of the waste management system will thus be stored in the existing landfills. The initial number of potential projects was determined through experimentation with the model due to a lack of data on the number of landfills in South Africa. As the number of landfills affects the LCOE, the number of potential projects could be determined by choosing the number of landfills resulting in the right LCOE of LFGE. Cudjoe and Han (2021) have determined the levelised cost of energy for LFG in South Africa to be 0.076 $/kWh in 2012. The model produces this LCOE with 70 potential projects. Comparing the resulting average electricity potential as calculated by the model, which is around 33000 MWh/year, to the electricity generation of South African landfills as estimated in literature confirms the choice of 70 potential projects. Njoku et al. (2020) estimated an average annual electricity potential of 25000 MWh for the Thohoyandou landfill over the next 14 years. Additionally, Njoku & Edokpayi (2022) estimated an average electricity potential of 47000 MWh per year. Therefore, the average annual electricity potential of 33000 MWh estimated by the model is considered to a representative value for the larger landfills in South Africa and the number of potential projects was set to 70.

The potential LFGE projects can be converted into pending LFGE projects through project planning. The number of planned LFGE projects in a year is affected by the level of formal legitimacy, informal legitimacy, market formation, and the length of the tender process. Slow tender processes, resulting from public ownership of the landfill (Barrier O1), will make it less attractive to develop a LFGE project. The planned projects are then implemented with a delay. The number of implemented projects per year depends on the completeness of the production system building block. Only if enough investment has been attracted to cover the implementation costs of all pending projects, and therefore the production system building block is complete, all pending projects will be implemented to become operational projects. Finally, the project lifetime is set to 20 years. The average lifetime of a landfill is 20-25 years (Scarlat et al., 2015). It is assumed that LFGE technology will be installed at a landfill within five years after opening, resulting in a project lifetime of 20 years. At end of life the project will be decommissioned.

The revenue generation from LFGE projects is based on the sale of electricity, as well as on the sale of carbon credits. The latter is determined by the emissions reduced by LFGE projects. Only the emission reductions from electricity generation are considered. As described in Section 2.2, these emissions reductions result from the avoidance of methane emissions as well as from the replacement of the electricity going through the national grid, which is largely based on coal, by electricity from LFGE. The emission reductions resulting from flaring are out of the scope of the model and therefore excluded. To determine the emission reductions from electricity generation, the amount of methane required to produce this electricity is calculated. An efficiency of 100% is assumed, as any additional methane needed due to lower efficiency would be considered losses and therefore cannot be counted as emission reductions. It is assumed that all carbon credits generated will be sold. Nevertheless, it takes time for certification bodies to approve and certify the emission reductions resulting from a project. Therefore, there is a delay between the emission reduction itself and the generation of a certified emission reduction, or carbon credit. The low and fluctuating carbon prices affect financial benefits resulting from a project and therefore the economic viability of LFGE projects (barrier E1).

It is assumed that the implementation of a requirement to collect the LFG from landfills will result in a decrease in the production of electricity. Moreover, it is expected that the requirement will result in more LFG being flared, as this is considered to be the cheaper alternative because less equipment is required. Additionally, both flaring and electricity generation can result in carbon credits, with the condition that no policy specifically requiring flaring or electricity generation is implemented. As the LFG collection requirement obliges the collection of LFG at every landfill, and the scope of the model is on country level, it is expected that a large part of the new landfill gas projects will choose the cheaper collection method, resulting in less LFG being used to generate electricity with the implementation of this policy. If these projects do not generate electricity, they are not considered LFGE projects yet. Implementing a policy that mandates the generation of electricity from LFGE results in the full electricity potential being achieved, provided that the production system and the product performance and quality building blocks are complete. Nevertheless, implementing a policy that obliges electricity generation from LFG prevents the generation of carbon credits as it is in conflict with the additionality requirement of carbon projects. The requirement of electricity generation means that LFGE projects would also be implemented without transforming them into a carbon project. As carbon finance is one revenue flow for LFGE projects, its disappearance could potentially create problems for the viability of a LFGE project.

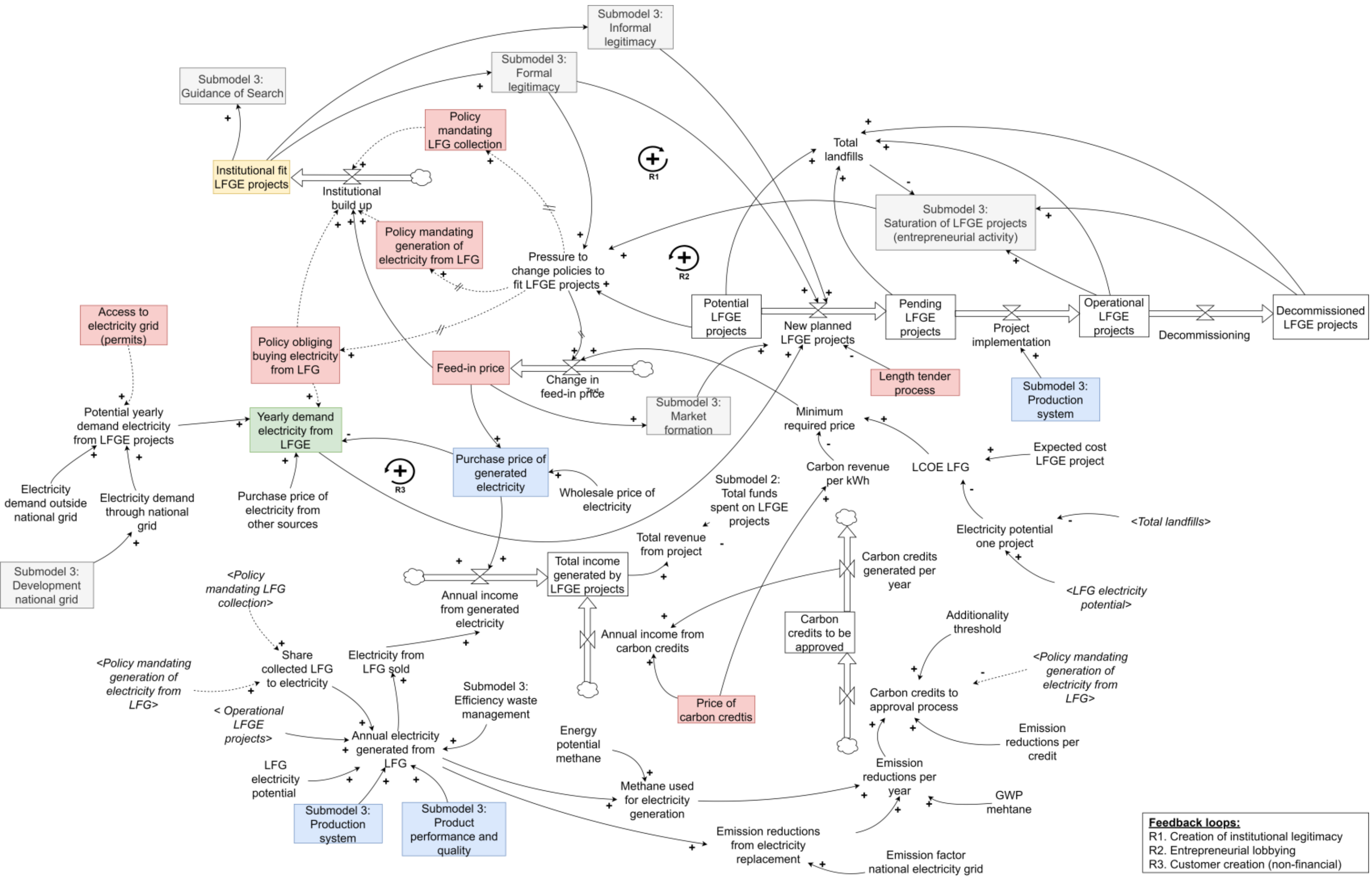

Figure 8. Stylised SFD of submodel 1 institutional alignment.
Structural policy effects are indicated by dotted lines. The signs crossing an arrow indicates a delayed relation. The barriers found are shown in red, while the TIS building blocks are shown in yellow, green, and blue. Source: Own work

7.1.2 Submodel 2: Funding

According to Mbazima et al. (2022), funding is the main barrier to the diffusion of LFGE projects in South Africa. From the interviews it can also be concluded that funding is an important factor in the diffusion of LFGE projects (barrier E2). Therefore, the funding processes are made explicit in the second submodel. This submodel focusses on investment in LFGE projects. Both international investment and domestic investment are included into the model. The investment flows modelled only consider investment into the production system. Therefore, the governmental resources flowing to knowledge development or policy implementation are not considered within this submodel.

Figure 9 shows the stylised SFD of the funding submodel. The funds becoming available every year are dependent on the yearly domestic and international investment in renewable energy as well as on the generated revenue from LFGE projects. The revenue can be used to cover the operational costs, whereas the investment covers the capital costs of LFGE projects.

The investment depends on the expected value of the investment. Following O'Regan and Moles (2006), the expected value is determined by Equation 2.

$$Expected\ Value = (Expected\ Revenue - Expected\ Costs) * Risk\ factor \quad (2)$$

The risk factor is modelled as a probability factor, where 1 represents low risk and 0 represents high risk. As explained in Section 5.3, the risk factor is composed of the policy risk, market risk, and technological risk. Policy risk is defined by 1 minus the institutional fit of LFGE projects, whereas technological risk is defined by 1 minus the product performance and quality building block. The external market risk is covered by the market formation function. An additional risk factor regarding international investment is the level of corruption within a country (barrier X1). Habib & Zurawicki (2001) argue that corruption has a substantial larger impact on foreign investment than on domestic investment. Because of the smaller impact of corruption on domestic investment and to reduce the complexity of the model, the effect of corruption on domestic investment is neglected in the model.

The expected value is affected by both the expected investment costs, the expected operational costs, and the expected revenue (O'Regan & Moles, 2006). The expected revenue is dependent on both the sale of electricity and the sale of carbon credits. It is assumed that the full electricity potential of a project will be considered when determining the expected revenue from electricity generation. If the expected value of the project is positive, the investment is considered viable and the investment is attracted. This goes for both domestic and international investment. The amount of resources invested through domestic investment depends on the level of resource mobilisation within the country. When resource mobilisation is 1, the required resources are available. Nevertheless, these resources have to be divided over knowledge development and diffusion, and investment. The amount of resources invested through international investment depends on the proportion of the costs the international investors are willing to cover, which is assumed to be 30%.

The available funds for LFGE projects are reduced by the funds spent on these projects. Every year, the funds spent on LFGE projects equal the operational costs of the already implemented projects and the investment costs of the pending projects.

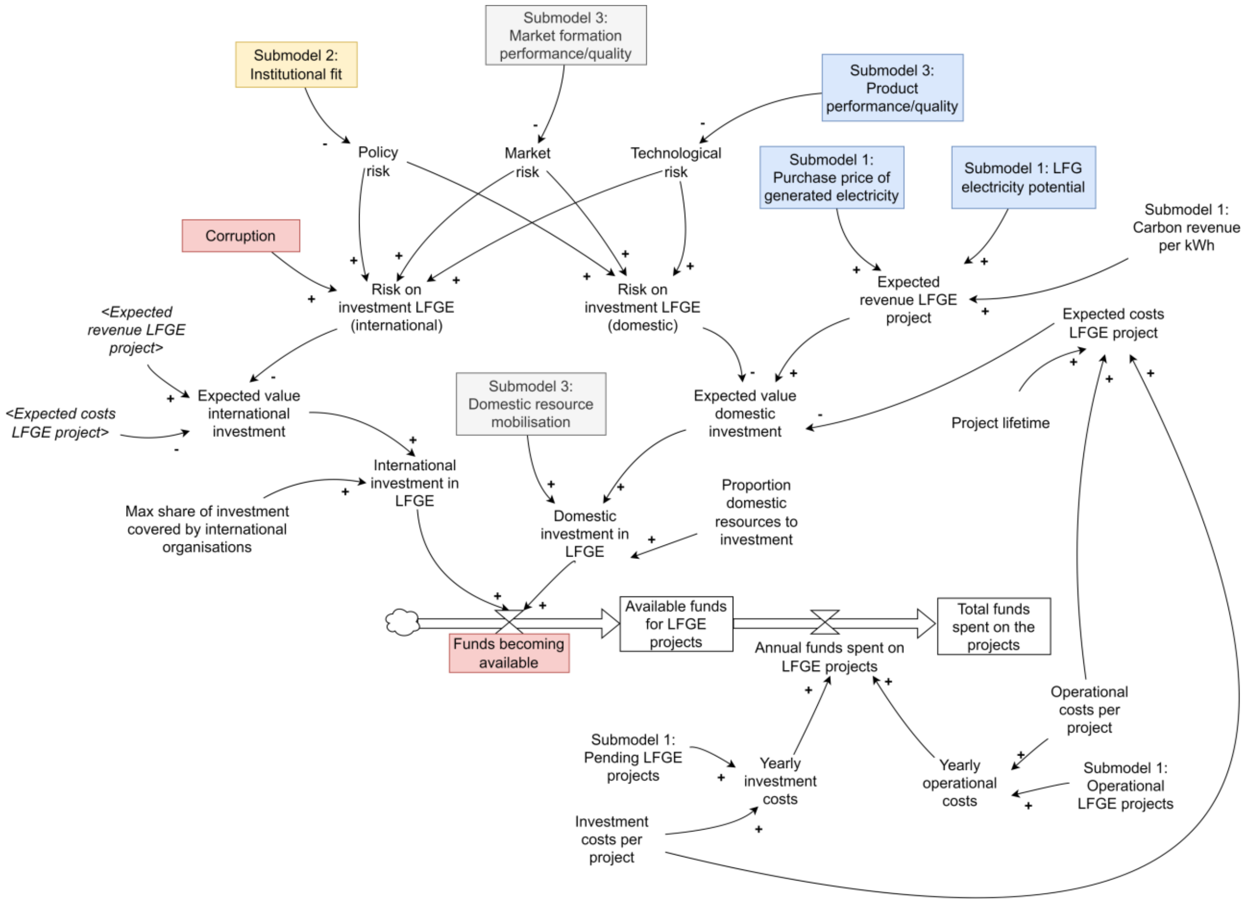

Figure 9. Stylised SFD submodel 2 Funding.
The barriers found are shown in red, while the TIS building blocks are shown in yellow, and blue. Source: Own work

7.1.3 Submodel 3: Aggregated TIS model

The model elements of the conceptualisation of the hybrid approach in Figure 7 that are not specified in either submodel 1 or submodel 2 are included in submodel 3, the aggregated TIS model. The conceptualisation of the aggregated TIS model calibrated to the LFGE TIS is shown in Figure 10. The building blocks and functions that are not modelled in more detailed are assumed to follow an S-curve. This is in line with the approach of Walrave and Raven (2016). It assumes that it is difficult to initialise growth, however once it has taken off, it progresses exponentially. The growth slows down again close to its peak. Nevertheless, the phase of exponential growth could be dampened with the existence of the barriers.

The complementary products and services building block is built up of the development of the national electricity grid and the efficiency of the waste management system, meaning that these barriers can either dampen or accelerate the development of the building block. The production system is operationalised in terms of resource availability. When there are enough financial resources available to cover the costs of the LFGE projects in a country, both pending and operational, it is assumed that the production system will be implemented in the most efficient way, and therefore the production system building block will be complete. However, when the resource availability is not sufficient, the development of the building block will be impeded. Finally, it should be noted that knowledge development affects knowledge diffusion positively, rather than negatively because the outflow of knowledge diffusion is not modelled.

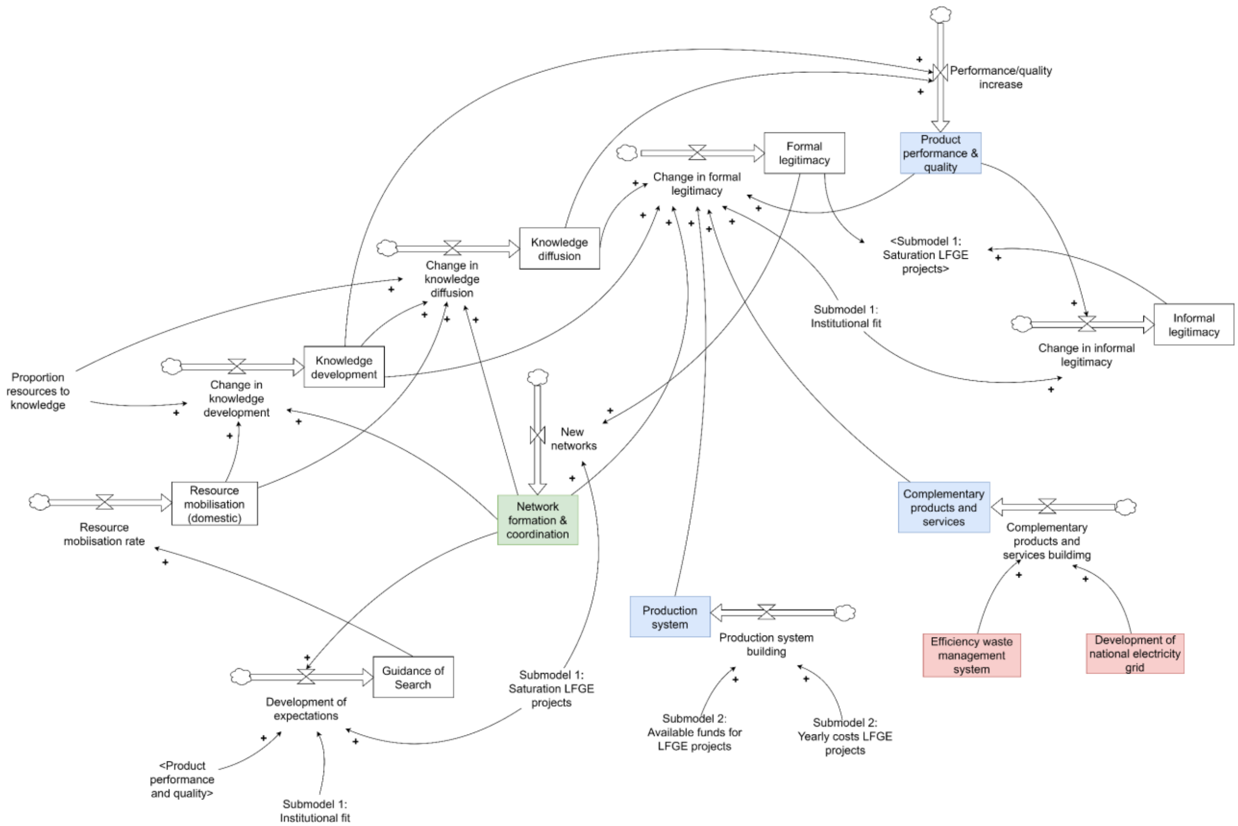

Figure 10. Stylised SFD model of submodel aggregated TIS.
The barriers found are shown in red. Source: Own work

7.2 Model settings

The conceptual models are implemented in Vensim to create a running model. The model consists of three views: institutional fit (submodel 1), funding (submodel 2) and the aggregated TIS model (submodel 3). The three submodels are described in Section 7.1. Additionally, the general aggregated TIS model is explained in Section 5.3.

7.2.1 Model setup

To test and utilise the model, it is calibrated to South Africa. Because the development of the LFGE TIS has already started in South Africa, but is not utilising its full potential yet, it provides a good case to test the conditions required for future diffusion as well as the conditions that will prevent further development of the TIS. The data specific to South Africa is presented in Table 7.

The model is run for 30 years because the model aims to model the formative phase of the TIS. Given that the model also aims to model scenarios in which the development is (temporarily) impeded, it is expected that the initial formative can become lengthy. The model starts in 2005 to simulate the development of the LFGE from the beginning as there are no LFGE reported before 2005. Additionally, 2005 is the year in which the Kyoto protocol became binding. Because of the non-continuous nature of the model due to switches and lookups, the Euler integration technique is used with a time step of 0.005, which is half of the smallest time variable in the model.

Table 7. Case specific data of South Africa

Variable	Value	Unit	Source
Projects implemented in 2024	9	Projects	Haya et al. (2024)
Energy potential LFG	230900	MWh/year	Scarlat et al. (2015)
LFG collection requirement	No		
Obligation to buy electricity from LFGE	No		
Obligation to generate electricity from LFG	No		
Feed-in tariff	No		
Grid access	Yes		
Wholesale price of electricity	0.055 – 0.08	$/kWh	Blimpo et al. (2018)
LCOE of LFG	0.076	$/kWh	Cudjoe & Han (2021)
Electricity demand	1.48 * 10^8 – 1.75 * 10^8	MWh/year	Inglesi (2010)

A detailed overview of all equations and parameter values and a visualisation of the implemented submodels can be found in Appendix E. Model variables and their implementation

7.2.2 Key Performance Indicator

The status of the LFGE TIS can be assessed by tracking the building blocks. For technological innovations to diffuse all building blocks need to be complete (Ortt & Kamp, 2022). However, the completeness of the entrepreneurial function is particularly of interest, as it shows the number of LFGE projects that are implemented compared to the potential projects in a country through the variable saturation of LFGE projects.

7.3 Model evaluation

To test whether the model is fit for purpose and therefore to build confidence in the model, the model is verified, tested and validated. The purpose of the model is to gain quantitative insights into the effects of the different barriers on the diffusion of the LFGE TIS over time. This provides the opportunity to investigate which combination of barriers results in impediment and which combination of barriers could still result in diffusion. This also provides the opportunity to compare the importance of each barrier to the other barriers. The validation is done by performing four tests.

7.3.1 Model verification

To ensure the model was coded correctly, it was constructed in a modular way. First, the different sections of the model were built and tested separately to ensure that the model section behaved as expected. Only when the behaviour of the different model sections was correct, the model sections were connected. Additionally, the dimensions of the variables and equations were checked repeatedly to ensure no dimensional errors were built into the model. The dimensional analysis went beyond the automatic dimensional check provided by the Vensim software, as it is possible to bypass this check, while still having dimensional errors within the model (Auping et al., 2023). Therefore, manual checks were performed during the model formation process. Finally, tests were performed to ensure the appropriate integration technique and time step were chosen. The model showed no differences in behaviour for a smaller time step than the chosen 0.005, providing confidence that the right trade-off between accuracy and computational power has been made.

7.3.2 Model validation

To build confidence in the model, both the structure of the model and the model behaviour are tested. The tests are performed in order; once a test is passed, the next test is performed. When a test fails, the model is adapted and the test will be conducted again.

7.3.2.1 Description of tests

Forrester and Senge (1980) identify two categories of test for building confidence in the model: test of model structure and tests of model behaviour. To build confidence in the model structure, a structure verification test was performed. This test compares the model structure directly to the structure of the real world system (Forrester & Senge, 1980). This was done by comparing the model structure of the aggregated model to literature. Additionally, the main model assumptions were validated through the consultation of an expert on LFGE from Anthesis – Climate Neutral Group. Besides the structure verification test, an extreme conditions test was performed to ensure the model is robust and shows plausible behaviour under these conditions. While Forrester & Senge (1980) identify the extreme conditions test as a test of model structure, in this research it is implemented as a test of model behaviour because the extreme conditions were implemented into the model to assess their effect on the model behaviour.

To build additional confidence in the model behaviour, a behaviour reproduction test was performed. More specifically, the symptom-generation test was used to examine whether the model produces the problematic behaviour that resulted in building the model in the first place (Forrester & Senge, 1980). Bala et al. (2017) state that the emphasis of the behaviour reproduction test should be on behavioural patterns rather than point by point comparisons. To this end, the model was calibrated to the case of South Africa. By choosing a specific country, the model behaviour can be compared to the actual situation regarding LFGE projects in South Africa.

After the model passed the behaviour reproduction test, a behaviour sensitivity test was performed. A behaviour sensitivity test shows the sensitivity of the model to small changes in parameter values (Forrester & Senge, 1980). The behaviour sensitivity test ensures that plausible small changes will not result in the model failing the other behaviour tests. Normally, the model is insensitive to these plausible changes (Bala, 2017). However, the model being sensitive to a specific parameter does not necessarily undermine the validity of the model, as long as this does not result in the model failing other behavioural tests (Bala, 2017). To perform the behaviour sensitivity test, a selection of parameters to which the model was expected to show sensitivity was created. This selection included the modelled barriers and the input parameters that were based on an assumption. Each parameter was varied by 10% to see the effects of small changes on the model behaviour. All parameters were adjusted by the same percentage to allow comparison of the results. For the variables to which the model is highly sensitive, it is particularly important that the estimation of their value is correct as a small change will have a great impact on the system. Therefore, extra attention was given to the collection of data for these variables, especially if the variable was not included in the experiments.

7.3.2.2 Results structure verification test

Following Walrave & Raven (2016), most TIS functions and building blocks in the aggregated submodel are assumed to follow an S-shaped growth pattern. Initially, growth is difficult to formalize, but once it starts, it progresses exponentially. However, reaching the full growth potential becomes increasingly challenging as growth nears its peak. This assumption implies that the growth of the TIS functions and building blocks in the aggregated submodel will always peak at a maximum, which corresponds with the real-world processes for the functions and building blocks. For example, the development of technological performances generally shows slow initial improvement because the fundamental aspects of the technology are not well understood yet (Schilling & Esmudo, 2009). This stage is followed by accelerated improvement once the fundamental understanding is established and grows. Nevertheless, the marginal improvements start to become small once the performance is near its peak (Schilling & Esmudo, 2009). Additionally, modelling the TIS functions and building blocks as following a S-shape prevents unlimited exponential behaviour, which is not realistic. Finally, the assumption of S-shaped growth for the TIS functions and building blocks in the aggregated model allows for high-level modelling of these functions. This allows for their inclusion in the model to investigate their effect on the system, without distracting focus from the purpose of the model, which is modelling the impact of the different barriers on the system.

A second assumption lies in the modelling of the stock-flow structure of the LFGE project life cycle without an inflow into the potential projects. This assumptions might deviate from the real-world. Although landfilling is the least preferred waste management solution and opening new landfills could be challenging due to a lack of space, it is the cheapest waste management solution (Olodu & Erameh. 2023; Mbazima et al., 2022). Especially in countries with a poorly developed waste management system, opening new landfills might be the best solution to improve their waste management system and to deal with the increasing amount of waste. Modelling the potential LFGE projects without an inflow results in the potential of LFGE being finite, as the development of the TIS will stop once all landfills are converted into a LFGE project. Additionally, this results in larger rather than more landfills when the waste management system is increased in the model. Therefore, a better waste management results in a higher electricity potential per landfill. Nevertheless, as the efficiency of the waste management system is kept constant during each simulation run, the size and therefore electricity potential of the landfill are also kept constant during a simulation run. As the base case assumes a realistic landfill size, this effect of the base case efficiency of the waste management system is modelled correctly. Additionally, the model is still suitable for assessing the potential of LFGE for the current number of potential projects in a country. However, if there are simulation runs in which waste management system is improved compared to the base case, the results should be viewed as an exploration of the impact of changes in landfill size.

Nevertheless, both the generated waste, and therefore the electricity potential, and the electricity demand will most likely increase due to population growth. In its current state, the model does not account for these increases. However, both an increase in demand and an increase in electricity potential will increase the attractiveness of the LFGE projects. Therefore, the increase in electricity potential and demand will most likely not result in impediment of the LFGE TIS. Since the purpose of the model is to determine the effect of the barriers that do impede the development of the LFGE TIS with the current number of landfills, modelling them in a static way is considered sufficient for the model to fulfil its purpose. Additionally, both variables are modelled exogenously, which means that in case their current values are too low and therefore do prevent the TIS from developing, they can easily be transformed into a table function and experimented with to see whether the increase in electricity demand and potential would be enough to stop the impediment of the TIS development. However, since this does require the collection of additional data, which can be a time consuming process, the development of these variables is left out of the current model.

Another assumption lies in the endogenous modelling of the innovation-specific policies. The model assumes that once a certain level of lobbying is achieved, these policies will be implemented, accelerating the development of the TIS. However, lobbying is more common in countries enjoying political stability compared to countries with high levels of corruption and unstable regimes (Campos & Giovanonni, 2007). Additionally, Campos & Giovanonni (2007) state that lobbying is the dominant method of influencing the government at higher levels of development, while corruption is dominant at lower levels of development. Although the model does not consider the relation between political stability and lobbying, it provides the possibility of accounting for the possible ineffectiveness of lobbying by setting the required lobbying pressure to implement the policies to a high value. Additionally, the effect of the institutional fit is modelled in a way that does not prevent the development of LFGE projects when the institutional fit is zero. This is similar to the real-world effect of the innovation-specific policies considered, as these are all incentivising policies, rather than obstructing policies. This means the implementation of LFGE projects can still happen without these policies.

Finally, the profitability of the investment in LFGE projects is determined by calculating the undiscounted expected value of the investment, which depends on the expected revenue, the expected cost, and a risk factor. By modelling profitability without discounting, the model fails to account for inflation and interest rates. Therefore, the revenue required to present the investment as profitable is lower in the model compared to the real-world. Therefore, the model is only valid when the revenue in present values is much higher than the costs, or the interest rate is zero, as either one would most likely also present the investment as profitable when the discounting would be considered. Nevertheless, as the exclusion of interest rates and inflation still allows for an assessment of the effect of the different barriers on the diffusion of LFGE and compare the effects of each barrier to the other barrier, this assumption is considered acceptable.

Additionally, the expected value is assumed to be the same for all projects since the model is not able to differentiate between different projects. In reality LFGE projects can differ in size, which will affect the electricity potential of a landfill. The model assumes all potential LFGE projects together to achieve the electricity potential of LFGE projects, provided the other TIS functions and building blocks are complete. Therefore, in the model, the larger projects will compensate for the smaller ones, ultimately achieving the total electricity potential. This assumption makes the model valid only at the country level, rather than at the project level. Since the barriers are also considered on country level, this is in line with the model purpose.

7.3.2.3 Results extreme conditions test

The design of the extreme conditions test is shown in Table 8. The extreme conditions will be tested one by one to ensure the effect is indeed related to the specific conditions.

Table 8. Extreme conditions and their expected impact

Condition	Expected behaviour
No investment in LFGE projects	This should result in no implementation of LFGE projects.
No policy implementation	When none of the innovation-specific policies are implemented, the TIS should still develop, albeit at a slower rate, since the policies are only meant to incentivise the development of LFGE projects, rather than impede this.
Full policy implementation	When the three policies and an adequate feed-in tariff are implemented in the initial year, the diffusion should take off fast as there is a more legitimacy. More importantly, the economic conditions are sufficient for LFGE projects to be attractive for entrepreneurs and investors.
Very high costs of LFGE projects.	This should result in very little investment into LFGE projects.
Low costs of LFGE projects.	It is expected that low implementation and operational costs of LFGE project result in faster diffusion of LFGE projects, as a lower price is required to make the investment attractive.
No electricity demand	No electricity demand should result in no implementation of LFGE projects as there is no use for the electricity.
No waste management	When there is no waste management system within a country, it is not possible to create LFGE projects, because this requires some form of waste management that ensures a share of the waste ends up at a sanitary landfill.
Perfect waste management	When the waste management system in a country works perfectly and therefore all waste is collected and send to landfills, the LFGE projects should diffuse rapidly as each landfill contains more waste to generate electricity with.

Appendix F. Extreme conditions tests shows the results of the extreme conditions test. The results illustrate that the model behaves as expected under these extreme conditions. However, the effect of no innovation-specific policies being implemented is only relevant for countries where the wholesale market price is higher than the minimum required price (adjusted by the carbon revenue per kWh). This means that a feed-in tariff is not required, and the market formation is considered to be 1, which will kick-start the diffusion process. For countries where the wholesale price is lower than the minimum required price, the market formation function will initially be zero. If the other policies are also zero and there is no way to endogenously change the institutional fit through lobbying at an early stage, there will be no incentive to implement LFGE projects. Therefore, this scenario will result in no development of the TIS functions and building blocks, leading to no LFGE projects being implemented.

7.3.2.4 Results behaviour reproduction test

The problematic behaviour of LFGE in South Africa to be reproduced by the model is the lack of development of LFGE projects. Figure 11 shows the development of the number of operational projects based on real-world data from the Berkley database (Haya et al., 2024), and the number of operational projects estimated by the model. The model results show similar behaviour as the real-world data. The model is therefore able to reproduce the problematic behaviour.

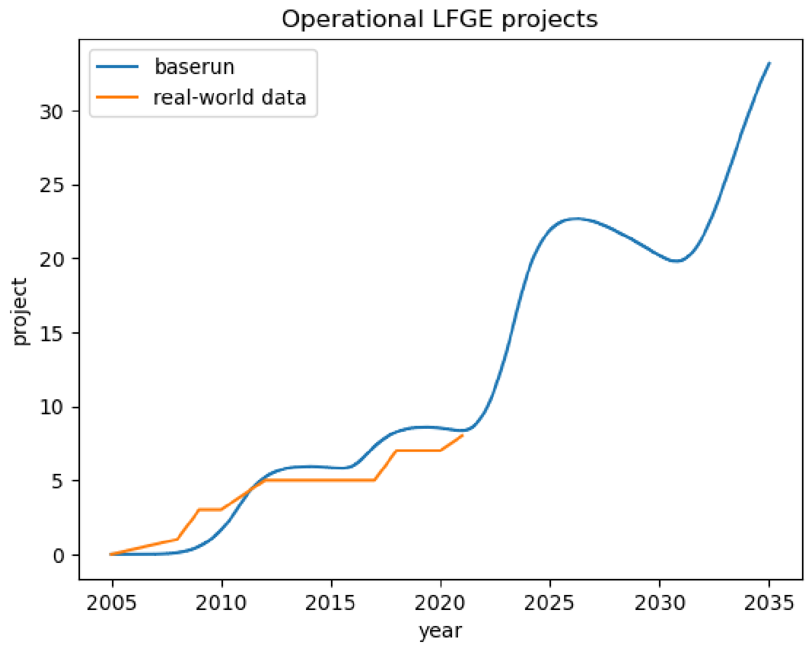

Figure 11. Behavioural reproduction test on operational LFGE projects
Note. Real-world data is collected from Haya et al. (2024).

7.3.2.5 Results behaviour sensitivity test

Table 9 shows the parameters tested, as well as the values used in the behaviour sensitivity test. First, behavioural sensitivity was tested univariately, by changing the parameters one by one. This was followed by multivariate sensitivity tests, in which closely related parameters were changed at once to investigate their combined effect. The sensitivity graphs of the tests illustrating the sensitivity of the model are presented in Appendix G. Behavioural sensitivity test. The results show that the model is insensitive to small changes of most of the tested parameters. Nevertheless, the model did show to be numerical sensitive to small changes in *average length of tender process, average time to implement paperwork before starting a project, additionality threshold, efficiency of the waste management system,* and *construction time.*

The model shows the greatest sensitivity to univariate changes in *efficiency of the waste management system.* Small changes in the waste management system can result in both faster diffusion or stagnation. This indicates that the purchase prices is close to the minimum required price. Changes in the waste management system change the average electricity potential of a landfill and therefore the LCOE of LFGE. The high sensitivity to the waste management system indicates that small changes in the waste management system result in changes in the LCOE of LFGE that are enough to push the minimum required price above or below the purchase price for large parts of the run, causing stagnation or diffusion respectively. The model also shows sensitivity to changes in the *average length of tender process* and *average time to implement paperwork before starting a project.* Changes in the length of tender processes can either slow down or speed up the planning of LFGE projects. Additionally, long tender processes result in fewer entrepreneurs being interested in joining the LFGE TIS due to the resource requirement of tender processes. This effect is amplified by shorter times to prepare the necessary paperwork in case there is no tender process as this creates a larger gap between the length of tenders and the alternative, which is no tender due to private landfill ownership. Therefore, the sensitivity of the model behaviour to changes in the length of the tender process and the time to prepare the paperwork in case there is no tender is in line with the expectations. The model is also numerically sensitive to changes in the additionality threshold, which is as expected as the additionality threshold allows for the generation of carbon credits for a longer period of time, increasing the economic benefits of LFGE. Finally, the sensitivity to *construction time* and *proportion domestic resources to investment* and *share of investment covered by international organisations*, is very small. Note that the model is not sensitive to most of the variables tested for which an assumption was made regarding its value, indicating that these assumptions do not change the model behaviour.

Table 9. Behavioural sensitivity test input values

Parameter	Lower value	Basecase value	Upper value
Average length tender process	10.8	12	13.2
Average time to prepare paperwork before starting a project	5.4	6	6.6
Construction time	0.9	1	1.1
Electricity demand outside national grid	2365200	2628000	2890800
Pressure needed to implement buying obligation[1]	0.72	0.8	0.88
Pressure needed to change feed-in tariff[1]	0.72	0.8	0.88
Pressure needed to implement LFG collection requirement[1]	0.54	0.6	0.66
Pressure needed to implement electricity mandate[1]	0.81	0.9	0.91
Share LFG collected to electricity with Policy 1	0.225	0.25	0.275
Share LFG collected to electricity without any policy	0.45	0.5	0.55
Average time for carbon credits to be validated	0.9	1	1.1
Time to implement policy	1.8	2	2.2
Proportion domestic resources to investment[2]	0.45	0.5	0.55
Share of investment covered by international organisations[2]	0.27	0.3	0.33
Time to build elements production system	0.9	1	1.1
Time to build networks	0.9	1	1.1
Time to increase performance	0.9	1	1.1
Additionality threshold	0.27	0.3	0.33
Efficiency waste management system	0.50058	0.5562	0.61182

1. Included in multivariate sensitivity test 1
2. Included in multivariate sensitivity test 2

7.3.3 Conclusions model evaluation

The tests performed during the model evaluation phase provide confidence that the model is fit for purpose. Although assumptions have been made while constructing the model, these assumptions are considered either in line with real-world processes or serve the model purpose. Additionally, the model shows plausible behaviour under extreme conditions, providing confidence in the robustness of the model to these extreme events. Furthermore, the model results are in line with real-world data on LFGE projects, indicating that the model is able to simulate the stagnation of LFGE in South Africa. Finally, the behavioural sensitivity tests show the model generates plausible behaviour to small changes in the parameters of which the values are based on assumptions. These increases the confidence in the model as most of the small changes do not result in the model failing to generate the expected behaviour.

However, the high sensitivity of the model to small changes in the efficiency of the waste management system shows that this is a highly important variable in the diffusion of LFGE in South Africa and care should be given to the selection of the right data for this parameter. Additionally, it should be noted that the model is only valid on the country-level. The model is based on averages and simplifications surrounding the electricity generation and economic viability of LFGE projects, making it unfit to investigate individual LFGE projects. This model scope is considered acceptable as an analysis on country level is in line with the scope of the research.

7.4 Experimental setup

To evaluate the effect of the different barriers on the diffusion of LFGE projects, a range of experiments was constructed. First, the base case was analysed to understand the diffusion under the current circumstances. However, as the model simulates future behaviour, which creates uncertainty in the model, experiments were conducted to investigate the model behaviour under different conditions, while simultaneously providing insight into the effect of the modelled barriers on the model behaviour. A total of 41 experiments were conducted. For each barrier, the effects of both its worst case and best case scenarios were investigated. Additionally, the combined effects of all barriers, considering both worst case and best case values, are tested. Moreover, the effects of the best case scenario of each individual barrier, as well as all best case scenarios combined, were tested in combination with the worst case scenario of the wholesale price to see whether the barriers can act as drivers even when LFGE projects are not economically attractive. Finally, the effects of the policies, feed-in tariffs, waste management, and carbon credits were investigated separately. Table 10 shows the base case, best case, and worst case values used in the experiments. Where possible, real-world values of African countries were used. Worst case values were chosen based on the worst performing country, while best case values were chosen based on the best performing country on the specific indicator. As the base case values for the pressure required to implement the policies only result in the implementation of policy 1 and the innovation specific institutions building block is not yet complete, the base case values are also considered to be the worst case values. Furthermore, the initial values of the policies are adjusted during several experiments to include cases where the policies have already been implemented in the past. However, as it is expected that most African will not have implemented one of the policies yet, the pressure required for the implementation of new policies is also adjusted in a way that results in implementation of the policies in 2025.

Table 10. Base case, best case and worst case values of the barriers

Barrier	Unit	Worst case	Base case	Best case
Waste management	Dmnl	0.1[1]	0.5562	0.995[2]
Grid access	Dmnl	0	0	1
Length of tender process	Months	0	12	36
Initial policy 1	Dmnl	0	0	1
Initial policy 2	Dmnl	0	0	1
Initial policy 3	Dmnl	0	0	1
Initial feed-in tariff	$/MWh	0	0	82
Pressure required to implement policy 1	Dmnl	0.6	0.6	0.5
Pressure required to implement policy 2	Dmnl	0.8	0.8	0.5
Pressure required to implement policy 3	Dmnl	0.9	0.9	0.5
Pressure required to implement feed-in tariff	Dmnl	0.8	0.8	0.5

1. Values corresponds to Eritrea value
2. Value corresponds to Mauritius value

Figure 12 until Figure 15 show the scenario input for the barriers that are modelled as table functions. The historical wholesale prices and carbon credit prices are kept constant to show the effects of different representations of the future values. Data for the wholesale prices is available from 2014 until 2017. Therefore the experimental values start as of 2018. The prices before 2014 are assumed to be equal to the 2014 price. Additionally, in the best case scenario, the wholesale price is assumed to start increasing only as of 2023, reaching a maximum of 0.09 $/kWh in 2035. In the base case, on the other hand, the wholesale price is assumed to rise as of the moment of the latest data, which is 2018), to the maximum value presented in the real-world data, which is 0.08 $/kWh (Blimpo et al., 2018). It is assumed that this growth will happen in two steps, keeping the price below the LCOE of LFGE up to the present. By 2035, the best case price of carbon credits is assumed to reach a slightly higher level than the price level at the start of the Kyoto protocol. The full experimental design and the graphs showing the different values for the table functions are shown in Appendix H. Experimental design.

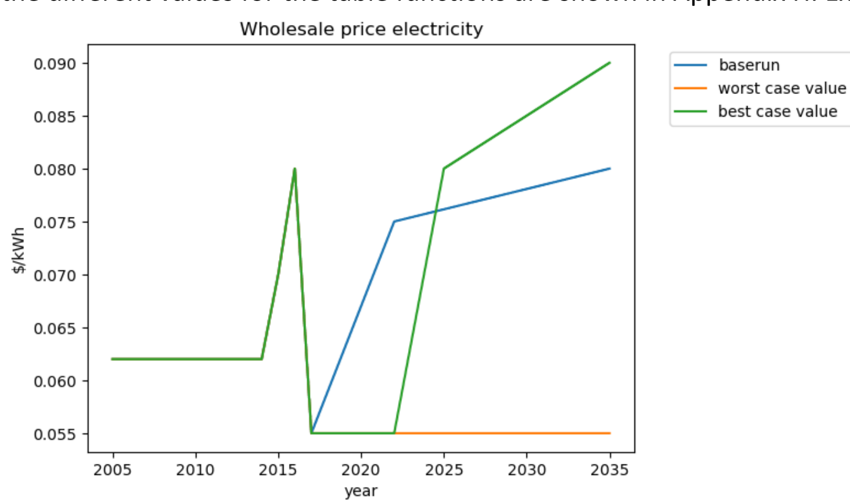

Figure 12. Scenario input wholesale price of electricity.

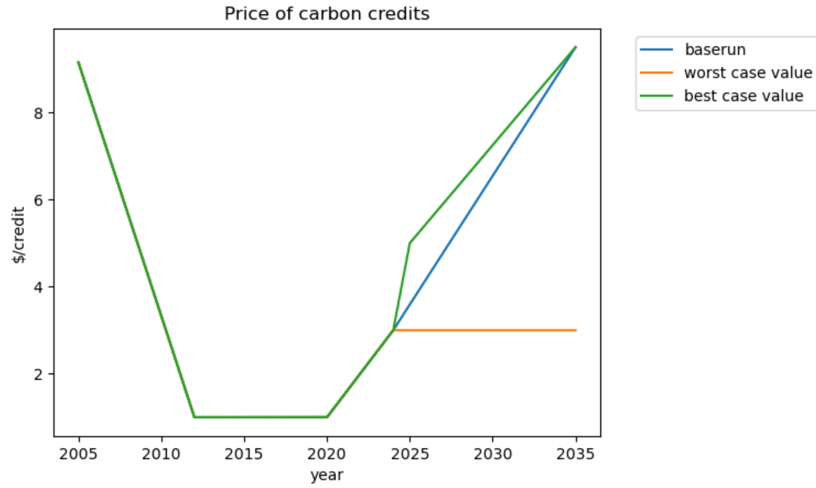

Figure 13. Scenario input price of carbon credits.

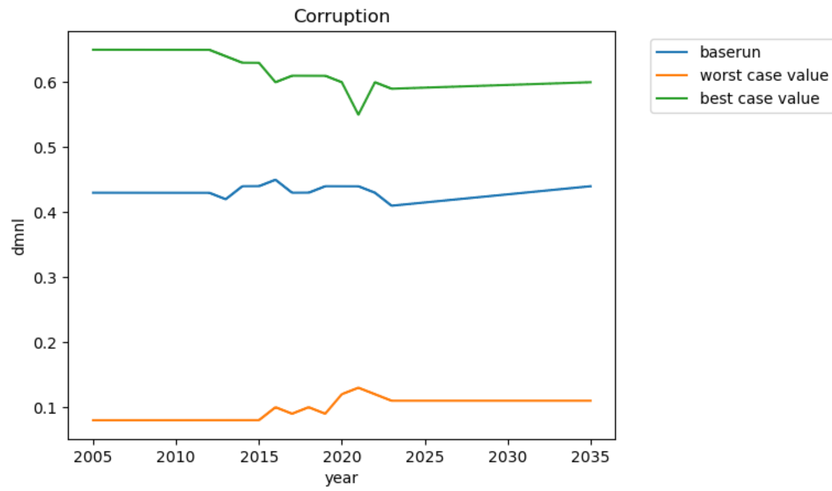

Figure 14. Scenario input corruption.
Best case is based on Botswana. Worst case based on Somalia.

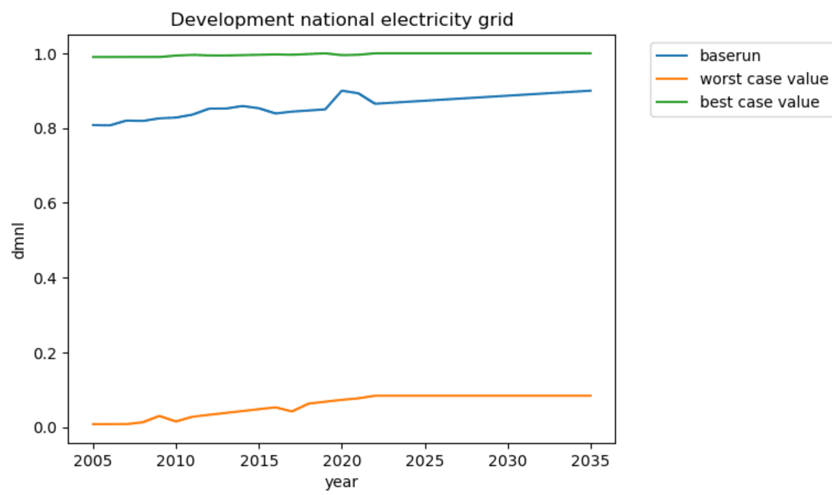

Figure 15. Scenario input development national electricity grid.
Best case is based on Mauritius. Worst case is based on South Sudan.

8. Results

This chapter presents the results from the model experiments. First, the base case results are presented, followed by the impact of the individual barriers and policies. The chapter concludes with a ranking of the barriers and policies .

8.1 Base case results

The base case represents the current status of the LFGE TIS in South Africa. Figure 16, Figure 17, and Figure 18 show the base case results for the saturation of LFGE projects, the number of pending projects, and the number of operational projects, respectively. Figure 19 shows the development of the wholesale price of electricity, as well as the LCOE of LFGE and the minimum required price when carbon is taken into account. As shown in Figure 16, the saturation of LFGE projects almost reaches 0.75, indicating that around 75% percent of the landfills has been converted into LFGE projects. While this suggests that LFGE will not have been fully diffused in South Africa within the coming 10 years, the increasing operational projects indicate that full diffusion under the current conditions could be possible with more time. The non-linearity of the saturation is related to the development of the pending LFGE projects. Pending projects are defined as those that have attracted entrepreneurial interest and are ready for implementation once funding becomes available. The pending project development shows ups and downs indicating that the implementation of projects has not been continuous. The development of operational projects show similar behaviour as the saturation of projects. The first projects were implemented around 2008, a few years after the first projects were planned. At the end of the simulation, the number of pending projects is decreasing, while the number of operational projects is still increasing, indicating that more projects are being implemented than decommissioned. Figure 19 shows that the wholesale price of electricity is not always sufficient to cover the LCOE of LFGE or even the minimum required costs when carbon credits are considered. The peaks in the number of operational projects are in line with the incidents in which the minimum required price drops below the wholesale price of electricity.

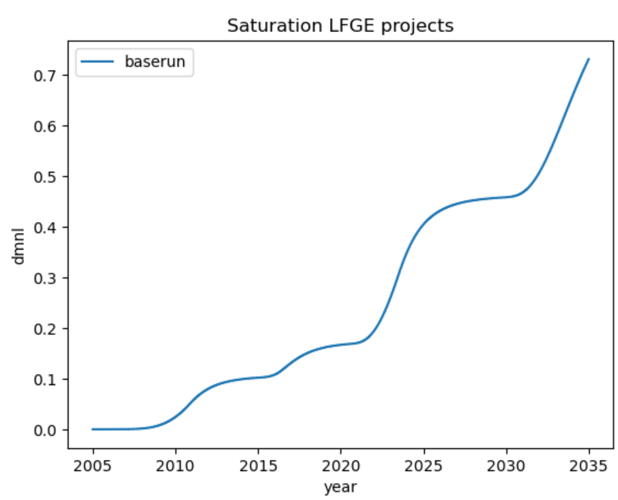

Figure 16. Base case saturation LFGE projects.

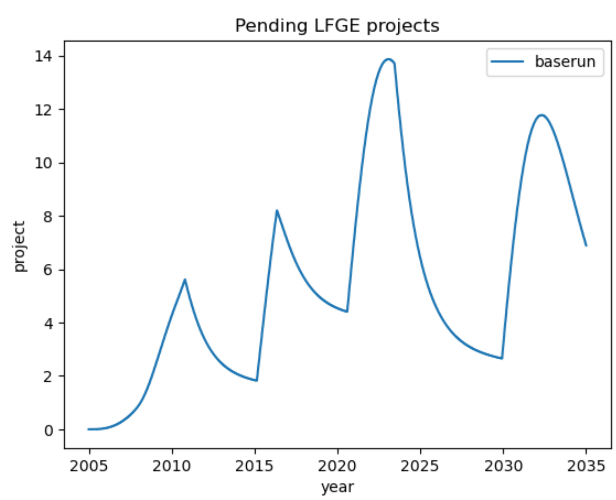

Figure 17. Base case pending LFGE projects.

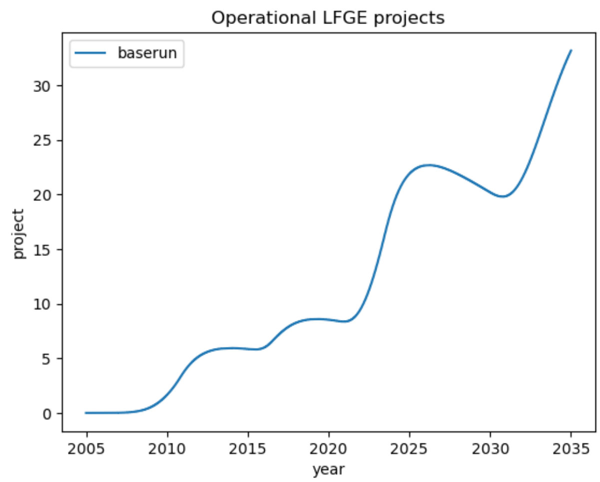

Figure 18. Base case operational LFGE projects.

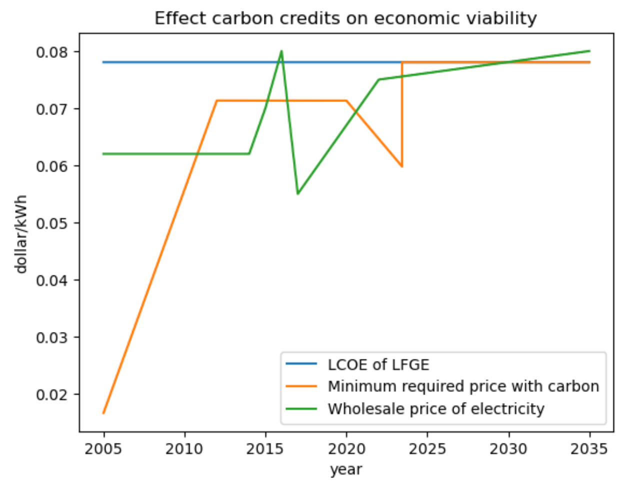

Figure 19. Effect carbon credits on economic viability in the base case.

8.2 Impact of barriers on LFGE diffusion

From the experiments of it can be concluded that the wholesale price of electricity and the efficiency of the waste management system are the most important barriers for diffusion of LFGE because they can cause both diffusion and stagnation. As shown in Figure 20, an increase in wholesale price to above base case levels results in accelerating of the development of LFGE because the price is high enough to make LFGE economically attractive. On the other hand, the worst case scenario of the wholesale price, when the wholesale price remains low after 2017, results in the development of LFGE only starting to progress once the minimum required price is decreased by high prices of carbon credits. Nevertheless, once the market share of LFGE projects exceeds the additionality threshold and the possibility to generate carbon credits is removed, the development of LFGE stops because it is not viable anymore to develop a LFGE project. In case of a low wholesale price, the effect of the low price can only be counteracted by a higher efficiency of the waste management system. The higher efficiency of the waste management results in a lower LCOE, meaning that a lower wholesale price can still result in economic viability. Graphs illustrating this effect can be found in Appendix I.1 Effect barriers in case of low wholesale price. Additionally, Figure 21 shows that the efficiency of the waste management system can also cause the diffusion to stagnate in the worst case scenario, and accelerate in the best case scenario. However, as the efficiency of the waste management system is more stable compared to the wholesale price, it is considered to be the second most important barrier. The increased efficiency of the waste management system results in larger landfills with a greater electricity potential, which results in faster development of LFGE and full saturation by 2025. On the other hand, the results indicate that a low efficiency of the waste management system prevents the development of LFGE projects. This indicates that the size of the landfills is a very important factor in the development of LFGE projects.

Appendix I.1 Effect barriers in case of low wholesale price also shows that the other barriers are not able to counteract the low wholesale price. In terms of policies, only the implementation of a feed-in tariff is able to counteract the low wholesale price. This is as expected as in this case the feed-in tariff determines the purchase price. The implementation of the other policies does not result in diffusion in case of a low wholesale price.

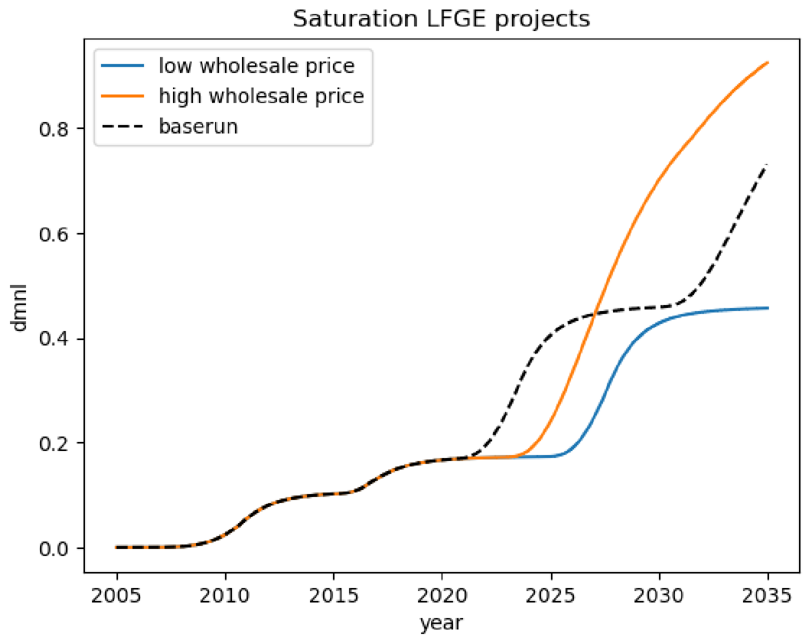

Figure 20. Effect wholesale price on saturation LFGE.

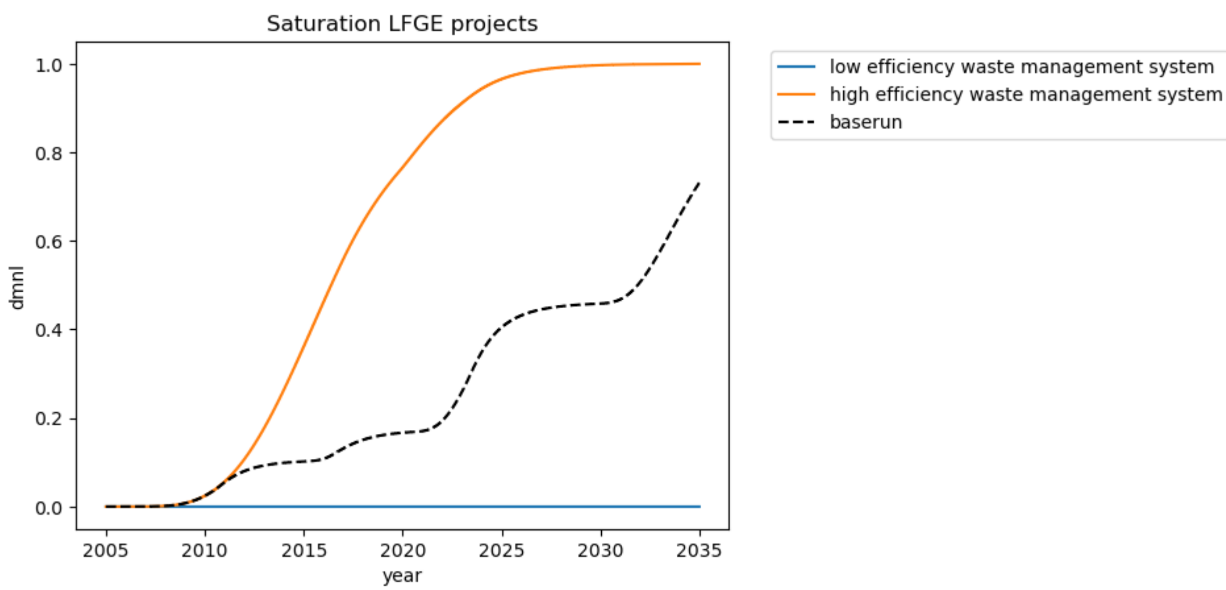

Figure 21. Effect efficiency waste management system on saturation LFGE.

The lack of grid access can impede the diffusion of LFGE (Figure 22) as can long tender processes, albeit to a lesser extent (Figure 23). However, removing either one of the barriers will not result in full diffusion of LFGE in the coming 10 years. In case there is no access to the electricity grid, the demand is limited to the electricity offtakers that are able to buy the electricity without going through the national grid. This requires the offtaker to be physically close to the LFGE project, allowing for the installation of a direct electricity cable to the offtaker. As the number of offtakers that fulfil this requirement is limited, the demand for electricity is significantly smaller than when the electricity demand is equal to the demand of the national grid. This results in fewer projects being planned and installed because of the risk of not being able to sell the electricity. Moreover, no access to the electricity grid results in the demand being smaller than the full electricity potential of LFGE, which will prevent the TIS from developing to its full potential, as it is not viable to generate electricity without being able to utilise it. In terms of the effect of landfill ownership, the best case scenario, when the landfill is privately owned and there is no tender process, it is more attractive for entrepreneurs to propose the implementation of a LFGE project at a landfill because tender processes can be tedious and complex (Mbazima et al., 2022). Therefore, countries with privately owned landfills show a faster development of LFGE projects. Nevertheless, this fast development is held back by the price of electricity. As shown in Figure 19, the wholesale price is not sufficient to cover the LCOE of LFGE before 2016. However, the extra revenue stream resulting from the sale of carbon credits reduces the minimum required price for LFGE to be attractive. After 2010, the minimum required price is equal to the LCOE of LFGE because the generation of carbon credits is not allowed anymore. Therefore, the quick development of LFGE stops after 2010, only taking off again after 2030, when the wholesale price is once again high enough to make LFGE economically attractive. In case the tender process is very long, it becomes less attractive for entrepreneurs to join the process, resulting in little to no LFGE projects being implemented. Only when the price of electricity starts to increase, LFGE becomes attractive enough for a few entrepreneurs to join the TIS and set up projects. However, no diffusion is achieved, nor will be achieved in the near future.

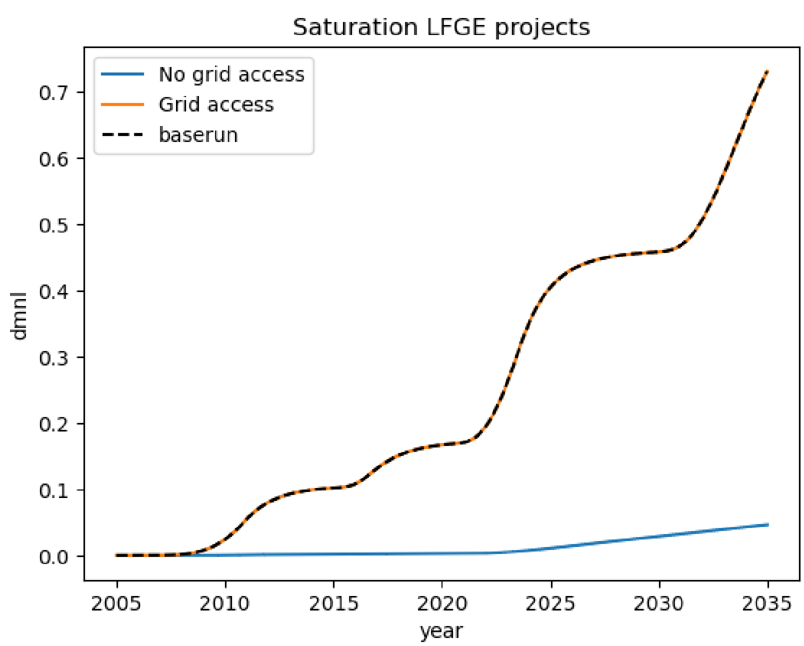

Figure 22. Effect grid access on saturation LFGE.

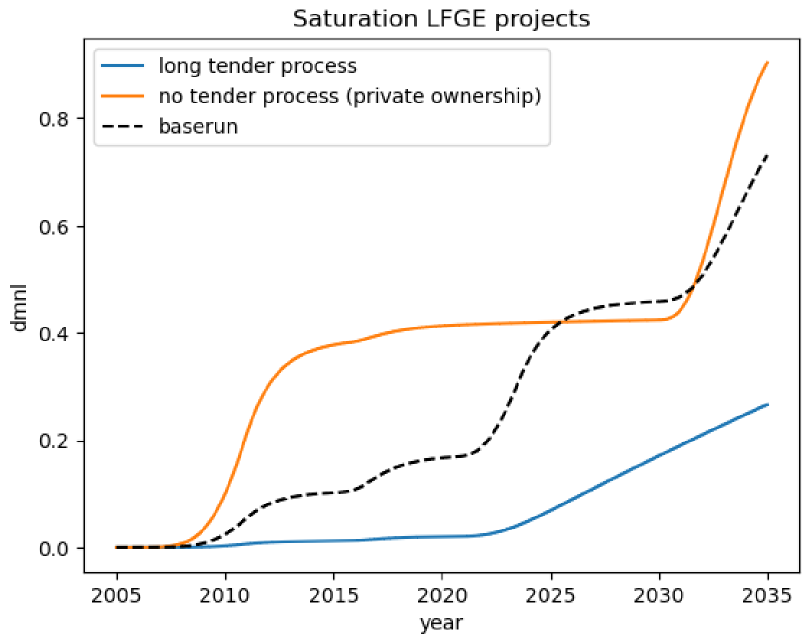

Figure 23. Effect tender process on saturation LFGE.

Corruption and the development of the national grid have little to no effect on the development of LFGE, as illustrated in Figure 24 and Figure 25. Corruption shows no effect on LFGE development because it is only part of the risk on international investment into LFGE and does not play a role in the determination of risk on domestic investment. The total risk factor on international investment is an average of the technological risk, policy risk, market risk, and corruption. Therefore the effect of an increase in corruption is levelled out and does not result in the expected value dropping below zero. The cases in which the expected value does drop below zero can be attributed to the lower expected revenue due to low prices, rather than the risk factor. In terms of the development of the national electricity grid, the worst case scenario, in which only 0.8% of the population has access to electricity increasing to only 8.4% by 2022, does not result in very large differences in the saturation of LFGE compared to the base case. Even a low development of the electricity grid does still result in sufficient demand to be able to sell all generated electricity by LFGE projects. Nevertheless, the development of LFGE progresses slightly slower than in the base case. This can be attributed to the slower development of formal legitimacy due to the complementary products and services building block being less complete. A high development of the national electricity grid, with values as high a 1, does not have a great impact on the saturation of LFGE projects because the difference between the base case and this best case scenario are small. In the base case, the share of the population with access to electricity is already very high, with shares between 0.8 and 0.9.

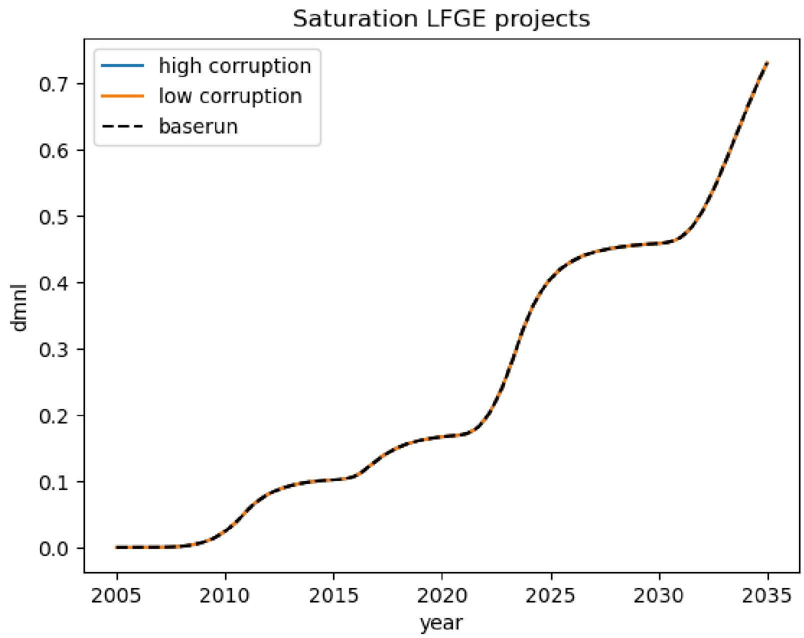

Figure 24. Effect corruption on saturation LFGE.

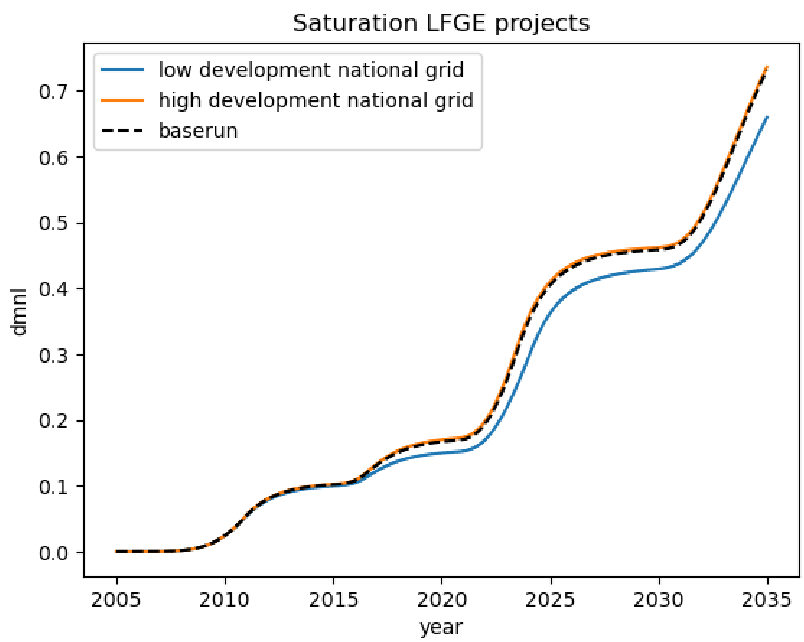

Figure 25. Effect development national electricity grid on saturation LFGE.

Finally, during the interviews, the hypothesis was raised that carbon credits can give the final push to make a LFGE economically viable. As Figure 26 indicates, changes in the future price of carbon do not play a role, when all the other input parameters are implemented with base case values. While the carbon credits did result in LFGE becoming economically attractive at the beginning of the simulation, when the wholesale price was below the LCOE of electricity (Figure 19), carbon credits do not have any effect on future development of LFGE. At the beginning of the simulation, the carbon credit price is high, reducing the minimum required price to make LFGE attractive to below the wholesale price of electricity. However, with the following reduction in the carbon credit price, the minimum required price exceeds the wholesale price, making LFGE unviable again. The carbon credit price then starts to rise again, reducing the minimum required price for LFGE to be attractive once more. However, this effect abruptly ends when the additionality requirement is exceeded and the sale of carbon credits is not allowed anymore. Moreover, at this point, the wholesale price has mostly surpassed the LCOE of LFGE, meaning that the wholesale price alone is sufficient to make LFGE economically attractive and carbon credits are not required anymore.

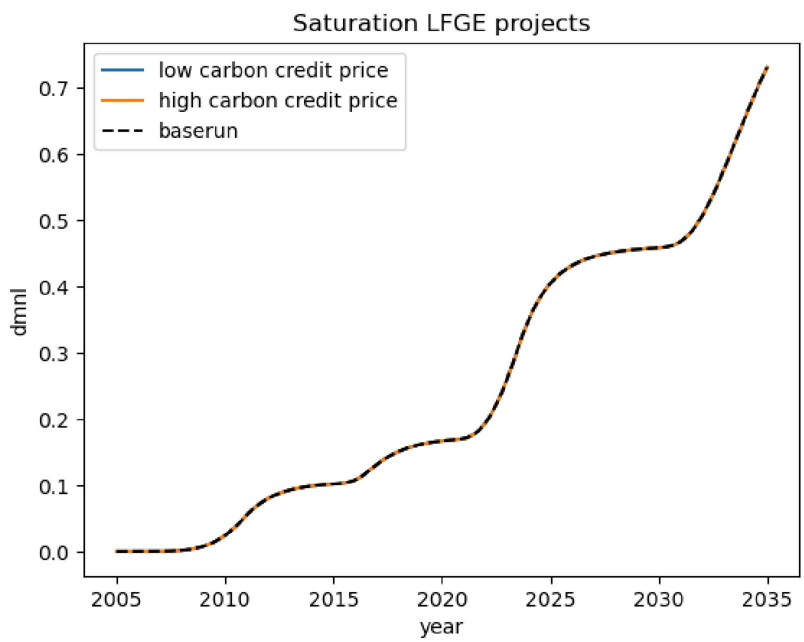

Figure 26. Effect carbon credits on saturation LFGE.

Although the sale of carbon credits does not have an effect on the development of LFGE projects when the wholesale price exceeds the levelised cost of energy from LFGE, it does affect the development of LFGE projects when the wholesale price of electricity is low. Figure 27 shows the saturation of LFGE projects in case of low wholesale prices and high carbon prices with varying additionality thresholds. In its current implementation, the sale of carbon credits at a high price cannot compensate for the low wholesale prices because of the additionality requirement, which requires the market share of LFGE to be below 30% to be able to generate carbon credits. With this additionality threshold, the role of carbon credits is limited to kick-starting the development in case the price of carbon credit is high. When the additionality threshold is increased to 70%, carbon credits also start to play a role in later stages of the development of LFGE. A threshold of 70% allows the LFGE to develop up to the point that enough lobbying power has been achieved to pressure the government into implementing an adequate feed-in tariff. The feed-in tariff can then take over once the additionality threshold has been passed and the generation of carbon credits is not allowed anymore, maintaining the economic attractiveness of LFGE until its full potential has been achieved. When the additionality threshold is increased to 1, the carbon credits themselves ensure that LFGE is economically attractive until its full potential is reached.

It should be noted that the effect of carbon credits, even with a high additionality threshold, is not unlimited. When the wholesale price of electricity drops too much, the sale of carbon credits might not able to compensate for the low wholesale price. The price of carbon credits should be high enough to cover the gap between the LCOE of LFGE and the wholesale price of electricity. Low carbon credit prices will not be able to achieve this, resulting in the stagnation of the development as illustrated by the worst case scenario of the wholesale electricity price (Figure 20).

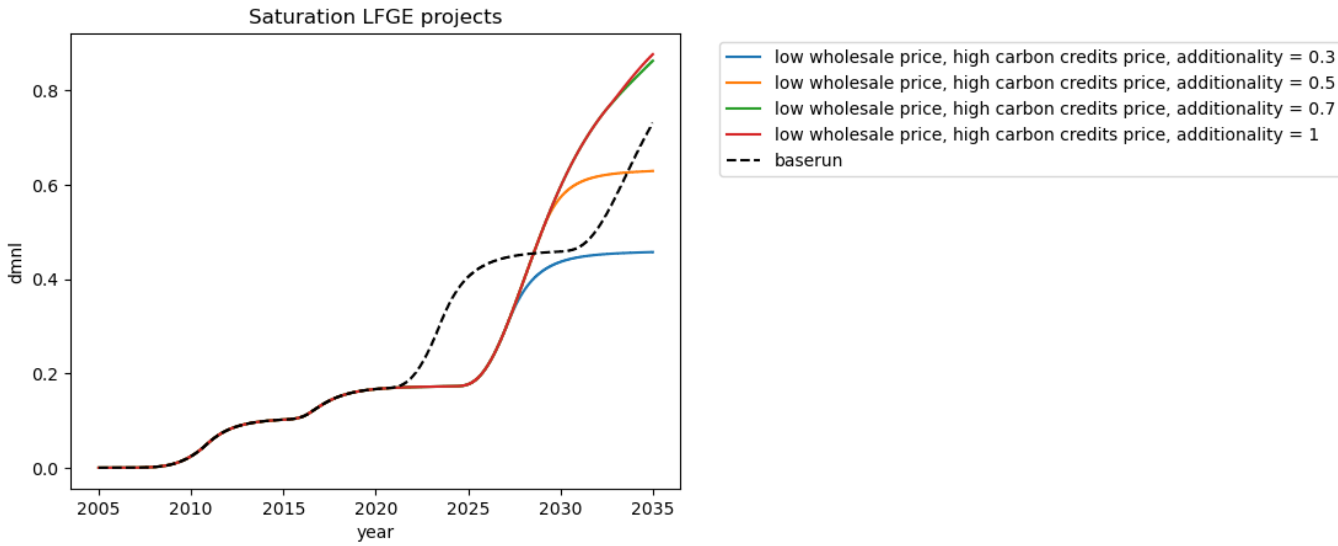

Figure 27. Effect carbon credits as compensation for low price.

8.3 Impact of innovation specific policies on LFGE diffusion

The model includes four innovation specific policies; a LFG collection requirement, an obligation to buy the electricity from LFGE projects, an obligation to generate electricity from LFG, and a feed-in tariff. In the base case, none of the innovation specific policies are initially implemented. This section explores the effect of these policies on the development of LFGE projects. Both the implementation of the policies before the start of the simulation as well as the implementation during the simulation run are explored. To investigate the latter, the pressure required to change the policies is reduced to 0.5.

Only the implementation of a feed-in tariff is able to counteract the low wholesale price. This is as expected as in this case the feed-in tariff determines the purchase price. The implementation of a feed-in tariff, provided its sufficient to cover the levelised cost of electricity from LFGE, immediately initiates the development of LFGE projects. This is not surprising as the feed-in tariff ensures the economic viability of LFGE projects. Therefore, the generation of carbon credits is not required anymore for the economic viability of LFGE. Implementation of an adequate feed-in tariff at the initial stage of the TIS allows for achieving the full potential of LFGE within a country within 20 to 25 years.

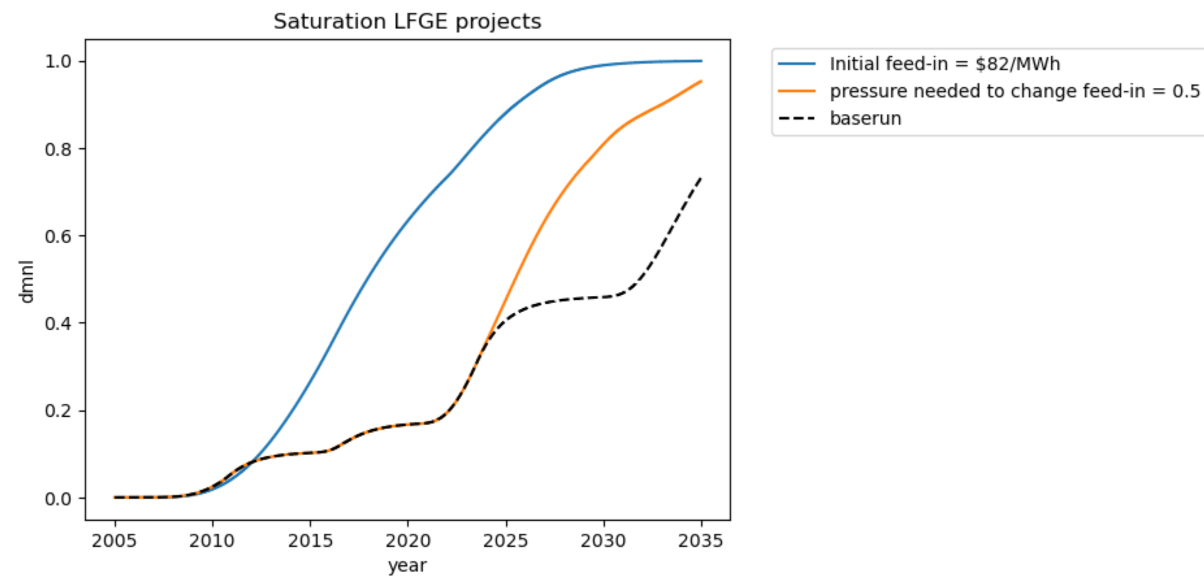

Figure 28. Effect feed-in tariff.

However, this effect is not achieved when the feed-in tariff is set too low. Figure 29 indicates the effects of a feed-in tariff that is above the wholesale market price, but not equal to the levelised cost of energy from LFGE, both in case of a high price of carbon credits and a low price. As the feed-in tariff will replace the wholesale price of electricity, an insufficient feed-in tariff can also prevent the development of LFGE projects, especially when the price of carbon credits is not high enough to fill the gap. However, when the price of carbon credits is able to cover the gap, LFGE development will take off.

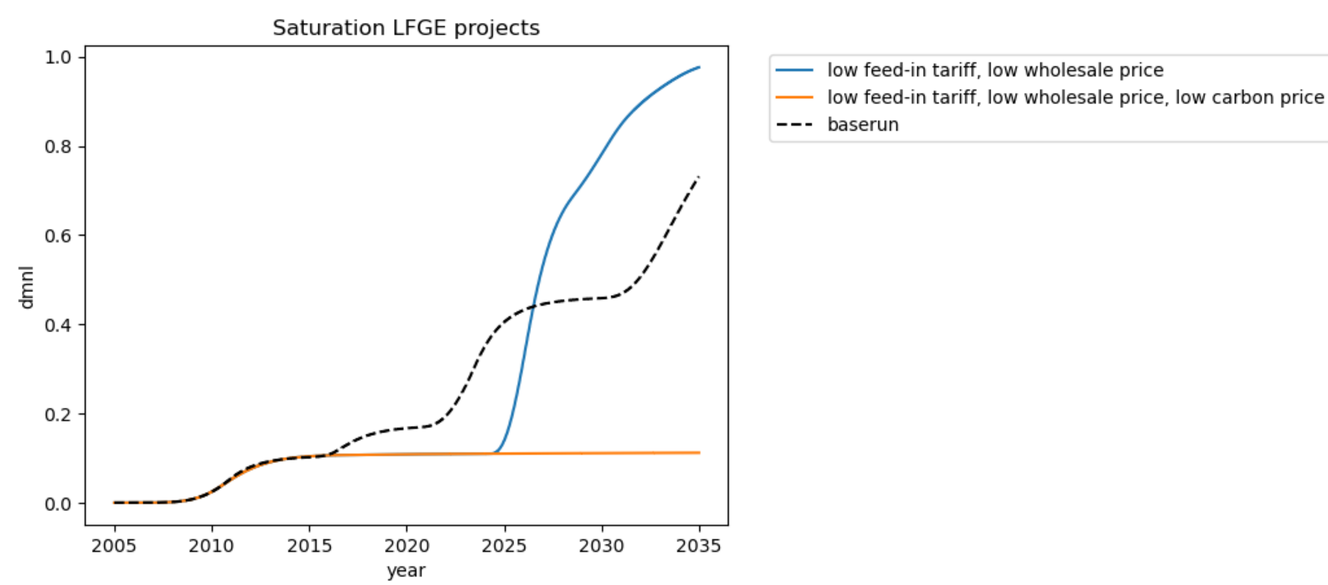

Figure 29. Effect inadequate feed-in tariff on different scenarios.

The implementation of the other policies does not result in diffusion in case of a low wholesale price. Nevertheless, both the obligation to collect LFG (Figure 30) and the obligation to buy the electricity from LFG (Figure 31) result in LFGE developing faster if implemented before 2005. For both policies, this effect is mainly due to the faster development of formal and informal legitimacy due to the initial increase in the institutional fit. This results in more projects being implemented at the beginning of the simulation, when the price is still high. However, the obligation to buy the electricity from LFG results in a faster development during this initial phase than the LFG collection requirement because it also reduces the risk for entrepreneurs as it is guaranteed that they will sell all the electricity generated. During this initial phase, the LFG collection requirement results in an annual electricity generation from LFGE projects that is slightly higher than in the base case, even though the LFG collection requirement results in a lower share of LFG being used for electricity generation because it is assumed that a larger share is flared, illustrating the increase in implemented projects. Nevertheless, for both policies, when the market share of LFGE becomes larger and the generation of carbon credits is not allowed anymore, the development of LFGE comes to a halt until the wholesale price becomes sufficient once more to make LFGE viable. The policies do therefore not compensate for low electricity prices. However, when the wholesale price increases again to a sufficient level, the development continues. Finally, reducing the pressure required to implement the policies during the simulation run has little effect on the development of LFGE, especially for the collection requirement, compared to the base case because the difference in the required pressure is small.

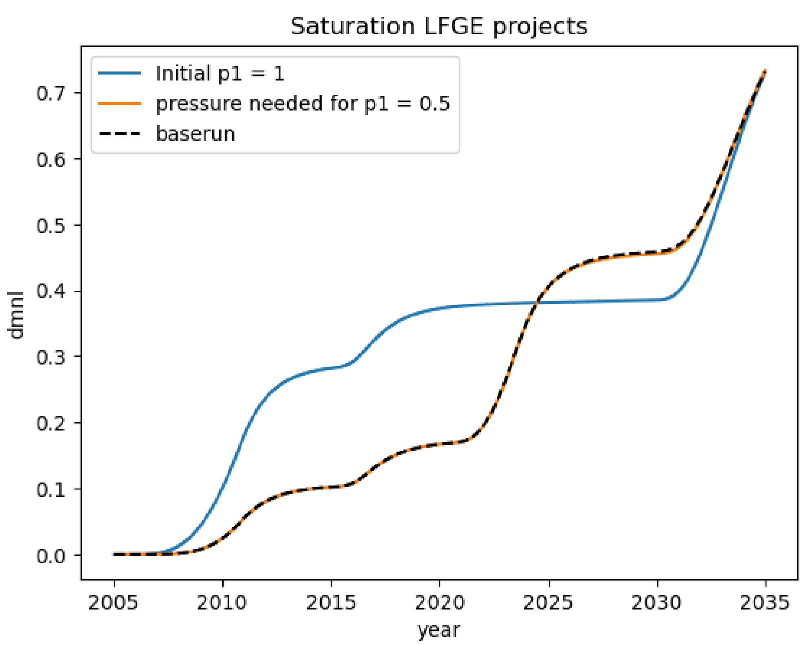

Figure 30. Effect implementation LFG collection requirement.

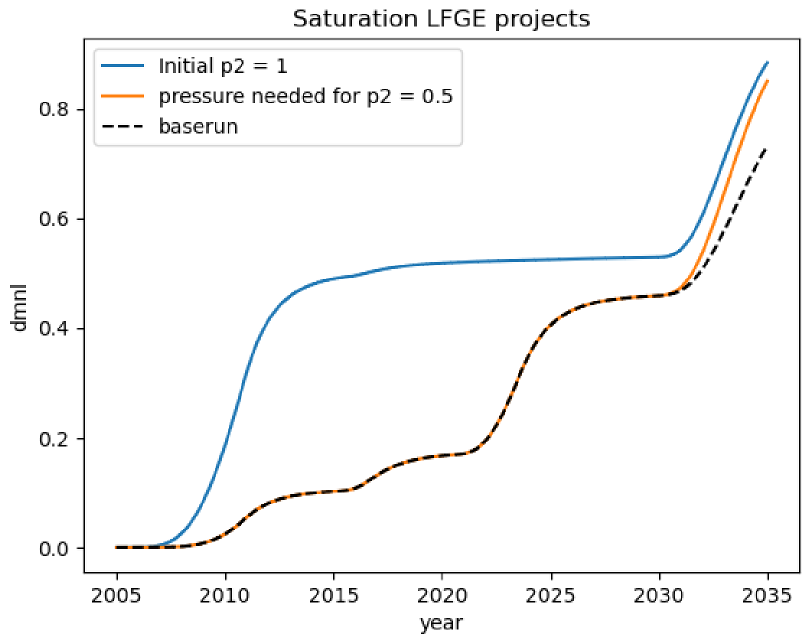

Figure 31. Effect obligation to buy electricity from LFGE projects.

Finally, the effect of the obligation to generate electricity from landfill gas is shown in Figure 32. The early implementation of the obligation does affect the development of LFGE projects negatively because it prevents the generation of carbon credits. At first, the development of LFGE projects is fully impeded. When the wholesale price exceeds the LCOE of LFG, a few projects are implemented. However, as Figure 19 indicates, the wholesale price quickly drops below the LCOE again, preventing the development of new projects until it exceeds the LCOE of LFG once more at the end of the simulation. A later implementation of the policy does only result in a slightly faster development of LFGE projects compared to the base case. This effect is small because the other functions and building blocks have already been developed at the time of implementation. The potential increase in legitimacy due to a better institutional fit is therefore small. Additionally, as LFGE was already viable after 2030, which is indicated by the increase in projects in the base case after 2030, the increase in electricity generation does not affect the investment decision.

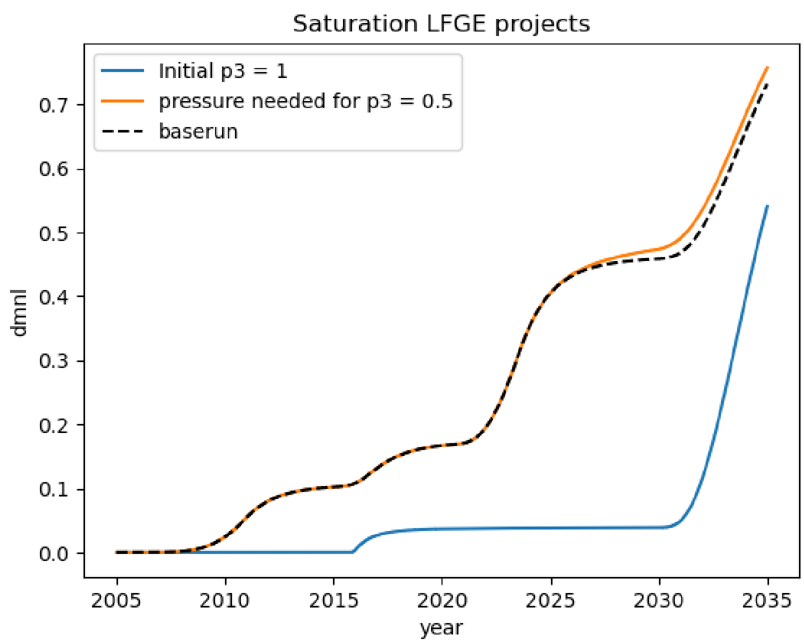

Figure 32. Effect obligation to generate electricity.

8.4 Summary of the results

From the results in Section 8.2 and 8.3 the barriers are ranked in terms of importance. This ranking is presented in Table 11. The figures in Appendix I.2 Comparison barriers in base case show the effects of all barriers in one figure, making comparison more straightforward.

Table 11. Relative importance barriers and policies.
1 indicates the most impactful barriers and 7 indicates the least impactful barriers.

Rank	Barrier	Rank	Policy
1	Wholesale price of electricity	**1**	Feed-in tariff
2	Efficiency waste management system	**2**	Electricity generation obligation (p3)
3	Grid access	**3**	Obligation to buy electricity (p2)
4	Tender process	**4**	LFG collection requirement (p1)
5	Price carbon credits		
6	Development national electricity grid		
7	Corruption		

9. Discussion

This research aimed to investigate the barriers to the development of LFGE in Africa and their effect over time through the TIS perspective. To this end, a hybrid model combining the TIS structures and building blocks was created, which is the first of its kind. Although the model builds on the model of Walrave & Raven (2016), the model created in this research is the first model that connects the TIS functions and the TIS building blocks into a single model. Additionally, the development of LFGE in Africa has not been investigated through a system dynamics model before. Previous research focussed on creating an inventory of the barriers to diffusion (e.g. Njuko et al., 2018; Karekezi et al., 2009; Mutezo, 2016), rather than assessing their effect on the diffusion over time or their effect relative to the other barriers.

9.1 Key findings

This section discusses the key results found through experimentation with the SD model.

9.1.1 Effect of the barriers on LFGE development

From the results in Chapter 8 it can be concluded that the wholesale price of electricity and the efficiency of the waste management are the most important barriers to the development of the LFGE TIS. To initiate the development of LFGE, the wholesale price of electricity should be high enough to cover the LCOE of LFGE, or at least to cover the minimum price to make LFGE projects economically viable while also considering the carbon revenue. Karekezi et al. (2009) already highlighted the need for carbon revenue by recommending carbon financing in countries with low electricity prices. However, to be able to utilise carbon financing, the price of carbon credits needs to be high enough to reduce the minimum required price to below the wholesale price. Moreover, Karekezi et al. (2009) indicate the need for a standard price to make LFG lucrative for local investors and create an equal playing field among energy sector investors. The importance of the stability of prices is also highlighted by Benáček et al. (2012) as they argue that price stability is one of the catalysts of foreign investment.

The efficiency of the waste management influences the LCOE of LFGE because a more efficient waste management system will create larger landfills, which have a greater methane potential. On the other hand, too little waste being collected within a country can prevent the development of LFGE projects as the landfills will be too small to generate a viable amount of electricity. This aligns with previous studies that inventoried the barriers to LFGE. Karekezi et al. (2009) argue that a minimum inflow of waste is required for economic recovery of LFG, with the main caveat being the collection and transportation of the waste to a landfill. Additionally, Adeleke et al. (2021) argue that the sustainability of waste to energy processes are dependent on a sustainable supply of waste. Moreover, Yan et al. (2020) argue that the biggest challenge for small scale waste to energy plants is the cost-benefit balance and thus creating a viable business case. Grid access also has a great impact on the development of the LFGE TIS because inaccessibility of the grid prevents the development of LFGE projects due to the demand being too low. Nevertheless, grid access only ranked 6^{th} out of 8 barriers in terms of relevance for waste to energy development in South Africa according to a study conducted by Amsterdam and Thopil (2017). This difference might be attributed to the fact that on the individual project level the off-grid demand could be high enough to sell the generated electricity of the individual project, and therefore the inaccessibility does not need to be a problem for every individual project. Nevertheless, the total off-grid demand will be too small to cover the full electricity potential from LFGE in a country, preventing full diffusion of LFGE. Additionally, Amsterdam and Thopil (2017) do recommend giving power producers access to the national electricity grid, and to streamline this process despite the barrier only ranking 6th out of 8. The length of the tender process, indicating the difference between publicly and privately owned landfills, can either accelerate or slow down the development of LFGE projects, which is in line with the hypothesis raised by the interviews. Nevertheless, its positive effect is largely dependent on the wholesale price of electricity. Only when the price is high enough, private ownership of the landfill will have an accelerating effect. The effect of the development of the national electricity grid is small, whereas corruption does not show any effect on the development of LFGE projects. A poorly developed electricity grid, with only a small share of the population having access to electricity, still results in sufficient demand in South Africa to sell electricity from LFGE. However the development will progress at a slower rate.

Although the efficiency of the waste management system was expected to be an important barrier — since waste must be collected and processed to have any value — the model might overestimate its effect during the experiments in which changes in the waste management system are included. In the base case, the effect is estimated correctly because the efficiency of the waste management system is kept constant and the number of potential projects is chosen accordingly. Nevertheless, when the efficiency of the waste management system is changed during the experiments, the number of potential projects is not changed. This means that during these experiments, the additional electricity potential resulting from better waste management is equally divided over the base case number of potential projects, whereas the possibility also exists that part of the additional waste will be processed in new landfills. This would reduce the average amount of waste send to the landfills, and therefore reduce the electricity potential of the potential LFGE projects in the best case scenario of the waste management system.

A potential underestimation of the model lies in the effect of corruption on the development of LFGE projects. The model results suggest that corruption does not affect the development of LFGE within a country. The explanation of this result is twofold: 1) corruption is just one of the four considered risk factors for international investment, which are all equally weighted, minimizing its individual effect. 2) the total risk factor affects the investment decision, which is modelled as binary. Therefore, it does not have an effect on the amount of money invested, but only on the decision whether money is invested or not. A literature review performed by Habib and Zurawicki (2001) indicates the effect of corruption on foreign investment is difficult to establish. Several papers they reviewed did not show a significant effect of corruption on foreign investment. Nevertheless, they also reviewed papers that indicated a significant negative effect of corruption on foreign investment. The lack of consensus on the effect of corruption is also indicated by Quazi et al. (2014). They indicate two views on corruption: the grabbing hand hypothesis, which indicates that corruption reduces the FDI because of the inefficiencies and distortions it causes, and the helping hand hypothesis, which suggests corruption increases FDI because it allows investors to bypass bureaucratic processes, among others. From their research Habib and Zurawicki (2001) concluded that corruption should be analysed in the broader social-economic context of a country, as the presence of certain social-economic variables can have a significant effect on the impact of corruption. More research is needed on the effect of corruption on investment into innovation systems in developing countries.

Finally, it should be noted that the data used for the total electricity potential slightly overestimates the real electricity potential. The data used in this research is based on the research conducted by Scarlat et al. (2015). They calculate the electricity potential in various countries, both based on the waste generated and the waste collected in each country under the assumption that all waste is landfilled. However, Njoku et al. (2018) indicate the share of waste in South Africa to be landfilled or deposited in dumpsite to be 95%, under the assumption that all collected waste in South Africa was accepted and no correction on the input data was performed. However, the 5% of waste being treated differently, might result in a small deviation from real-world electricity potential of LFGE.

9.1.2 Effect of the innovation specific policies on LFGE development

The most important innovation specific policy is the feed-in tariff. If set adequately, the feed-in tariff will fully compensate a potential low wholesale price. This aligns with the effect of feed-in tariffs on European renewable energy markets, such as Spain and Germany, where feed-in tariffs are considered the main contributor to their success (Ndiritu & Engola, 2020). Nevertheless, Ndiritu & Engola (2020) also acknowledge that the design of the feed-in is critical to its success. They state that a feed-in tariff should be simple, flexible, specific, and long-term. Additionally, as indicated by the current model, the feed-in tariff should be able to cover the levelised costs of energy. This feed-in design aligns with the feed-in tariff already implemented in Uganda (Meyer – Renschhausen, 2013). However, the model indicates that a feed-in below the levelised cost of energy could also be a short term solution to kick-start the development of LFGE as long as it is complemented by carbon revenue. If the feed-in tariff is insufficient to cover the LCOE of LFGE, the gap can be compensated by carbon credits, which could reduce the minimum required price to below the level of the feed-in tariff, provided the price of carbon credits is high enough. Nevertheless, this is not a permanent solution, as the additionality requirement prevents the indefinite generation of carbon credits.

The obligation to generate electricity is also an important policy, but surprisingly this is mainly due to its impeding rather than its incentivising effect. This conflicts with the hypothesis that the different policies will incentivise the development of LFGE projects. The implementation of the obligation to generate electricity eliminates the possibility to generate carbon credits as the LFGE projects would also be implemented without the opportunity to create carbon credits. This is problematic when the wholesale price is not sufficient to create economic viability on its own, as it will prevent the development of LFGE from taking off. Nevertheless, there exists an exception for policies being implemented after 2001. To prevent perverse incentive, the UNFCCC (n.d.) has introduced so called E- policies, which are policies that incentivise the implementation of less emission intensive technologies. These policies need to be implemented after the Marrakech accords in 2001. The E- policies are not considered in the determination of additionality. Therefore, if the obligation to generate electricity was implemented before the start of the simulation runs in 2005 and before 2001, the implementation of the policy does indeed prevent the generation of carbon credits. However, if the policy was implemented between 2001 and 2005, or even later, the generation of carbon credits is still allowed. Nevertheless, this specific scenario is not included in the current model and should be investigated by future research. When the obligation to generate electricity is implemented while the wholesale price is sufficient to ensure economic viability, the development proceeds more rapidly than in the base case. Nevertheless this positive effect is minimal. Finally, in line with the hypothesis from the interviews, both the obligation to buy electricity from LFGE projects as well as the requirement to collect the LFG have an incentivising effect. However, their effect is only visible when LFGE is economically viable. Ramli and Twaha (2015) argue that the implementation of the obligation to buy the electricity as a part of the feed-in policy is the most desirable policy to support renewable energy. Future research should quantify the effect of this specific combination.

9.2 Diffusion pathways

The flowchart in Figure 33 illustrates the scenarios in which diffusion will or will not occur. Outcomes in red indicate that there is no potential for LFGE within a country under current conditions. Outcomes in yellow indicate that diffusion of LFGE will not occur, but the conditions are sufficient for a few projects to be implemented. Outcomes in green indicate that full diffusion of LFGE will occur within the short term. As the figure shows, the absence of an adequate purchase price prevents the diffusion of LFGE. In this branch of the flowchart, LFGE will only diffuse eventually when the political situation within a country allows for lobbying to be effective. When the purchase price is adequate, LFGE will most likely diffuse. The conditions in this branch of the flowchart mostly affect the pace at which the development takes place.

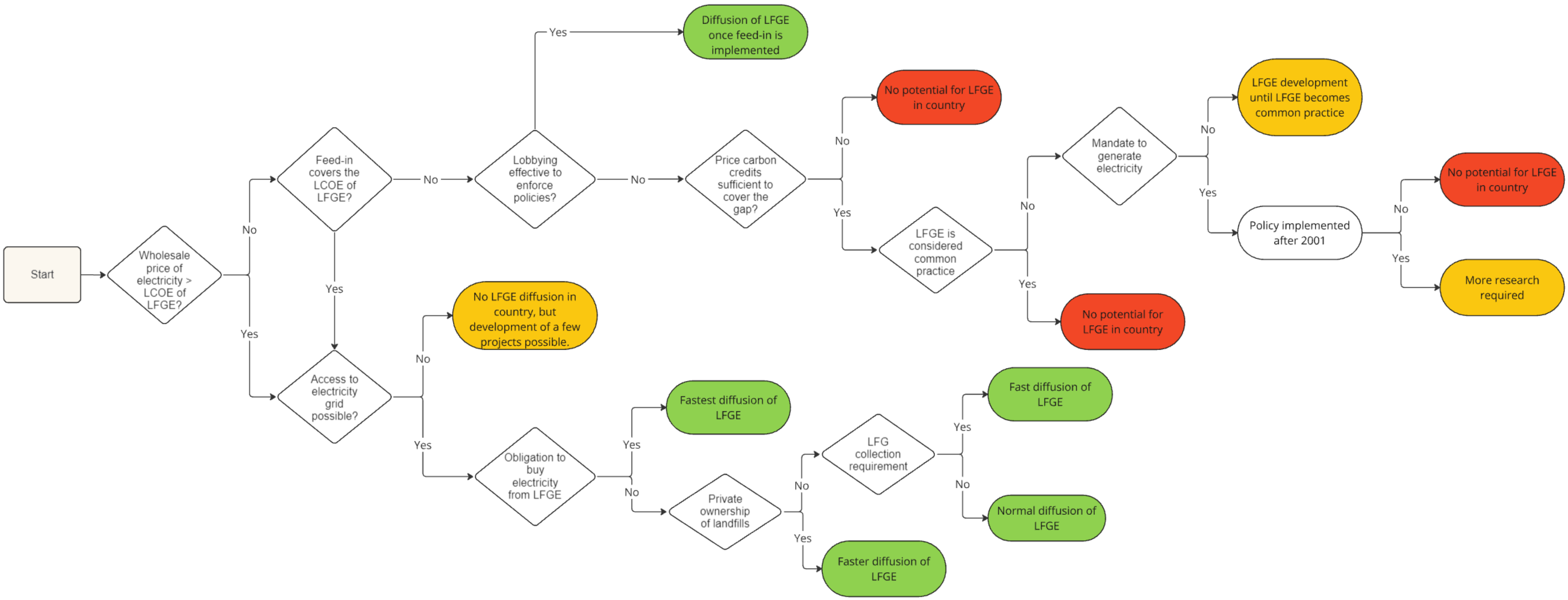

Figure 33. Flowchart indicating the conditions required for the diffusion of LFGE projects.

9.3 Reflection on the hybrid approach

This first part of this research focused on creating a conceptual connection between the functional and the structural approach of assessing the performance of a TIS. Until now, the assessment of a TIS has only been performed by applying either one of the approaches. No attempts had been made to combine the two approaches into one model by investigating the relations between the structures and the functions. However, the connection allows for the assessment of the effect of structural barriers on the development of the TIS over time. Additionally, the inclusion of the building blocks, which are of a lower level of aggregation compared to the TIS functions, allow for a relatively easy implementation of case data on the barriers. While creating the link between the different TIS elements, it turned out that the building blocks mainly influence the TIS functions rather than the other building blocks, suggesting that connecting the two approaches adds value to the overall analysis of TIS development. Nevertheless, linking the two approaches also came with some difficulties. First, the conceptual model of the hybrid approach is highly sensitive to the definition used for the TIS functions. Bergek et al. (2008a) provide an overview of the different definitions used in different research papers. While most definitions are similar, subtle changes exist for some of the functions. For example, Hekkert et al. (2007) define the creation of legitimacy as the development of advocacy coalitions, while the Bergek et al. (2008a) take a broader definition of the same functions by not only including the manipulation of institutions, but also the conformance to and creation of new institutions. Additionally, the definitions of the TIS functions are broad, allowing for a wide range of possible indicators that could potentially measure the status of the function. This creates difficulties in measuring the TIS functions with a single variable, which is required for the aggregated version of the hybrid model. Take market formation for example, Hekkert et al. (2007) argue that this function could be measured by mapping the number of niche markets, tax regimes and new environmental standards. This research has chosen to measure the market formation function by analysing the feed-in tariffs, but choosing another indicator could have resulted in different relations with other functions and building blocks. Therefore, careful consideration should be given to the definitions and indicators used. A consequence of fitting the broad TIS functions into single indicators could be the oversimplification of the functions and therefore missing potentially important elements of the functions within the model.

Another difficulty found in connecting the functional and the structural approach lies in the overlap that can be found between some of the building blocks and the TIS functions. For example, it could be argued that the building blocks product price and demand show overlap with the market formation function, depending on the definition and indicator used for market formation. Nevertheless, the definitions in this research are chosen in a way that eliminates the overlap between the building blocks and functions as much as possible, making it easier to connect the two approaches.

Despite these difficulties, the application of the model of the hybrid approach to the case of LFGE in South Africa did provide promising results. The model accurately reflects the past behaviour of the development of LFGE accurately, as is illustrated in Figure 11. Still, this research only provides a first attempt in connecting the two approaches and creating a dynamic model of it. Future research should develop this hybrid approach further. One potential way to further develop the hybrid approach is by testing the model on other cases of TIS diffusion to increase confidence in the model and the relations found.

9.4 Implications of the research

The implications of the research are both of a scientific and a societal nature. Additionally, the research can be generalised to other TIS cases and geographical scopes. The conceptual model of the hybrid approach is constructed in an aggregated manner, which allows for generalisation to other TIS cases in the context of developing countries. This requires specifying parts of the model as was done for the LFGE case. Additionally, the SD model was created with the aim of being generalisable to LFGE in other African countries. However, the performance of the SD model on other LFGE cases in Africa has not yet been tested.

9.4.1 Scientific contributions

The scientific implications of this research are twofold: 1) it adds to the literature on TIS and its performance assessment through dynamic modelling 2) it adds to the literature on LFGE in Africa by identifying the main barriers impeding the development of LFGE and their quantitative effect.

This research contributes to the body of literature of TIS in two ways. First, by connecting the structural TIS approach with the functional TIS approach into one (dynamic) model, this research provides a novel way to assess the development of a TIS over time. Indicating the causal relations between the TIS functions and the TIS building blocks allows for the qualitative study of the effect of the TIS building blocks on the functions, and vice versa. Translating this conceptual model into a system dynamics model, allows to quantitatively study the effect of these interrelationships over time, rather than at a specific moment in time. This provides the opportunity to investigate the effect of the barriers, which are often of a more structural nature, on the development of a TIS over time. Additionality, the lower level of aggregation of the building blocks allows for easier application of the model on a specific case. Second, limited attempts have been made to assess the emergence of a TIS through system dynamics modelling. While Uriona and Grobbelaar (2019) describe studies that model part of an innovation system, only Walrave & Raven (2016) and Raven & Walrave (2020) have developed a system dynamics model that assesses a TIS as a whole. However, they focus on the TIS functions rather than the TIS structures, or a combination of the two. The integration of the TIS functions and the building blocks into one model is a novel approach that has not been studies before.

This research also adds to the literature on the development of LFGE in Africa. Firstly, this research provides a synthesis of the barriers found in literature and through the interviews. Additionally, this research assesses the barriers to LFGE through the TIS perspective. Although several papers have listed the drivers and barriers of LFGE in Africa, an assessment through the TIS perspective has not been provided before. Additionally, this research investigates the effect of the barriers over time, as well as the relations between the barriers themselves and the rest of the system. This allows for assessing the effect of the barriers on the TIS development and the conditions required for diffusion. Moreover, this provides the opportunity to assess the importance of each barrier compared to the other barriers. Finally, this research has investigated the effect of carbon markets on the development of LFGE in Africa. Limited research has been conducted on the effect of carbon markets on the development of LFGE. Adding the effect of carbon credit generation to the model fills this gap.

9.4.2 Societal contributions

Applying the created conceptual model of the hybrid approach to analyse a TIS to the case of LFGE in Africa allows for testing the functionality of the hybrid approach. A working model to evaluate the diffusion of technological innovation systems provides insights into the barriers for their diffusion. This allows to create effective policies to remove these barriers. Additionally, such a model allows for testing the effectiveness of different policies, guiding policymakers to select and implement those that accelerate the diffusion of technological innovation systems. As the TIS approach is important for the analysis of the development of sustainable transitions (Markard, 2020), this could aid the acceleration of environmental shifts.

An implication of the application of the model to the LFGE case is the possibility for project developers to test the potential of LFGE in various countries in Africa against the conditions that were deemed essential by the model results. These conditions are summarised in the flowchart in Figure 33. This flowchart provides a comprehensive way to assess the potential of LFGE projects in other African countries, without directly using the SD model. This is an important contribution as the SD model is large and complex and therefore difficult to use by policymakers and project developers. By using the flowchart, the model results can still be applied and generalised to other countries. This could result in opportunities for LFGE projects that were not considered before. Additionally this could guide resources into countries with potential, rather than spending resources on projects that are doomed to fail because the conditions in the country are not sufficient yet. This leads to the efficient use of resources into sustainable development. Finally, the results could be used by policymakers to determine the most effective policies for the development of LFGE.

9.5 Limitations

As with any research, this research comes with its limitations. The limitations are divided into limitations of the research design in general and the limitations related to the implementation of the model.

9.5.1 Limitations of the research design

One of the limitations of the research design is the selection of the interview participants. The participants were selected through convenience sampling. This resulted in four of the five participants being employees of Anthesis – Climate Neutral Group. While all participants have been involved in the development of LFGE projects, now or in the past, and can therefore be considered experts on the topic, the lack of variation in the participants might have influenced the results from the interviews. As all participants work for a commercial party, the importance of economic barriers might have been overestimated. Without economic benefits, commercial parties are not likely to be interested in being involved in projects. Including the perspectives of a wider variety of stakeholder, such as landfill owners, local governments, or academics might shift the perceived importance of the different barriers. Additionally, only one of the participants is based in South Africa. Therefore, the African representation is limited, increasing the risk of incorporating European perspectives and biases into the research, which can be different from African perspectives. Although this limitation is partially addresses by the complementary literature review, which aimed to involve as many African authors as possible, the results should be considered with these potential biases in mind.

Another limitation can be found in the validation of the system dynamics model. While one expert has been consulted to validate the model structure by going over the main model assumptions, most of the validation was performed by the author herself, based on the available information in literature and documentation of existing carbon projects. Additionally, the consulted expert was again an employee of Anthesis – Climate Neutral Group. While the expert validation provided valuable information on the model assumptions, which resulted in the improvement of the model, as well as new insights on the implication of certain assumptions, increasing the number of expert validation interviews might provide additional information and insights, which could improve the model even further.

A third limitation of the research design lies in the choice of system dynamics to evaluate the diffusion of LFGE in Africa. While system dynamics is considered a suitable method to analyse technological innovation systems because of the ease with which it can handle the feedbacks, time delays, and other non-linearities of such systems, its strengths lie in the prediction of behavioural patterns rather than point predictions (Bala et al., 2017). Therefore, the exact values required for the barriers to be overcome could not be determined with accuracy, but only conditions based on the system behaviour and feedback between the barriers and the TIS could be provided.

9.5.2 Model limitations

As no model is perfect, the model created within this research comes with its limitations. The first limitation is related to the choice to only model the inflows of the TIS functions and building blocks. As the scope of the research was to investigate the formative phase, potential decline of the TIS was not considered. Therefore, it was assumed that the TIS functions and building blocks would grow rather smoothly and no outflows were required. This smooth growth was especially assumed for the functions and building blocks that were modelled in a more abstract way. Nevertheless, it could be possible that the formation phase of a TIS does not progress easily and functions and building blocks do grow and collapse before reaching a stable growth pattern. Modelling the outflows of the functions and building blocks would allow for testing this hypothesis.

Another model limitation lies in the fact that the effect of the status quo, the regime, is not considered. Although the model does compare the purchase price of LFGE with the wholesale market price of electricity in general to determine the attractiveness of electricity from LFGE on the demand side, it does not consider the effect of the status quo on the supply side. The model assumes that in case of economic viability, when the price is able to cover the LCOE of LFG, entrepreneurs will join the TIS to develop projects. However, it does not consider the costs of the generation of electricity from other sources, such as coal or solar. Low LCOEs of other electricity sources could affect the decision to enter the LFGE TIS. Although LFGE might be viable, the profits of the other technologies might be higher and therefore more attractive.

Finally, the model does not include any financial incentives to enhance demand. However, financial incentives, such as subsidies could be a good alternative to the obligation to buy the electricity generated from LFG as both increase the demand. As financial incentives would be taken from the domestic resources, their implementation would result in less resources being available for knowledge development and diffusion or domestic investment. This could be an avenue for future research.

9.6 Suggestions for further research

This research provides a first attempt to combine the functional TIS approach and the structural TIS approach into one model. However, this avenue could be further investigated. The model created in this research could be applied to a wider variety of case studies to further validate the relations found in this research. Additionally, this might highlight potential shortcomings that did not arise in the LFGE case, allowing for further improvement. Besides, further research is needed on the potential decline of the TIS functions and building blocks during the formation phase of the TIS. This requires modelling of the outflows of the stocks of the functions and building blocks in the current model. Moreover, research on the whole lifecycle of a TIS is still limited. While Markard (2020) takes a lifecycle perspective and identifies the different stages of TIS development, further research could be conducted on modelling each of the stages, especially the maturity and decline stage. Future research on TIS modelling could also add the impact of the regime to the current model, which will allow for the assessment of the effect of incumbent technologies on the development of the TIS. To this end, Walrave & Raven (2016) could be taken as a starting point as they do include the regime in their functional system dynamics model. Their approach could be connected to the hybrid model to investigate the effect of incumbent technologies in combination with the structural barriers. Pressure enforced by the regime on the development of the TIS is excluded from the model created in this research.

Furthermore, more research is needed to investigate the LFGE case itself. Firstly, due to the manual implementation of the experiments, only a limited number of experiments could be conducted. Nevertheless, a large number of experiments could provide more insights into the model configurations that prevent or accelerate diffusion, and allows to go beyond the effect of the individual barriers. To this end, future research could apply Exploratory Modelling and Analysis. This method allows for searching over a large ensemble of models and therefore provides the opportunity to investigate the implementation of a large number of scenarios.

Furthermore, the flowchart provided in Figure 33 could be extended. Currently, the flowchart gives a static overview of which conditions lead to which scenario. This implementation of the flowchart is useful for project developers seeking a suitable country to develop LFGE projects. National policymakers could use the current flowchart as a static assessment of the LFGE potential in their country. However, the flowchart could be extended to a dynamic map, for example through the adaptive pathways approach, indicating the most promising policy to implement in each scenario, either current or future, to initiate diffusion. This would make the flowchart adaptive and policy-oriented.

Additionally, further research could consider the application of Agent Based Modelling, either in combination with system dynamics modelling or as a model of its own, to allow modelling the production system of individual landfills in more detail. The current model operates at country level. However, the technical barriers of a TIS can only be investigated on the project level. Traditional SD modelling does not allow for the differentiation in the level of aggregation within one model. Modelling the individual landfills through Agent Based Modelling could provide insights in the technical barriers and their relative importance. Combining this with SD modelling allows for the inclusion of different levels of aggregation into a single model, which will provide insights into the effect of the varying levels of development in individual LFGE production systems on the diffusion of LFGE within a country.

Finally, the current model could be improved to overcome the limitations mentioned in Section 9.5.2 and the effect of the excluded barriers could be investigated. Additionally, the waste generation and electricity demand could be implemented in a dynamic way, accounting for their increase due to for example population growth. Consequently, the inflow of potential projects could be modelled to investigate the effect of new landfills being opened due to this increase in waste generation.

10. Conclusion

The objective of this research was to answer the following question: *What conditions within the landfill gas to energy innovation system enhance the diffusion of landfill gas to energy projects in Africa considering the dynamic behaviour of the innovation system?* The research aim contained in this question was twofold: 1) to combine the functional and structural TIS approaches into one hybrid approach to allow for a more detailed assessment of the barriers to the emergence of a TIS over time. 2) to investigate the causes of the limited adoption of LFGE projects in Africa by creating an understanding of the dynamic behaviour of the LFGE TIS. To answer the main question, first the five sub-questions are addressed. The answers to the sub-questions are then synthesised into an answer to the main question.

10.1 Answer to the sub-questions

1. *How can the TIS framework of Ortt and Kamp (2022) be connected to the TIS functions?*
   The TIS building blocks and the TIS functions can be combined into one causal loop diagram by defining the causal relations between the functions and building blocks. Walrave & Raven (2016) have identified the relations between the different functions defined by Hekkert et al. (2007). This research builds on their model by adding the structural TIS building blocks defined by Ortt & Kamp (2022) to their conceptual model, as well as additional functions proposed by Edsand (2019) to adapt the TIS framework to the context of developing countries. Walrave & Raven (2016) have incorporated the TIS functions as stocks in their model because these functions indicate processes that need to be built up for the TIS to emerge. The same argument is applied for the TIS building blocks, which are also modelled as stocks, as the building blocks need to be developed over time. The building blocks need to be complete for the TIS to diffuse (Ortt & Kamp, 2022). This results in a high-level conceptual model of the relations between the building blocks and the functions. Each of the TIS functions and building blocks can be further specified in a more detailed (sub)model, depending on which functions and building blocks are most relevant to the case under investigation.

   While determining the set of TIS functions, it is important to clearly define the TIS elements, especially the TIS functions, and choose the indicators accordingly. The TIS functions are of a high level of abstraction, making them quite broad. This provides difficulties in defining the relationship between the functions and the building blocks. Reducing the level of abstraction by clearly defining the TIS functions and determining indicators eases this process and creates more clarity in the conceptual model.

2. *What are the key drivers and barriers influencing the adoption of landfill gas to energy projects in Africa?*
   Through expert interviews and an extensive literature review, 27 impeding factors were found, which could be aggregated into 21 barriers. These barriers were categorised into five categories: economic, technical, organisational, social, and other to include the barriers that did not fit into one of the other four categories. The economic barriers include economic viability of the project and funding. The economic viability is related to market prices of electricity, feed-in tariffs, costs of LFGE projects, and carbon credits. The technical barriers mainly determine the efficiency of the methane generation, and therefore the electricity potential of a project. The institutional barriers include the lack of permits to sell the electricity generated with LFG on the national electricity grid, as well as the absence of regulations on LFG handling. This does not create

incentive to develop a LFGE project. The LFGE specific policies that could be implemented are adequate feed-in tariffs, a requirement to collect the LFG as well as a requirement to generate electricity from the LFG, and an obligation for offtakers to buy the electricity from LFGE, reducing the risk of not being able to sell the electricity. The length of carbon processes and the complexity of PPAs were also identified as institutional barriers. The organisational and social barriers include public landownership, the lack of human capacity, a monopolised energy sector and the limited awareness of the benefits of a LFGE project. Finally, corruption, the lack of public support, the lack of demand, and the dependency on cheap fossil fuels were identified as barriers.

3. *What are the causal relations between the drivers and barriers and the TIS model as defined in SRQ1?*
   As expected, most of the barriers identified in SRQ2 were related to one of the TIS building blocks. Most of the barriers were of a structural nature, meaning that they only change slowly, as opposed to the more dynamic functions, which develop more quickly. Additionally, the lower level of abstraction of the building blocks eased the connection of the barriers to the model. This emphasises the need for a connection between the functional and structural TIS approaches, as this research aims to investigate the effect of the barriers over time.

4. *What are the key factors or combinations of factors within the landfill gas to energy innovation system influencing the diffusion of landfill gas to energy projects in Africa?*
   From the interviews, the hypothesis was raised that the economic barriers would be the most impactful. Model experiments confirmed this hypothesis. Based on the model results a ranking of the barriers and LFGE specific policies was created, which is presented again in Table 12.

Table 12. Relative importance barriers and policies.
1 indicates the most impactful barriers and 7 indicates the least impactful barriers.

Rank	Barrier	Rank	Policy
1	Wholesale price of electricity	**1**	Feed-in tariff
2	Efficiency waste management system	**2**	Electricity generation obligation (p3)
3	Grid access	**3**	Obligation to buy electricity (p2)
4	Tender process	**4**	LFG collection requirement (p1)
5	Price carbon credits		
6	Development national electricity grid		
7	Corruption		

Nevertheless, not all 21 barriers were implemented into the model. Further research could investigate the effect of the excluded barriers on the diffusion of LFGE over time.

5. *Which system conditions will result in the diffusion of landfill gas to energy projects in Africa?*
   The most important condition for the diffusion of LFGE projects in Africa is economic viability. More specifically, the purchase price of the electricity from LFGE should be above the levelised cost of energy of LFGE. If the wholesale market price of electricity is not sufficient to cover the LCOE of LFGE, a feed-in tariff of a least the LCOE is required. If the purchase price is sufficient, LFGE can be considered economically viable, and there is a great chance that the LFGE TIS will

diffuse. Nevertheless, even with a sufficient purchase price the diffusion of LFGE can still be impeded. This impediment can either be caused by a lack of demand or a lack of electricity potential. There could be a lack of demand when the electricity generated from LFGE cannot be supplied to the national electricity grid. While individual projects might be able to find demand through local grids, rather than the national electricity grid, this will most likely not be the case for all potential projects within a country. Therefore, on a country level the demand does not meet the supply, which removes the incentive to develop LFGE projects, impeding the diffusion of the TIS. On the other hand, there could be a lack of electricity potential to cover the costs of the projects. In case of a poor waste management system, the landfilled waste will be too little to profitably generate electricity from. A low electricity potential will drive up the LCOE of LFGE, resulting in the unviability of LFGE projects, which prevents the development of LFGE projects. Therefore, the purchase price of electricity from LFGE should not only cover the LCOE, but it should also be possible to sell the electricity on the national grid, and the waste management system must be efficient enough to landfill an adequate amount of waste. This will ensure sufficient supply and demand. One condition that would accelerate the development of LFGE projects is private ownership of the landfill. Nevertheless, public ownership will not fully prevent the diffusion of LFGE projects, but will only slow it down. An average duration of the tender process of one year will still result in acceptable development of LFGE over the coming ten years. A requirement to collect LFG and an obligation to buy the electricity from LFGE projects will also accelerate the development of LFGE projects. Although the collection requirement reduces the share of LFG used for electricity generation, the increase in institutional fit will result in an increase in projects in the end. The buying obligation will reduce the risk of entrepreneurs, while also increasing the institutional fit, which will also speed up the development of LFGE. Nevertheless, these three accelerating factors will only be effective if LFGE is economically viable. Finally, the generation of carbon credits could temporarily accelerate the development of the LFGE TIS. Carbon credits provide an additional revenue stream that decreases the minimum price that is required to ensure economic viability of LFGE projects. This could kick-start the development of LFGE projects when the wholesale price of electricity is slightly below the LCOE of LFG. Nevertheless, the effect of carbon credits is not unlimited. Their generation is prohibited when the market share becomes larger and the use of LFGE can be considered common practice.

In countries that have implemented obligation to generate electricity before 2001 it is not possible to generate carbon credits. This is not a problem when the purchase price is sufficient, but in cases where there are no feed-in tariffs and the wholesale price of electricity is low it will prevent the development of LFGE projects. More research should be conducted on the effect of this policy on the diffusion of LFGE in case of an implementation after 2001.

10.2 Answer to main question

It can be concluded that the conditions enhancing the diffusion of the LFGE TIS are of a structural nature and therefore it is not possible to rapidly change them. The most impactful factors are the wholesale price of electricity, the possibility to access the national electricity grid, and the efficiency of the waste management system. An adequate purchase price, either the wholesale price of electricity or a feed-in tariff, in combination with the possibility to sell the electricity on the grid, and a well-developed waste management system will result in the diffusion of LFGE projects in Africa. If one of these factors is missing, diffusion will not occur in the short term. The diffusion can be accelerated when an obligation to buy the electricity from LFGE is implemented. The implementation of a requirement to collect the LFG and private ownership of the landfills will also accelerate the diffusion. Carbon credit generation provides an additional revenue stream, which could make LFGE viable in case of a low purchase price. Nevertheless, this effect is limited because, once LFGE becomes the common practice, carbon credit generation is no longer allowed.

10.3 Recommendations

Based on this research, several recommendations can be provided. The recommendations can be divided into recommendations for national governments, recommendations for project developers, and recommendations for overarching international organisations, such a carbon credit certification bodies or international development agencies.

10.3.1 Recommendations for national governments

National governments should be proactive in creating beneficial conditions for the development of LFGE projects in their country. This mainly involves creating a supporting institutional framework for LFGE. The recommendations for national governments are as follows:

- To create a viable economic environment for LFGE projects. This means keeping track of the wholesale market price and taking action when the market is not able to create a viable price on its own. Taking action in this case means to implement a long-term feed-in tariff that is sufficient to cover the LCOE of LFGE.
- To implement an obligation to buy the electricity generated from LFGE projects. This will accelerate the development of LFGE projects and will be an effective addition to the implementation of an adequate feed-in tariff.
- To invest in the waste management system, especially in the collection system. This results in more waste reaching the landfill, and therefore a higher electricity potential, which will reduce the LCOE of LFGE.
- To invest in the development of the national electricity grid. A well-developed electricity grid will create capacity for electricity from LFGE on the grid. Additionally, local governments should be encouraged to issue permits allowing LFGE projects to connect to the national grid.

10.3.2 Recommendations for project developers

For projects developers it is recommended to assess the potential for LFGE projects within a certain country based on the flowchart in Figure 33. While certain conditions do not result in full diffusion of LFGE projects, they could provide opportunities for individual projects. These cases might still be worth exploring. Additionally, the flowchart provides insights into the scenarios that do result in diffusion. However, not all diffusion scenarios allow for the generation of carbon credits. In countries where the diffusion has taken off and LFGE is considered common practice, or the obligation to generate electricity from LFG had been implemented before 2001, the generation of carbon credits is not allowed anymore.

10.3.3 Recommendations for overarching organisations

The main recommendation for overarching international organisations is to increase the threshold indicating LFGE to be common practice in countries where political instability results in the ineffectiveness of lobbying. If lobbying is ineffective in enforcing policy changes, the implementation of a feed-in tariff will not be achieved endogenously. Carbon credits could, to a certain extent, cover the gap between the wholesale price of electricity and the LCOE, creating economic viability even when the wholesale price is insufficient. By loosening the requirements for the generation of carbon credits in countries where enforcing the implementation of feed-in tariffs proves to be difficult due to political instability, carbon credits could continue to ensure economic viability for a longer period of time.

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Appendices

Appendix A. Interview guide

This appendix provides the interview guide that was used for the semi-structured interviews conducted. First, the drivers and barriers were explored (question 1-3). These were followed by questions about the TIS structures (question 4-6). Finally, a question connecting the drivers and barriers to the TIS structures is included (question 7). The interview was ended with a round-up question (question 8).

1. **Identifying participant's experience with landfill gas to energy projects in Africa**
    a. What is your experience with landfill gas to energy projects?
    b. What is your experience with landfill gas to energy projects in Africa, specifically?

2. **Identifying drivers and barriers**
    a. What are, in your opinion, the main drivers of landfill gas to energy projects?
    b. What are, in your opinion, the main barriers of landfill gas to energy projects?

3. **Identifying relative importance of drivers and barriers**
    a. Which drivers and barriers do you expect to be most important?
        i. Why?

4. **Exploring actor & networks structure**
    a. Who do you consider to be the main stakeholders in the implementation of landfill gas to energy projects?
    b. Do you think these stakeholders are collaborating to enhance the implementation of landfill gas to energy projects?
    c. How do you think this (lack of) collaboration influences the process of implementing landfill gas to energy projects?

5. **Exploring institutional structure**
    a. What kind of laws or policies do you think are necessary to enhance the implementation of landfill gas to energy projects?
    b. Do you think these laws and policies are present in African countries?
        i. If yes, in which countries are they present?

6. **Exploring technology structure**
    a. What factors influence the price of energy resulting from a landfill gas to energy project.
    b. What factors determine the performance of the landfill gas to energy technology?

7. **Connection TIS structures and TIS functions**
    a. How do you think the drivers and barriers you mentioned relate to the stakeholders you identified?
        i. Does this relation change when the level of collaboration is also considered?
    b. How do you think the drivers and barriers you mentioned relate to the laws and policies you have identified?

c. How do you think the drivers and barriers you mentioned relate to the performance and price of the energy resulting from landfill gas to energy projects.

8. Closing question

a. Is there anything you would like to discuss about landfill gas to energy projects that we have not discussed yet?

Appendix B. Conceptual models 'hybrid approach'

This appendix provides the causal loop diagram (CLD) the hybrid approach (Figure 34). The TIS functions are shown in bold, whereas the relations identified by Walrave & Raven (2016) are depicted in red. During the creation of the model, these relations were taken as a starting point.

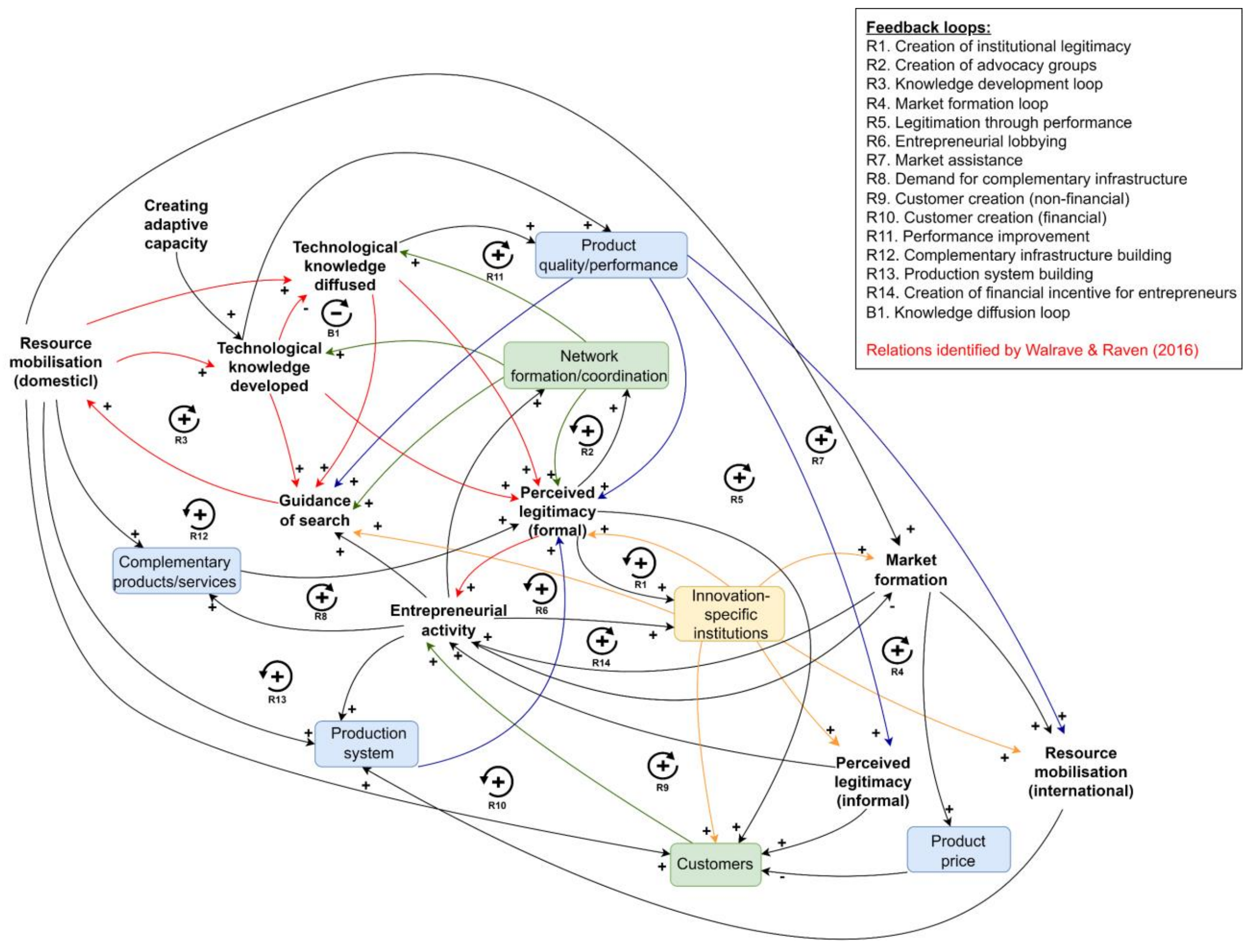

Figure 34. Causal loop diagram hybrid approach.
Source: Own work

Appendix C. Drivers and barriers to LFGE projects

This appendix presents the barriers found in literature and the barriers identified through the expert interviews. These barriers are aggregated and categorised in Chapter 6.2.

Table 13. Full list of drivers and barriers to LFGE project gathered from expert interviews and literature.

Interviews		Literature		
Barriers	**Subfactors**	**Barriers**	**Subfactors**	**Source**
Economic				
Economic viability	- Low rate of return - Low market prices - Low feed-in tariffs - Low carbon prices - High investment costs - High maintenance costs	**Worry about recovery of costs**	- High investment costs - High operational costs - Absence of standard price for generated power - High transportation costs	Karekezi et al. (2009); Njoku et al. (2018); Mbazima et al. (2022); Dlamini et al. (2019)
Funding	- Possibility to get a loan. - Finding private investment challenging - International investment prevented or discouraged	**Funding**		Karekezi et al. (2009); Njoku et al. (2018); Dlamini et al. (2019)
		Absence of production tax credit		Adeleke et al. (2021)
		Inaccuracy of potential energy generation		Bogner & Lee (2005); Couth et al. (2011); Karekezi et al. (2009)
Technical				
Uncertainty of electricity generation	- Intermittency of electricity generation	**Quality and duration of LFG generation**		Njoku et al. (2018)
Insufficient waste management		**Insufficient waste management**	- Unreliable flow of waste to the landfill - Incorrect waste composition - Poor infrastructure - Poor data on waste generation	Karekezi et al. (2009); Njoku et al. (2018); Adeleke et al. (2021); Mbazima et al. (2022)
Low efficiency	- High leakage of methane	**Lack of technical solutions**		Njoku et al. (2018)
Distance from the grid	- Cost of distribution cable to the grid	**Availability and accessibility of**		Karekezi et al. (2009); Dlamini et al. (2019)

		land/large area of land required		
Scale of the landfill	- Small landfill			
Organisational				
Public landfill ownership	- Slow tender and permitting processes - Challenging process of securing a long-term contract. - Hidden agenda - Limited capacity to operate the project	**Lack of human capacity**	- Lack of skilled personnel	Adeleke et al. (2021); Agbejule et al. (2021); Karekezi et al. (2009); Njoku et al. (2018)
		Monopolised energy sector		Njoku et al. (2018)
Institutional				
No access to the electricity grid	- No permits for grid connection - Distance to the grid	**No access to the electricity grid**		Adeleke et al. (2021)
Regulations on LFG handling	- Obligation to flare	**Complexity of Power Purchase Agreements**		Karekezi et al. (2009)
Long process of carbon projects		**Unsupportive institutional framework**		Karekezi et al. (2009); Njoku et al. (2018); Mbazima et al. (2022); Adeleke et al. (2021)
		Lengthy CDM process		Njoku et al. (2018); Couth et al. (2011)
Social				
Limited awareness of benefits	- Awareness of (local) governments - Awareness of landfill operators - Awareness of local communities	**Limited awareness of benefits**	- Limited knowledge by decision-makers	Adeleke et al. (2021); Njoku et al. (2018); Mbazima et al. (2022)
Other				
Lack of government support	- Blocking of projects by public organisations	**Lack of government support/political will**		Adeleke et al. (2021); Njoku et al. (2018);
Corruption		**Availability of end-users**		Njoku et al. (2018)
		Dependency on cheap fossil alternatives		Adeleke et al. (2021)

Appendix E. Model variables and their implementation

This appendix presents a visual representation of the different submodels as well as the formulas and values used for each variable. These visualisations are more detailed than the ones shown in Section 7.1.

E.1 Implementation submodel 1: Institutional alignment

Figure 35 shows the implementation of the first submodel in Vensim. The building blocks are shown in yellow, green, and blue, corresponding with the colours used in the conceptualisation of the hybrid approach. The saturation of LFGE projects, the KPI, is depicted in grey, whereas the barriers found in Section 6.2 are depicted in red.

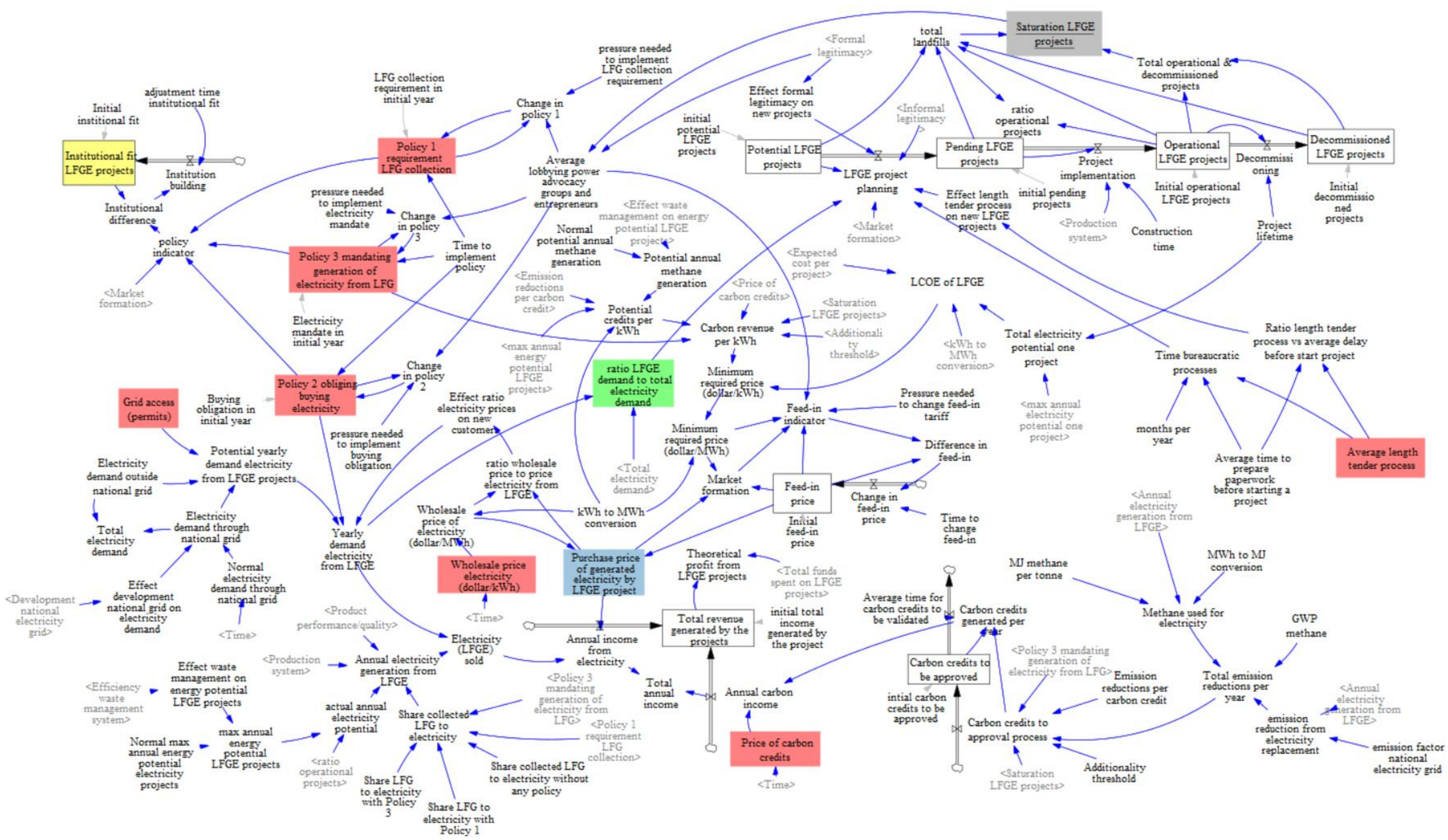

Figure 35. Model implementation of submodel 1 Institutional alignment.

Table 14 shows the values and equations used to operationalise the model.

Table 14. Values and equations submodel 1 Institutional alignment.

Variable	Variable type	Value	Unit	Source	Comments
actual annual electricity potential	Auxiliary	max annual energy potential LFGE projects * Effect waste management	MWh/Year		On country level

		on energy potential LFGE projects * Ratio operational projects			
Additionality threshold	Constant	0.3	Dmnl	Assumption	The maximum share of the market using LFGE technology for LFGE still be considered additional.
Adjustment time institutional fit	Constant	0.01	Year		
Annual carbon income	Flow	Carbon credits generated per year*price of carbon credits	dollar/Year		
Annual electricity generation from LFGE	Auxiliary	actual annual electricity potential * Share collected LFG to electricity * Production System * Product performance/quality	MWh/Year		If either the production system or the product performance /quality building block is not complete, it is assumed the full electricity potential will not be met.
Annual income from electricity	Flow	Electricity (LFGE) sold * Purchase price of generated electricity by LFGE project	dollar/Year		
Average length tender processes	Constant	12	Month	Assumption	
Average lobbying power advocacy groups and entrepreneurs	Auxiliary	(Formal legitimacy + Saturation LFGE projects)/2	Dmnl		
Average time for carbon credits to be validated	Constant	1	Year	Assumption	
Average time to prepare paperwork before starting a project	Constant	6	Month	Assumption	Generally it takes time to prepare the necessary paperwork

					for a project. It is assumed that this process is faster with private partners compared to the public tender processes.
Buying obligation in initial year	Constant	0	Dmnl		This variable is used to implement the status of the policy in the initial year.
Carbon credits generated per year	Flow	DELAY3I(Carbon credits to approval process, Average time for carbon credits to be approved, Carbon credits to be approved/Average time for carbon credits to be approved)	credit/Year		
Carbon credits to approval process	Flow	IF THEN ELSE(Policy 3 mandating generation of electricity from LFG=0 :AND: Saturation LFGE projects <= Additionality threshold, Total emission reductions per year/Emission reductions per carbon credit, 0)	credit/year		If Policy 3 is implemented , it is not possible to generated carbon credits because the additionality requirement is not met. Also, when a large part of the market creating LFGE projects, it cannot be considered additional anymore.
Carbon credits to be approved	Stock	INTEG(Carbon credits to approval process - Carbon credits generated per year) (Initial value = 0]			

Carbon revenue per kWh	Auxiliary	IF THEN ELSE(Policy 3 mandating generation of electricity from LFG = 0, Potential credits per kWh*Price of carbon credits, 0)	dollar/kWh		
Change in feed-in price	Flow	Difference in feed-in/Time to implement policy	Dmnl		
Change in Policy 1	Auxiliary	IF THEN ELSE(Policy 1 requirement LFG collection = 0, IF THEN ELSE(Average lobbying power advocacy groups and entrepreneurs >= pressure needed to implement LFG collection requirement,1,0),1)	Dmnl		
Change in Policy 2	Auxiliary	IF THEN ELSE(Policy 2 obliging buying electricity = 0, IF THEN ELSE(Average lobbying power advocacy groups and entrepreneurs >= pressure needed to implement buying obligation,1,0),1)	Dmnl		
Change in Policy 3	Auxiliary	IF THEN ELSE(Policy 1 mandating generation of electricity from LFG = 0, IF THEN ELSE(Average lobbying power advocacy groups and entrepreneurs >= pressure needed to implement electricity mandate,1,0),1)	Dmnl		
Construction time	Constant	1	Year	Assumption	
Decommissioned LFGE projects	Stock	INTEG(Decommissioning) [Initial value = 0]	Project		
Decommissioning	Flow	Operational LFGE projects/Project lifetime	Project/Year		
Difference in feed-in	Auxiliary	"Feed-in indicator" - "Feed-in price"	dollar/MWh		
Effect development national grid on electricity demand	Table function	With “Development national electricity grid” ([(0,0)-(10,10)],(0,0),(0.852,1),(1,1.2))	Dmnl		
Effect formal legitimacy on new projects	Table function	With "Formal legitimacy" ([(-0.572441,0)-(1.56234,1.3016)],(0,0),(0.25,0.125),(0.5,0.25),(0.6,0.38),(0.75,0.6),(0.9,0.85),(1,1))	Dmnl		

Effect length tender process on new LFGE projects	Table function	with "Ratio length tender process vs average delay before start project" [(0,0)-(10,10)],(0,0),(1,0.9),(12,1))	Dmnl		If the input is 0, the tender length is very high compared to the average time and therefore the multiplier is 0. If the input is 1, the tender length is equal to the average preparation time. It is assumed that entrepreneur s are likely to take the opportunity if they do not have to wait longer than average, so the multiplier is assumed to be 0.9. When the tender process is shorter than the average preparation time, the multiplier will go to 1.
Effect ratio electricity prices on new customers	Table function	with "ratio electricity from other sources vs electricity from LFGE" ([(0,0)-(10,10)],(0,0),(1,0.5),(10,1))	Dmnl		
Effect waste management on energy potential LFGE projects	Table Function	With “Efficiency waste management system” ([(0,0)-(10,10)],(0,0),(0.5562,1),(1,2.3))	Dmnl		

Electricity (LFGE) sold	Auxiliary	IF THEN ELSE(Yearly demand electricity from LFGE>=Annual electricity generation from LFGE, Annual electricity generation from LFGE , Yearly demand electricity from LFGE)	MWh/year		
Electricity demand outside national grid	Constant	2628000	MWh/year	Assumption: 1% of electricity demand through grid in 2000	The demand that does not need the national grid to be fulfilled, for example because the customer is very close and a direct cable can be installed.
Electricity demand trough national grid	Auxiliary	Normal electricity demand through national grid* Effect development national grid on electricity demand	MWh/year		
Emission factor national electricity grid	Constant	0.985	tCO2e/MWh	Department of Forestry, Fisheries, and the Environmen t (2024)	
emission reduction from electricity replacement	Auxiliary	Annual electricity generation from LFGE * emission factor national electricity grid	tCO2e/year		
Normal electricity demand through national grid	Table function	With "Time" ([(0,0)-(10,10)],(2000,1.75e+08),(2006,2.1e+08),(2012,1.6e+08),(2020,1.35e+08),(2024,1.4e+08),(2026,1.42e+08),(2030,1.48481e+08),(2035,1.5e+08))	MWh/year	Inglesi (2010).	The demand through the grid is the amount of electricity that is purchased by energy offtakers. This is assumed to be equal to the demand of end-users using the national grid.

Electricity mandate in initial year	Constant	0	Dmnl		This variable is used to implement the status of the policy in the initial year
Emission reductions per carbon credit	Constant	1	tCO2e/credit		
Feed-in indicator	Auxiliary	IF THEN ELSE(Market formation<1:AND:Average lobbying power advocacy groups and entrepreneurs>"Pressure needed to change feed-in tariff", "Minimum required feed-in tariff (dollar/MWh)" , "Feed-in price")	dollar/MWh		This variable will track whether the conditions have been met for the feed-in tariff to be adjusted.
Feed-in price	Stock	INTEG(Change in feed-in price) [Initial value = 0]	dollar/MWh	World Bank. (z.d.a)	
Grid access (permits)	Constant	1	Dmnl		
GWP methane	Constant	28	tCO2e/tCH4		
Institution building	Flow	Institutional difference/Adjustment time institutional fit	Dmnl/year		
Institutional difference	Auxiliary	Policy indicator - Institutional fit LFGE projects	Dmnl		
Institutional fit LFGE projects	Stock	INTEG(Institution building) [Initial value = 0]	Dmnl		
kWh to MWh conversion	Constant	1000	kWh/MWh		
LFG collection requirement in initial year	Constant	0	Dmnl		
LFGE project planning	Auxiliary	Perceived viability one project*Potential LFGE projects*Effect formal legitimacy on new projects*Informal legitimacy*ratio LFGE demand to total electricity demand *Effect length tender process on new LFGE projects*Market formation/Time bureaucratic processes	Project/Year		

Market formation	Auxiliary	IF THEN ELSE(Purchase price of generated electricity by LFGE project>"Minimum required price (dollar/MWh)" , 1 , "Feed-in price"/"Minimum required price (dollar/MWh)")	Dmnl		If the wholesale market price is higher than the feed-in price, there is no need for market entry assistance and the market formation function is set to 1, even though the feed-in tariff will be 0 in this scenario
Wholesale price of electricity from LFGE (dollar/kWh)	Table function	With "Time" ([(0,0)-(10,10)],(2000,0.062),(2014,0.062),(2015,0.07),(2016,0.08),(2017,0.055),(2022,0.075),(2035,0.08)) Now	dollar/kWh	Blimpo et al. (2018)	Average wholesale prices for the Southern African Power Pool used.
Wholesale price of electricity from LFGE (dollar/MWh)	Auxiliary	Wholesale price of electricity from LFGE (dollar/kWh)*kWh to MWh conversion	dollar/MWh		
Normal max annual energy potential LFGE projects	Constant	2309000	MWh/Year	Scarlat et al. (2015)	2012 value. Assumes that all collected waste is landfilled.
max annual energy potential LFGE projects	Table function	Normal max annual energy potential LFGE projects * Effect waste management on energy potential LFGE projects	MWh/year		
Methane used for electricity	Auxiliary	Annual electricity generation from LFGE*MWh to MJ conversion/MJ methane per tonne	tCH4/Year		
LCOE LFGE	Auxiliary	IF THEN ELSE(Total electricity potential one project>0, Expected cost per project/Total electricity potential one project/kWh to MWh conversion , 100000)	$/kWh		Levelised cost of energy of electricity from LFG. According to

					Cudjoe & Han (2021), the LCOE of LFGE in South Africa is 0.076 $/kWh
Minimum required price (dollar/kWh)	Auxiliary	LCOE LFGE - carbon revenue per kWh	dollar/kWh		The minimum price for the electricity needed to make the project economically feasible. It is assumed that carbon revenue reduces the minimum required price as it increases the revenue from the project.
Minimum required price (dollar/MWh)	Auxiliary	Minimum required feed-in tariff (dollar/kWh)*kWH to MWh conversion	dollar/MWh		
MJ methane per tonne	Constant	50400	MJ/tCH4	UNFCCC (2019)	
months per year	Constant	12	Month/Year		
MWh to MJ conversion	Constant	3600	MJ/MWh		
Operational LFGE projects	Stock	INTEG(Project implementation-Decommissioning) [Initial value = 0]			
Pending LFGE projects	Stock	INTEG(LFGE project planning - Project implementation) [Initial value = 0]	Project		
Policy 1 requirement LFG collection	Auxiliary	DelayFixed(Change in policy 1, Time to implement policy, LFG collection requirement in initial year)	Dmnl		1: policy is in place 0: policy is not in place

					There might be a requirement to collect the LFG from landfills. The LFG can then be flared or used for electricity generation.
Policy 2 obliging buying electricity	Auxiliary	DelayFixed(Change in policy 1, Time to implement policy, Buying obligation in initial year)	Dmnl		1: policy is in place 0: policy is not in place
Policy 3 mandating generation of electricity from LFGE	Auxiliary	DelayFixed(Change in policy 1, Time to implement policy, Electricity mandate in initial year)	Dmnl		1: policy is in place 0: policy is not in place
Policy indicator	Dmnl	(Policy 1 requirement LFG collection+Policy 3 mandating generation of electricity from LFG +Policy 2 obliging buying electricity+Market formation)/4	Dmnl		Keeps track of whether the four innovation specific institutions are implemented or not.
Potential annual methane generation	Constant	15494300	tCO2e/Year	Calculated based on electricity potential provided in Scarlat et al. (2015)	
Potential credits per kWh	Auxiliary	IF THEN ELSE(max annual energy potential LFGE projects>0, (Potential annual methane generation/max annual energy potential LFGE projects)/kWh to MWh conversion/Emission reductions per carbon credit,0)	credit/kWh		Switch to prevent division by 0 when there is not electricity potential.
Potential LFGE projects	Stock	INTEG(-LFGE project planning) [Initial value = 70]	Project		Determined through experimentation.

Potential yearly demand electricity from LFGE projects	Auxiliary	IF THEN ELSE(Grid access (permits) = 1, Electricity demand through national grid + Electricity demand outside national grid, Electricity demand outside national grid)	MWh/year		
Pressure need to implement buying obligation	Constant	0.8	Dmnl	Assumption	The lobbying power required to pressure the government to implement this policy.
Pressure needed to change feed-in tariff	Constant	0.8	Dmnl	Assumption	The lobbying power required to pressure the government to implement this policy.
Pressure needed to implement electricity mandate	Constant	0.9	Dmnl	Assumption	The lobbying power required to pressure the government to implement this policy.
Pressure needed to implement LFG collection requirement	Constant	0.6	Dmnl	Assumption	The lobbying power required to pressure the government to implement this policy.
Price of carbon credits	Table function	With Time ([(0,0)-(10,10)],(2005,9.15),(2012,1),(2020,1),(2024,3),(2035,9.5))	dollar/credit	Loffler et al. (2024); Opanda (2024).	Loffler et al. (2024) state that the carbon credit price in March 2024 of LFGE projects is $9.50. Additionally, Opanda (2024) show that the carbon credit

					prices of biogas projects ranges from $1 to $20+. These values are used during experimentation.
Project implementation	Flow	Pending LFGE projects * Production system / Construction time	project/Year		Only the projects for which the resources are available are implemented.
Project lifetime	Constant	20	Year		
Purchase price of generated electricity by LFGE project	Auxiliary	IF THEN ELSE("Feed-in price">0, "Feed-in price" , Wholsesale price of electricity from LFGE (dollar/MWh))	dollar/kWh		
Ratio length tender process vs average delay before start project	Auxiliary	Average time to prepare paperwork before starting a project/ Average length tender process	Dmnl		
Ratio LFGE demand to total electricity demand	Auxiliary	IF THEN ELSE(Total electricity demand > 0, Yearly demand electricity from LFGE/Total electricity demand, 0)	Dmnl		
ratio market price to price electricity from LFGE	Auxiliary	Wholesale price of electricity from LFGE (dollar/MWh)/Purchase price of generated electricity by LFGE project	Dmnl		
Ratio operational projects	Auxiliary	Operational LFGE projects/Total landfills	Dmnl		
Saturation LFGE projects	Auxiliary	Total operational & decommissioned projects/Total landfills	Dmnl		KPI Equal to entrepreneurial activity.
Share collected LFG to electricity	Auxiliary	IF THEN ELSE(Policy 3 mandating generation of electricity from LFG=1, Share LFG to electricity with Policy 3, IF THEN ELSE(Policy 1 requirement LFG collection =1, Share LFG to electricity with Policy 1 , Share collected LFG to electricity without any policy))	Dmnl		If there is no policy implemented, the amount of LFG to electricity is considered to be lower than when

					Policy 1 is implemented. It is assumed that Policy 1 will increase the share of LFG to electricity because it will reduce the number of carbon credits that can be generated with flaring. When Policy 3 is implemented, the share of electricity to LFG is assumed to be 1.
Share LFG collected to electricity with Policy 1	Constant	0.25	Dmnl	Assumption	
Share LFG collected to electricity without any policy	Constant	0.5	Dmnl	Assumption	
Share LFG to electricity with Policy 3	Constant	1	Dmnl	Assumption	
Time bureaucratic process	Auxiliary	MAX(Average time to prepare paperwork before starting a project, Average length tender process)/months per year	Year		
Time to implement policy	Constant	2	Year	Assumption	It takes time to implement a policy, which is accounted for by this variable.
Total electricity demand	Auxiliary	Electricity demand through national grid + Electricity demand outside national grid	MWh/Year		

Total emission reductions per year	Auxiliary	Methane used for electricity * GWP methane + emission reduction from electricity replacement	tCO2e/project /year		
Total annual income	Stock	INTEG(Annual income from generated by project+Annual carbon income) [Initial value = 0]	dollar		
Total landfills	Constant	Potential LFGE projects + Pending LFGE projects + Operational LFGE projects + Decommissioned LFGE projects	Project		
Total operational & decommissioned projects	Auxiliary	Operationa LFGE projects + Decommissioned projects	Project		LFGE projects that are implemented or have been implemented within a country
Yearly demand electricity from LFGE	Auxiliary	IF THEN ELSE(Policy 2 obliging buying electricity=1, Potential yearly demand electricity from LFGE projects, Potential yearly demand electricity from LFGE projects *Effect ratio electricity prices on new customers)	MWh/year		
TJ to MWh conversion	Constant	277.778	MWh/TJ		
Total revenue generated by the projects	Stock	INTEG(Annual carbon income+Annual income from electricity) [Initial value = 0]			
Time to change feed-in	Auxiliary	0.01	Year		

E.2 Implementation submodel 2: Funding

Figure 36 shows the model implementation of the second submodel in Vensim, whereas Table 15 shows the implementation of the submodel describing the funding processes of LFGE projects.

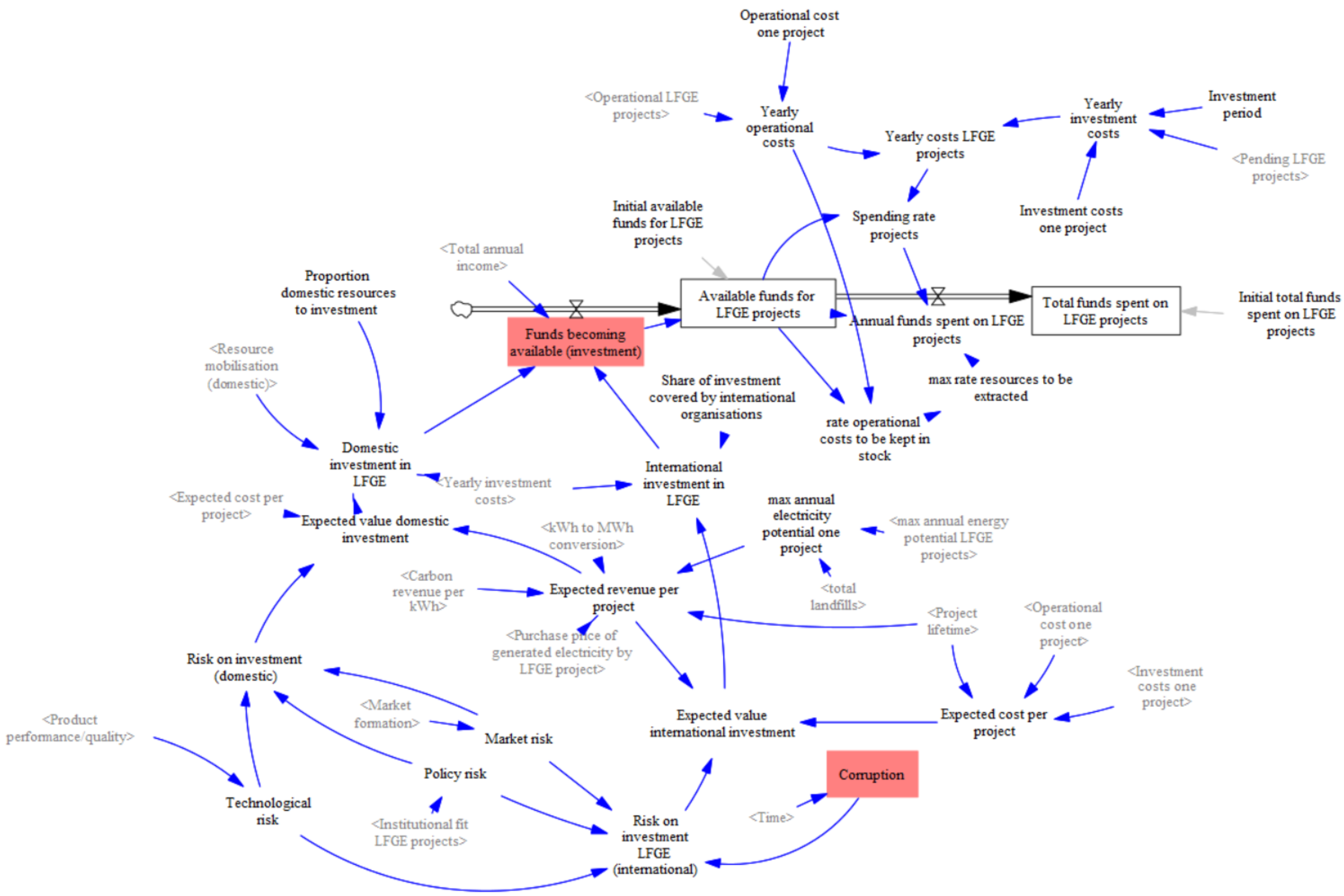

Figure 36. Model implementation of submodel 2 Funding.

Table 15. Values and equations submodel 2 Resources.

Variable	Variable type	Value	Unit	Source	Comments
Annual funds spent on LFGE projects	Flow	MIN(Available funds for LFGE projects * Spending rate projects, Available funds for LFGE projects*max rate resources to be extracted)	dollar/Year		
Available funds for LFGE projects	Stock	INTEG(Funds becoming available (investment)-Annual funds spent on LFGE projects) [Initial value = 0]	dollar		
Corruption	Table Function	With Time ([(0,0)-(10,10)],(2005,0.43),(2012,0.43),(2013,0.42),(2014,0.44),(2015,0.44),(2016,0.45),(2017,0.43),(2018,0.43),(2019,0.44),(2020,0.44),(20	Dmnl	World Bank (2024)	Corruption Perception Index divided by 100 to get to a value between 0 and 1. 0 means the

		21,0.44),(2022,0.43),(2023,0.41),(2035,0.44))			country is highly corrupt, while 1 means the country is very clean.
Domestic investment in LFGE	Auxiliary	IF THEN ELSE(Expected value domestic investment > 0, Yearly investment costs * Resource mobilisation (domestic) * Proportion domestic resources to investment, 0)	dollar/Year		
Expected costs per project	Auxiliary	Investment cost one project + Operational costs one project * project lifetime	dollar/project		
Expected revenue per project	Auxiliary	Max electricity potential one project *Purchase price of generated electricity by LFGE projects + Max electricity potential one project * carbon revenue per kWh * kWh to MWh conversion)*Project lifetime	dollar/project		
Expected value domestic investment	Auxiliary	(Expected revenue per project - Expected cost per project)*(1-Risk on investment (domestic))	dollar/project	O'Regan and Moles (2006)	
Expected value international investment	Auxiliary	(Expected revenue per project - Expected cost per project)*(1-Risk on investment (international))	dollar/project	O'Regan and Moles (2006)	
Funds becoming available (investment)	Flow	Domestic investment in LFGE+International investment in LFGE+Total annual income	dollar/Year		
International investment in LFGE	Auxiliary	IF THEN ELSE(Expected value international investment>0, Yearly investment costs*Share of investment covered by international organisations,0),0	dollar/Year		
Investment costs one project	Constant	19090000	dollar/project	Godlove & Singleton (2010)	

Investment period	Constant	1	Year	Assumption	The period over which the investment is made
Market risk	Auxiliary	1-Market formation	Dmnl		
Max electricity potential one project	Auxiliary	Max annual electricity potential LFGE projects/total landfills	MWh/Year		
Max rate resources to be extracted	Auxiliary	IF THEN ELSE(rate operational costs to be kept in stock<0,0, rate operational costs to be kept in stock)	1/Year		Makes sure there are enough resources left to cover the operational costs of the existing projects.
Operational costs one project	Constant	1620000	dollar/project/year	Godlove & Singleton (2010)	
Policy risk	Auxiliary	1-Institutional fit LFGE projects	Dmnl		
Proportion domestic resources to investment	Auxiliary	0.5	Dmnl	Assumption	The other half will go to knowledge development and diffusion.
Rate operational costss to be kept in stock	Auxiliary	IF THEN ELSE(Available funds for LFGE projects >0, 1-Yearly operational costs/Available funds for LFGE projects, 0)	1/Year		
Risk on investment (domestic)	Auxiliary	(Market risk + Policy risk + Technological risk)/3	Dmnl		
Risk on investment LFGE (international)	Auxiliary	(Market risk + Policy risk + Technological risk+(1-Corruption))/4	Dmnl		
Share of investment covered by international organisations	Constant	0.3	Dmnl	Assumption	
Spending rate	Auxiliary	IF THEN ELSE(Available funds for LFGE projects>0, IF THEN ELSE(Yearly costs LFGE projects/Available funds for LFGE projects<1 , Yearly costs LFGE projects/Available funds for LFGE projects , 1), 0)	1/year		
Technological risk	Auxiliary	1-Product performance/quality	Dmnl		
Theoreatical profit from LFGE projects	Auxiliary	Total income generated by the project - Total funds spend on the LFGE project	dollar		

Total funds spent on LFGE projects	Stock	INTEG(Annual funds spent on LFGE projects) [Initial value = 0]	dollar		
Yearly costs LFGE projects	Auxiliary	Yearly investment costs + Yearly operational costs	dollar/year		
Yearly investment costs	Auxiliary	Investment costs one project * Pending projects / Investment period	dollar/year		
Yearly operational cost	Auxiliary	Operational costs one project * Operational LFGE projects	dollar/year		

E.3 Implementation submodel 3: Aggregated TIS model

Figure 37 shows the model implementation of the aggregated TIS model. The building blocks regarding the demand and the purchase price of electricity from LFG, and the market formation function are not directly included in this submodel as they only affect variables within the institutional alignment submodel.

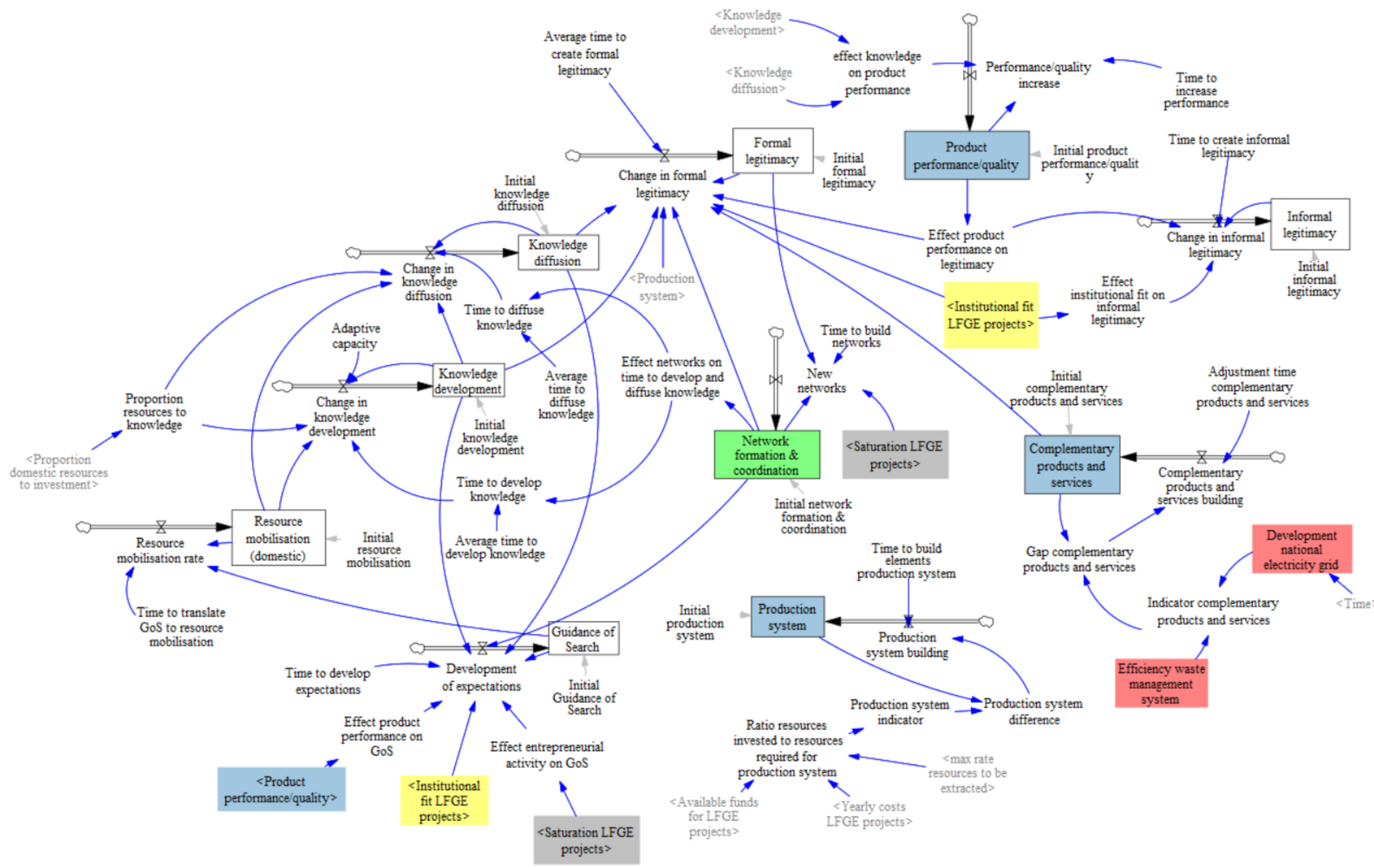

Figure 37. Model implementation submodel 3 Aggregated TIS model

Table 16 presents the values and equations used to convert the conceptualisation into a running model.

Table 16. Values and equations submodel 3 Aggregated TIS model

Variable	Variable type	Value	Unit	Source	Comments
Adaptive capacity	Constant	0.5	Dmnl	Assumption	This function is not modelled as a stock flow structure to reduce the complexity of the model.
Adjustment time complementary products and services	Constant	1	Year	Assumption	
Average time to create formal legitimacy	Constant	1	Year	Walrave & Raven (2020)	
Average time to develop knowledge	Constant	0.25	Year	Walrave & Raven (2020)	
Average time to diffuse knowledge	Auxiliary	0.25	Year	Walrave & Raven (2020)	
Change in formal legitimacy	Flow	(1-Formal legitimacy)*((Knowledge development*Knowledge diffusion*Effect product performance on legitimacy*"Network formation & coordination" *Production system*Complementary products and services+Institutional fit LFGE projects)/2)/Average time to create formal legitimacy	1/Year		The incomplete building block institutional fit does not act as a full barrier to LFG projects as the policies are not essential for the implementation of LFGE projects, but they do provide an additional incentive. Therefore, its effect is not modelled as multiplicative, like the effect of the other building blocks and functions.
Change in informal legitimacy	Flow	(1-Informal legitimacy) *(Effect product performance on legitimacy+Effect institutional fit on informal legitimacy)/2/Time to create informal legitimacy	1/Year		

Change in knowledge development	Flow	(1-Knowledge development)*Resource mobilisation (domestic)*Adaptive capacity*(Proportion resources to knowledge/2)/Time to develop knowledge	1/Year	Adapted from Walrave & Raven (2020)	
Change in knowledge diffusion	Flow	(1-Knowledge diffusion)*"Resource mobilisation (domestic)"*Knowledge development*(Proportion resources to knowledge/2)/Average time to diffuse knowledge	1/Year	Adapted from Walrave & Raven (2020)	
Complementary products and services	Stock	INTEG(Complementary products and services building) [Initial value = 0]	Dmnl		
Complementary products and services building	Flow	Gap complementary products and services/Adjustment time complementary products and services	1/Year		
Development national electricity grid	Table function	With Time ([(0,0)-(10,10)],(2005,0.808),(2006,0.807),(2007,0.82),(2008,0.819),(2009,0.826),(2010,0.828),(2011,0.836),(2012,0.852),(2013,0.852),(2014,0.859),(2015,0.853),(2016,0.839),(2017,0.844),(2018,0.847),(2019,0.85),(2020,0.9),(2021,0.893),(2022,0.865),(2035,0.9))	Dmnl	World Bank (2023)	
Development of expectations	Flow	(1-Guidance of Search)*((Knowledge development*Knowledge diffusion*Effect product performance on GoS* Effect entrepreneurial activity on GoS *"Network formation &	1/Year		

		coordination"+Institutional fit LFGE projects)/2)/Time to develop expectations			
Effect entrepreneurial activity on GoS	Table function	With "Saturation LFGE projects" ([(0,0)-(1,1)],(0,0),(0.274566,0.0967742),(0.407514,0.245968),(0.601156,0.604839),(0.760116,0.923387),(0.8,1),(1,1))	Dmnl		S-shaped growth assumed.
Effect institutional fit on informal legitimacy	Table function	With "Institutional fit LFGE projects" ([(0,0)-(4.17848,2.91276)],(0,0),(0.25,0.0722433),(0.5,0.6),(0.75,0.95),(1,1))	Dmnl		It is assumed that when there is only one policy the informal legitimacy is still low, but this grows rapidly once there is 2 or 3 of the policies implemented. Finally, it is expected that the effect of implementing the 4th policy is not that great anymore. This is different from the effect on formal legitimacy, as it is expected that formal legitimacy if affected in a linear way by the institutional fit.
effect knowledge on product performance	Table function	With "Knowledge development * Knowledge diffusion" ([(0,0)-(1,1)],(0,0),(0.2,0.8),(1,1))			80/20 rule used. 80% of the performance is caused by 20% of the knowledge, the last 20% of the performance is caused by the last 80% of the knowledge

Effect networks on time to develop and diffuse knowledge	Table function	With "Network formation & coordination" ([(0,0)-(1,1)],(0,1),(0.242775,0.927757),(0.67052,0.171103),(1,0.1))	Dmnl		More networks result in the knowledge development and diffusion processes being faster. S-shaped growth is assumed for the effect of networks.
Effect product performance on GoS	Table function	With "Product performance/quality" ([(0,0)-(10,10)],(0,0),(0.196532,0.0494297),(0.398844,0.100806),(0.8,1),(1,1))	Dmnl		S-shaped growth assumed.
Effect product performance on legitimacy	Table function	With "Product perforamnce/quality" ([(0,0)-(4.17848,2.91276)],(0,0),(0.25,0.0722433),(0.5,0.6),(0.75,0.95),(1,1))	Dmnl		
Efficiency waste management system	Auxiliary	0.5562	Dmnl	Yale Center for Environmental Law & Policy (2022)	Based on the controlled solid waste indicator, which indicates the percentage of waste ending up in landfills (and therefore not on the streets)
Formal legitimacy	Stock	INTEG(Change in formal legitimacy) [Initial value = 0]	Dmnl		
Gap complementary products and services	Auxiliary	Indicator complementary products and services-Complementary products and services	Dmnl		
Guidance of Search	Stock	INTEG(Development of expectations) [Initial value = 0]	Dmnl		
Indicator complementary products and services	Auxiliary	Efficiency waste management system *Development national electricity grid	Dmnl		
Informal legitimacy	Stock	INTEG(Change in informal legitimacy) [Initial value = 0]	Dmnl		

Knowledge development	Stock	INTEG(Change in knowledge development) [Initial value = 0]	Dmnl	Adapted from Walrave & Raven (2020)	
Knowledge diffusion	Stock	INTEG(Change in knowledge diffusion) [Initial value = 0]	Dmnl	Adapted from Walrave & Raven (2020)	
Network formation & coordination	Stock	INTEG(New networks) [Initial value = 0]	Dmnl		At first it is easy to form new networks because there are not a lot of different actor networks. However, since there are not a lot of different actors involved, it remains difficult to form new networks. Once the number of actors increases, it becomes increasingly easy to develop new networks, until almost all actor groups are represented. Then it is difficult again to form a new network.
New networks	Flow	(1-"Network formation & coordination")*((Saturation LFGE projects+Formal legitimacy)/2)/Time to build networks	Dmnl/Year		
Performance/quality increase	Flow	(1-"Product performance/quality")*effect knowledge on product performance/Time to increase performance	Dmnl/Year		
Product performance/quality	Stock	INTEG(Performance/quality increase) [Initial value = 0]	Dmnl		
Production system	Stock	INTEG(Production system building) [Initial value = 0]	Dmnl		

Production system building	Flow	Production system difference/Time to build elements production system	Dmnl/Year		
Production system difference	Auxiliary	Production system indicator-Production system	Dmnl		
Production system indicator	Auxiliary	IF THEN ELSE(Ratio resources invested to resources required for production system>1, 1, Ratio resources invested to resources required for production system)	Dmnl		
Proportion resources to knowledge	Auxiliary	1-Proportion domestic resources to investment	Dmnl		The other half goes to investment.
Ratio resources invested to resources required for production system	Auxiliary	IF THEN ELSE(Yearly costs LFGE projects>0, (Available funds for LFGE projects*max rate resources to be extracted)/Yearly costs LFGE projects , 1)	Dmnl		
Resource mobilisation (domestic)	Stock	INTEG(Resource mobilisation rate) [Initial value = 0]	Dmnl	Adapted from Walrave & Raven (2020)	
Resource mobilisation rate	Flow	(1-"Resource mobilisation (domestic)")*Guidance of Search/Time to translate GoS to resource mobilisation	1/Year	Walrave & Raven (2020)	
Time to build elements production system	Constant	1	Year	Assumption	
Time to build networks	Constant	1	Year	Assumption	
Time to create informal legitimacy	Constant	0.25	Year	Assumption	Assumed to be as fast as formal legitimacy creation
Time to develop expectations	Constant	0.25	Year	Walrave & Raven (2020)	

Time to develop knowledge	Auxiliary	Average time to develop knowledge * effect networks on time to develop and diffuse knowledge	Year		
Time to diffuse knowledge	Auxiliary	Average time to diffuse knowledge * effect networks on time to develop and diffuse knowledge	Year		
Time to increase performance	Constant	1	Year	Assumption	
Time to translate GoS to resource mobilisation	Constant	0.5	Year	Walrave & Raven (2020)	

E.4 Main model assumptions

As with any model, the one developed in this research relies not only on factual data but also on certain assumptions. The main assumptions are as follows:

- All TIS functions and building blocks that are modelled generally follow a S-shaped growth curve.
- No new potential projects are created during the simulation runs. The full potential of LFGE is met when all initial potential projects are converted into LFGE projects.
- Funding is not considered during the planning phase, but only was a project is pending to be installed funding will be sought. Nevertheless, economic viability is considered during the planning phase through the market formation function.
- Lobbying will eventually result in innovation-specific institutions being implemented. Additionally, lobbying is the only way to get these policies installed during a simulation run.
- The amount of waste generated and the electricity demand are constant over a simulation run.
- Larger landfills or well-performing landfills will compensate for smaller or badly performing landfills resulting in a consistent average electricity potential across all landfills.
- All landfills are large enough and managed well enough to be able to meet the average electricity potential. This means that only the larger landfills are considered and the smaller landfills in a country are not considered in the model.
- International organisations will only cover a share of the costs of LFGE projects. The larger share is covered by domestic investment.
- Domestic investment cannot cover the full costs of LFGE projects because domestic resources are divided between knowledge development and diffusion, and project funding.
- Both informal and formal legitimacy do not play a role in the formation of demand in the LFGE case as it is expected that every population wants to increase their access to electricity. As electricity distributors follow the demand of the population they serve, informal and formal legitimacy do not impact the demand.
- There is no inflation. The value of money does not change over time.
- The interest rate is very low, and therefore no discounting has to be considered.

Appendix F. Extreme conditions tests

The results of the extreme conditions tests are provided in this appendix. The conclusion drawn from these results are presented in Section 7.3.2.3.

F.1 No investment

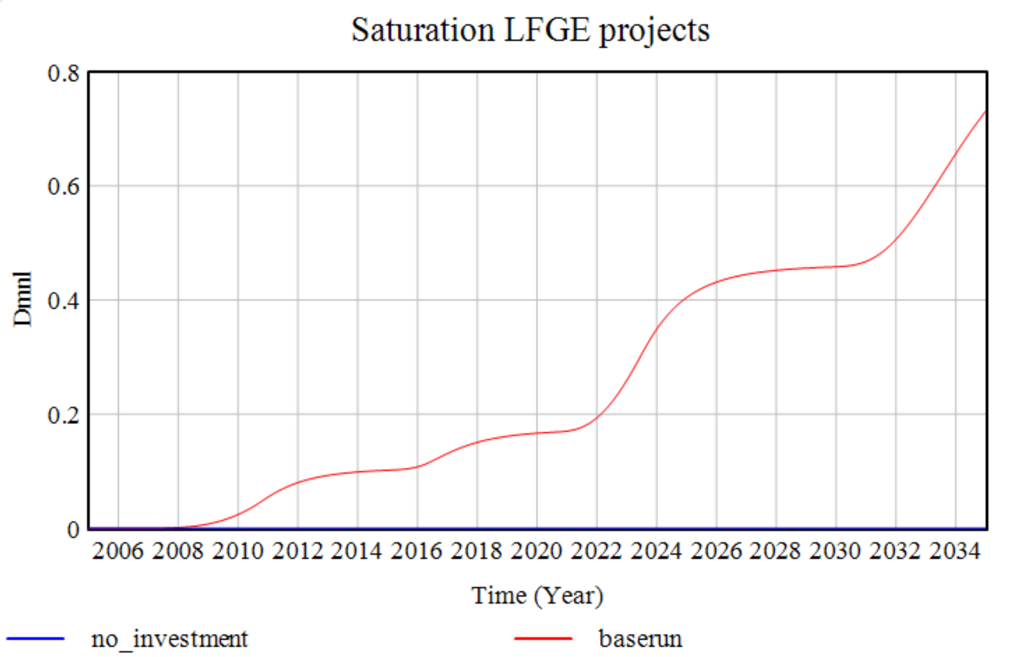

Figure 38. Extreme conditions test no investment.

F.2 Policy implementation

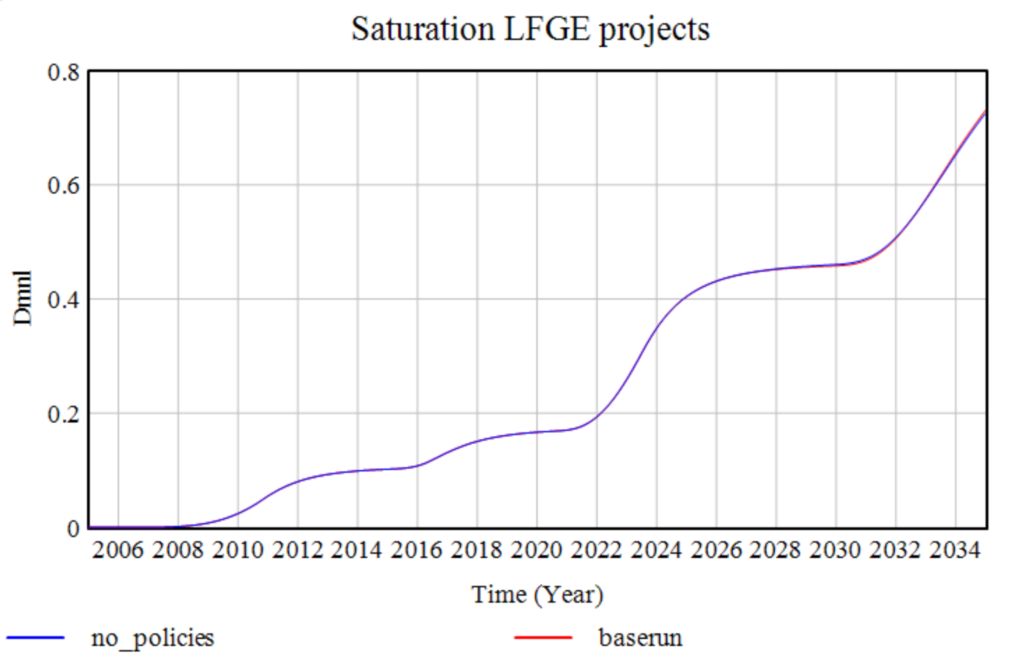

Figure 39. Extreme conditions test no policy implementation

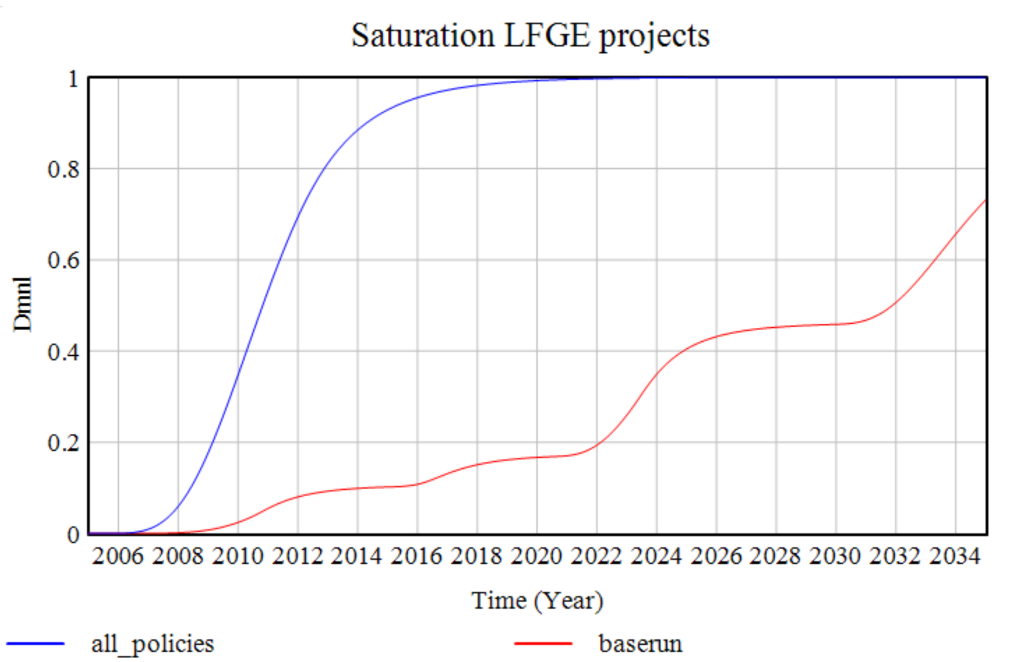

Figure 40. Extreme conditions test all policies implemented.

F.3 Costs of LFGE projects

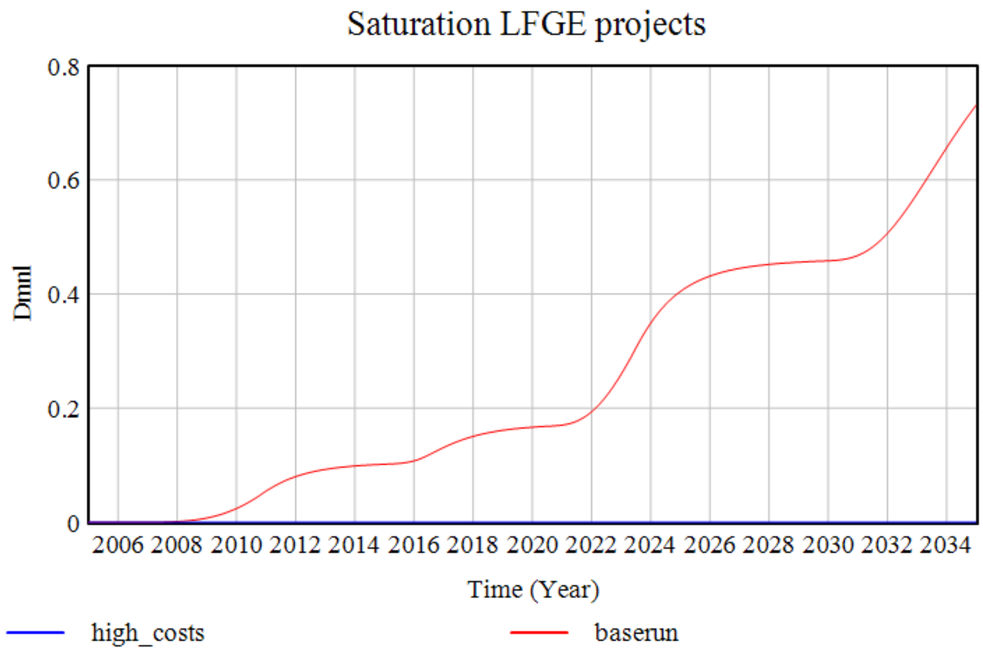

Figure 41. Effect high costs on saturation of LFGE projects.

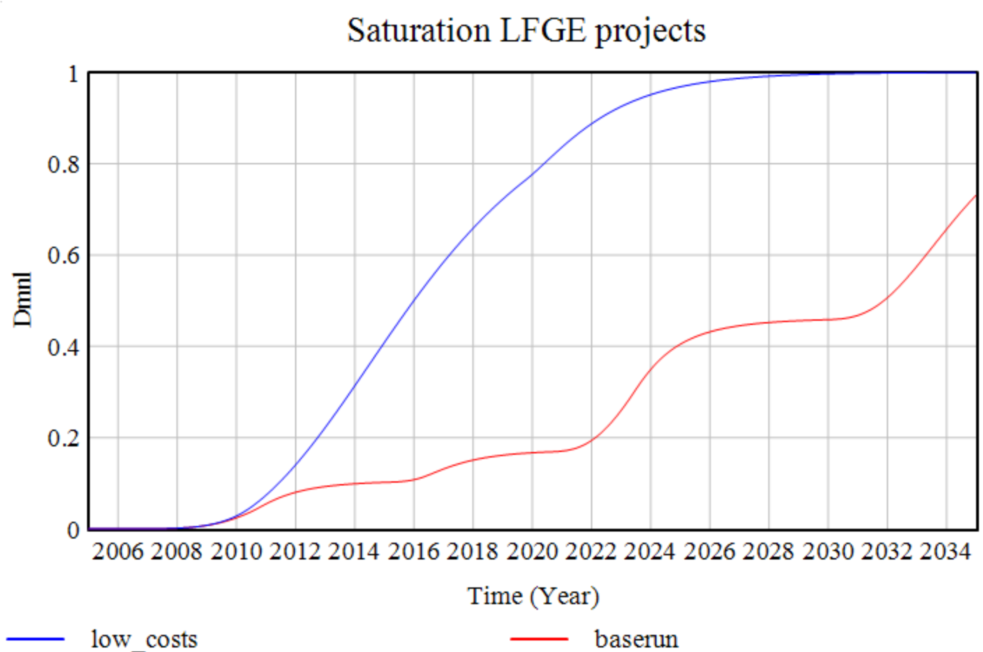

Figure 42. Effect low costs on saturation of LFGE projects.

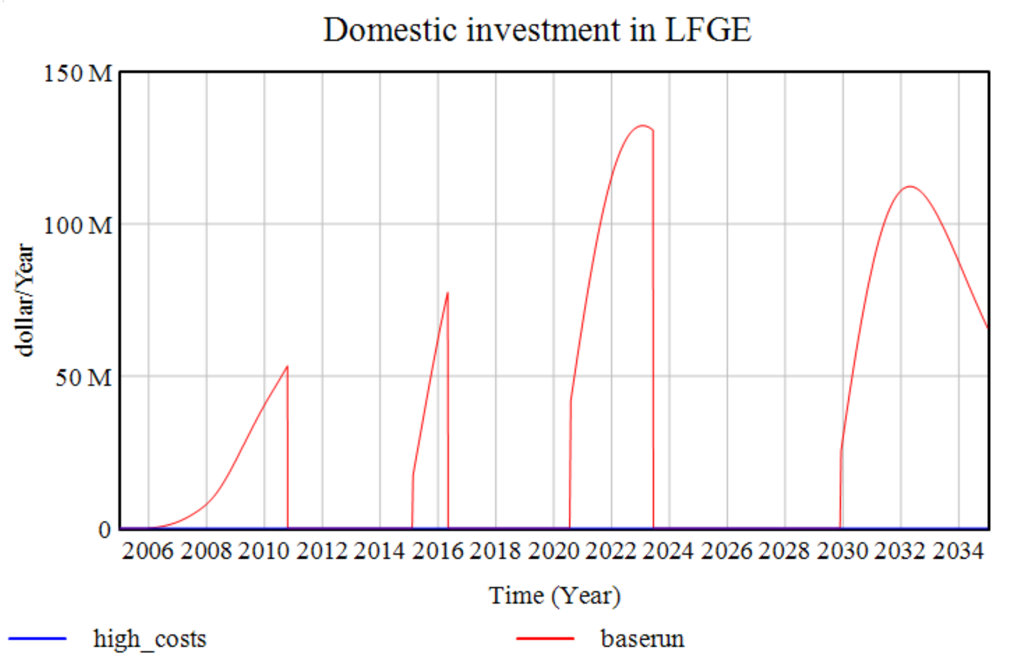

Figure 43. Effect high costs on domestic investment.

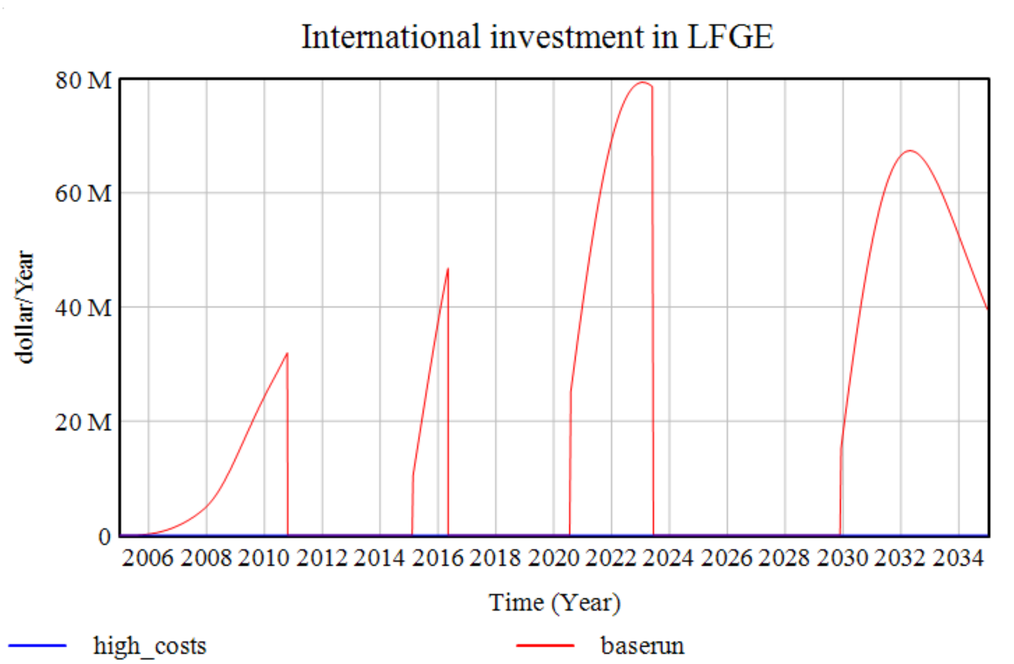

Figure 44. Effect high costs on international investment.

F.4 No electricity demand

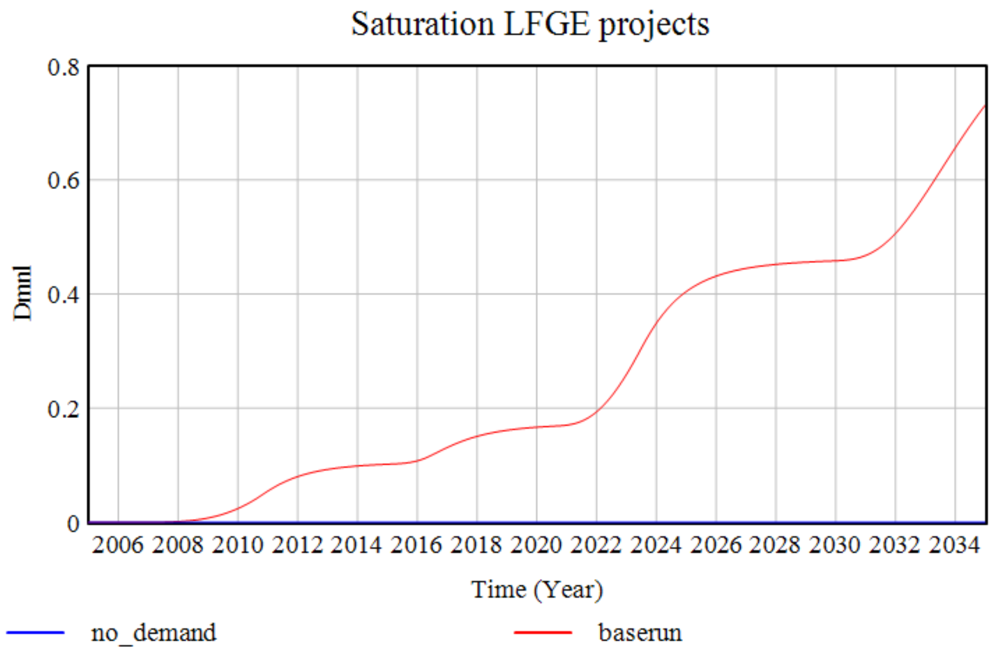

Figure 45. Extreme conditions test no electricity demand.

F.5 Waste management

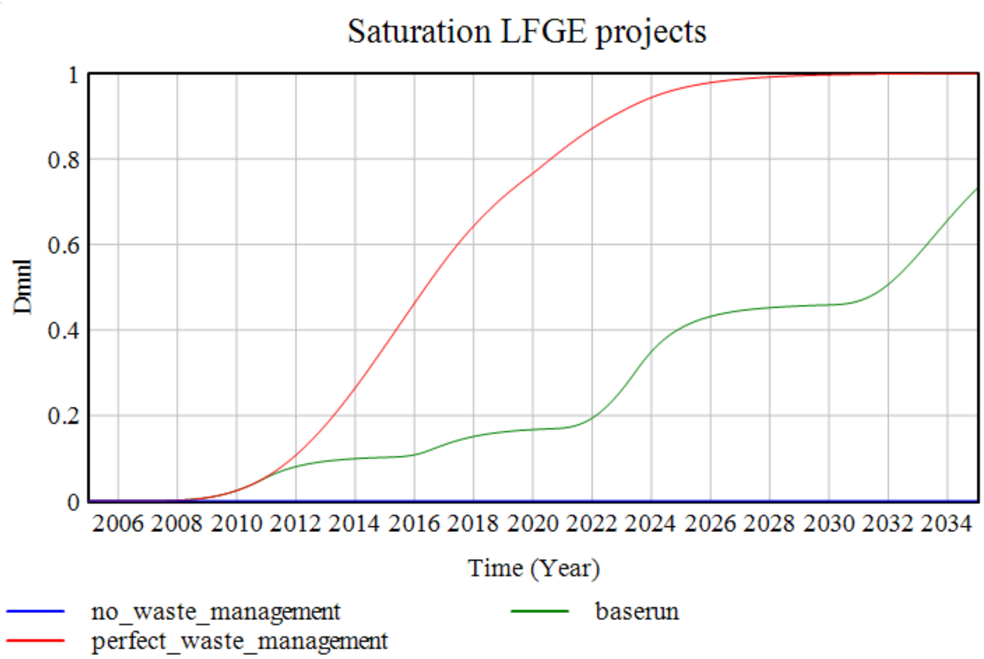

Figure 46. Extreme conditions test waste management.

Appendix G. Behavioural sensitivity test

This appendix shows the sensitivity graphs of the parameters that resulted in the model showing sensitivity.

G.1 Results univariate sensitivity tests

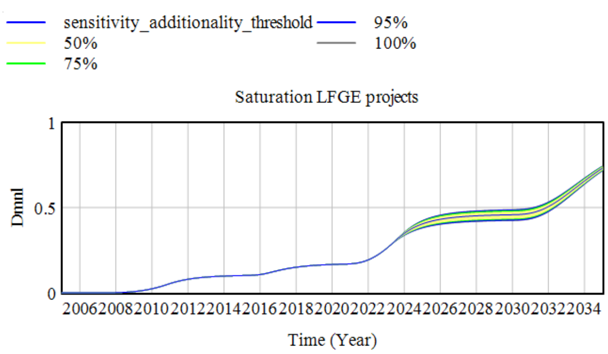

Figure 48. Sensitivity graph Average length tender process.

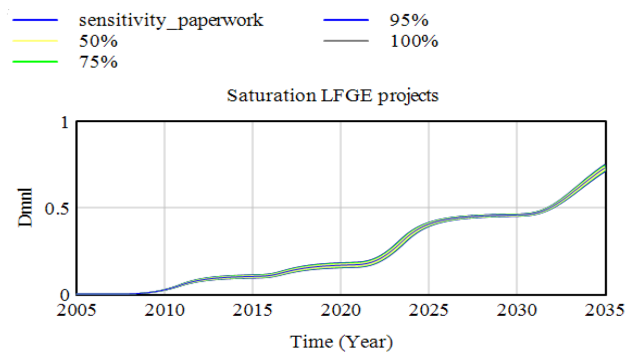

Figure 47. Sensitivity graph time to prepare paperwork before starting the project.

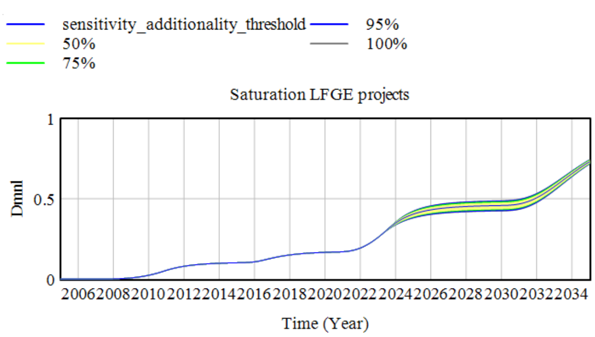

Figure 49. Sensitivity threshold additionality threshold.

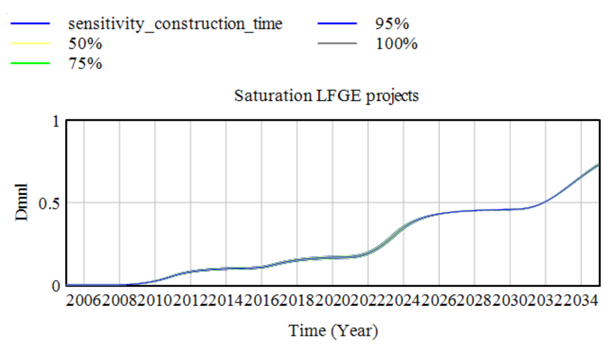

Figure 50. Sensitivity graph construction time.

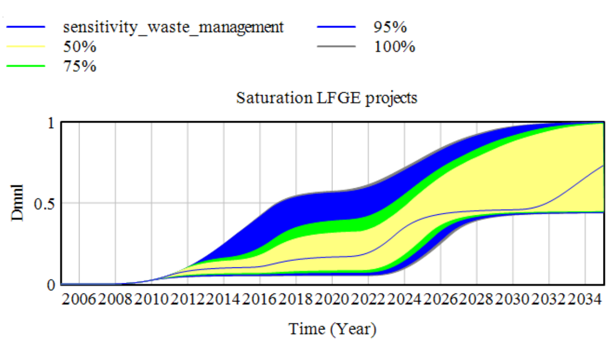

Figure 51. Sensitivity graph waste management.

G.2 Results multivariate sensitivity tests

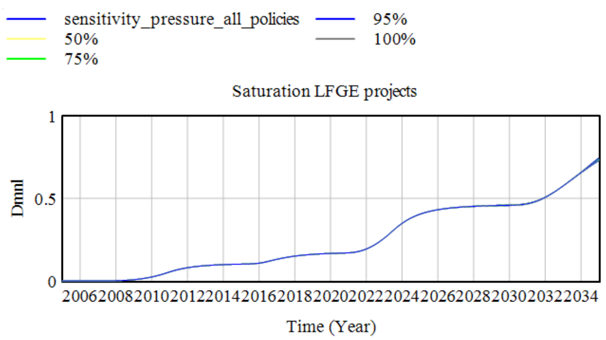

Figure 52. Sensitivity graph multivariate analysis of pressure all policies.

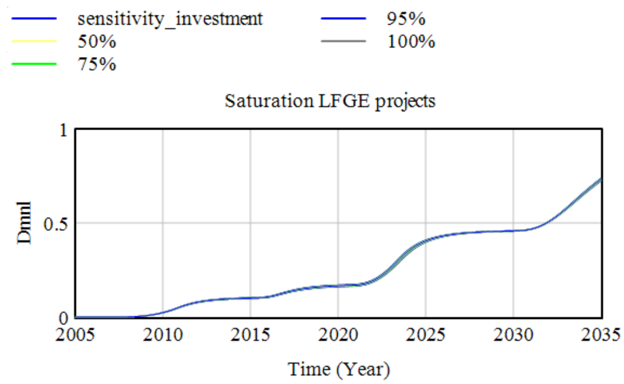

Figure 53. Sensitivity graph multivariate analysis of share domestic and international investment.

Appendix H. Experimental design

This appendix presents the experimental design employed during the model use phase. The values used in the experiments are included in Table 17 and the Figures below. In total, 41 scenarios were tested. The scenarios are shown in Table 18. Worst case values are depicted in red, while the best case values are depicted in green, and base case values are depicted in yellow. To test the effect of the carbon credit system on the diffusion of LFGE projects, not only experiments are conducted with the carbon price, but also with the additionality threshold as this variable determines the duration of the carbon revenue stream. Note that for the initial policies and the feed-in the worst case value is equal to the base case value.

Table 17. Values used in experiments.

Parameter	Unit	Worst case	Base case	Best case	Special case
Waste management	Dmnl	0.1[1]	0.5562	0.995[2]	
Grid access	Dmnl	0	0	1	
Length of tender process	Months	0	12	36	
Initial policy 1	Dmnl	0	0	1	
Initial policy 2	Dmnl	0	0	1	
Initial policy 3	Dmnl	0	0	1	
Initial feed-in tariff	$/MWh	0	0	82	60
Pressure required to implement policy 1	Dmnl	0.6	0.6	0.5	
Pressure required to implement policy 2	Dmnl	0.8	0.8	0.5	
Pressure required to implement policy 3	Dmnl	0.9	0.9	0.5	
Pressure required to implement feed-in tariff	Dmnl	0.8	0.8	0.5	
Additionality threshold	Dmnl			0.5	0.7
1. Values corresponds to Eritrea value 2. Value corresponds to Mauritius value					

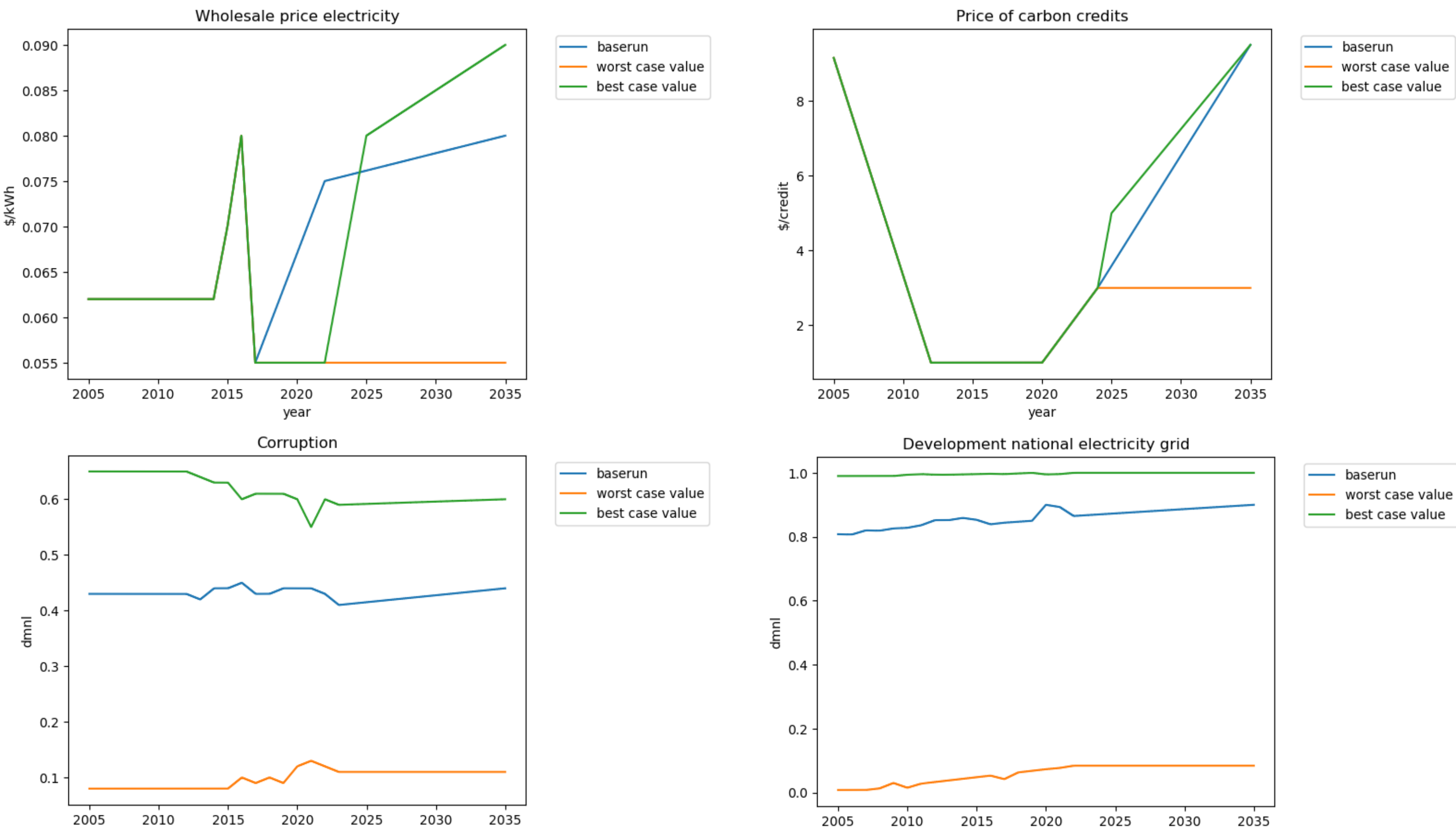

Figure 54. Input values scenarios table functions.
Upper left: Wholesale price of electricity, Upper right: Carbon credits
Lower left: Corruption, Lower right: Development national electricity grid

Table 18. Experimental design.
Worst case values are depicted in red, whereas best case values are depicted in green and base case values in yellow. Some experiments use a value that lies in between the worst case and best case, which differs from the base case. These values are depicted in blue.

S	WM system	Grid access	Length of tender process	Wholesale price ($/kWh)	Price of carbon credits	Corruption	Development national grid	P1 - Initial	P2 - Initial	P3 - Initial	Feed-in - Initial	P1 - Pressure	P2 - Pressure	P3 - Pressure	Feed-in - Pressure	Add. threshold
1	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
2	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
3	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
4	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
5	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
6	yellow	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
7	yellow	yellow	yellow	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
8	red	red	red	red	red	red	red	red	red	red	red	yellow	yellow	yellow	yellow	yellow
9	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
10	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow
11	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow
12	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow
13	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
14	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
15	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
16	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
17	yellow	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
18	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
19	green	green	green	green	green	green	green	green	green	green	green	yellow	yellow	yellow	yellow	yellow
20	green	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
21	yellow	yellow	yellow	red	yellow	yellow	yellow	green	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow
22	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow
23	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow
24	yellow	yellow	yellow	red	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
25	yellow	yellow	green	red	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
26	yellow	yellow	yellow	red	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
27	yellow	yellow	yellow	red	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
28	yellow	yellow	yellow	red	yellow	yellow	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
29	green	green	green	red	green	green	green	green	green	green	green	yellow	yellow	yellow	yellow	yellow
30	green	green	green	red	green	green	green	green	green	green	yellow	yellow	yellow	yellow	yellow	yellow
31	yellow	green	green	red	green	green	green	green	green	green	yellow	yellow	yellow	yellow	yellow	yellow
32	yellow	yellow	yellow	red	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	red
33	yellow	yellow	yellow	red	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	blue
34	yellow	yellow	yellow	red	green	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green
35	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow	yellow
36	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	yellow	yellow
37	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow	green	yellow	yellow
38	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green	yellow
39	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	blue	yellow	yellow	yellow	yellow	yellow
40	yellow	yellow	yellow	red	yellow	yellow	yellow	yellow	yellow	yellow	blue	yellow	yellow	yellow	yellow	yellow
41	yellow	yellow	yellow	red	red	yellow	yellow	yellow	yellow	yellow	blue	yellow	yellow	yellow	yellow	yellow

Appendix I. Additional model results

This appendix shows additional model results in case of a low wholesale price of electricity. Additionally, it provides figures that allows for comparison of the barriers.

Appendix I.1 Effect barriers in case of low wholesale price

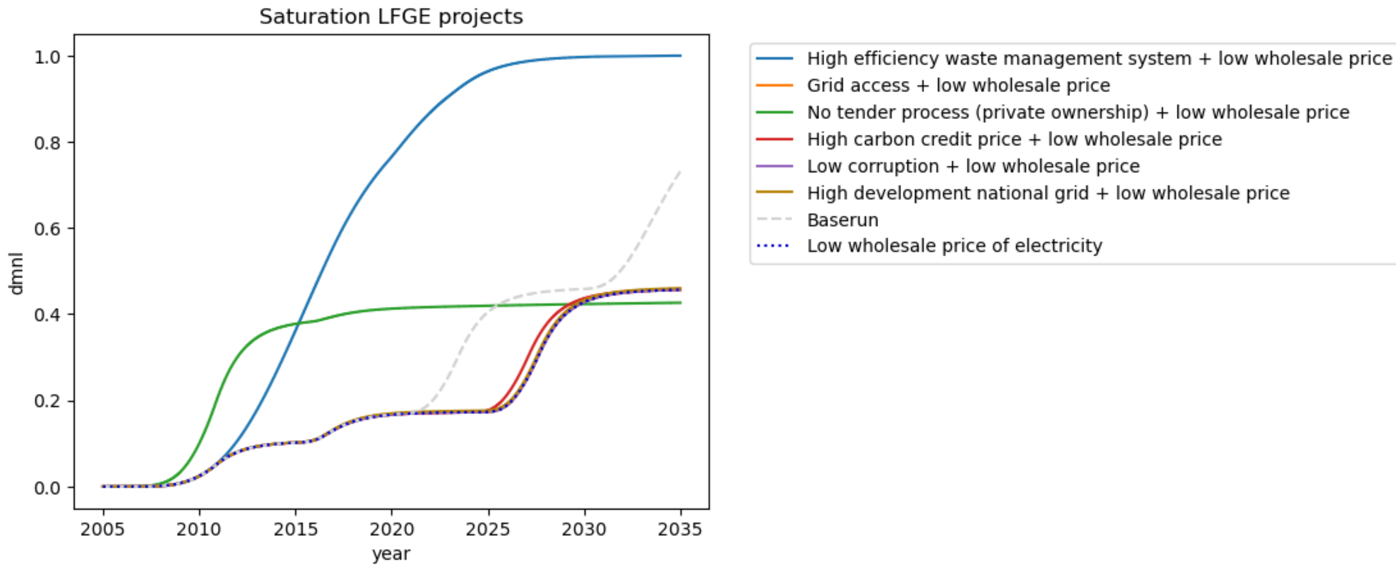

Figure 55. Effect best case barriers in case of low wholesale price.

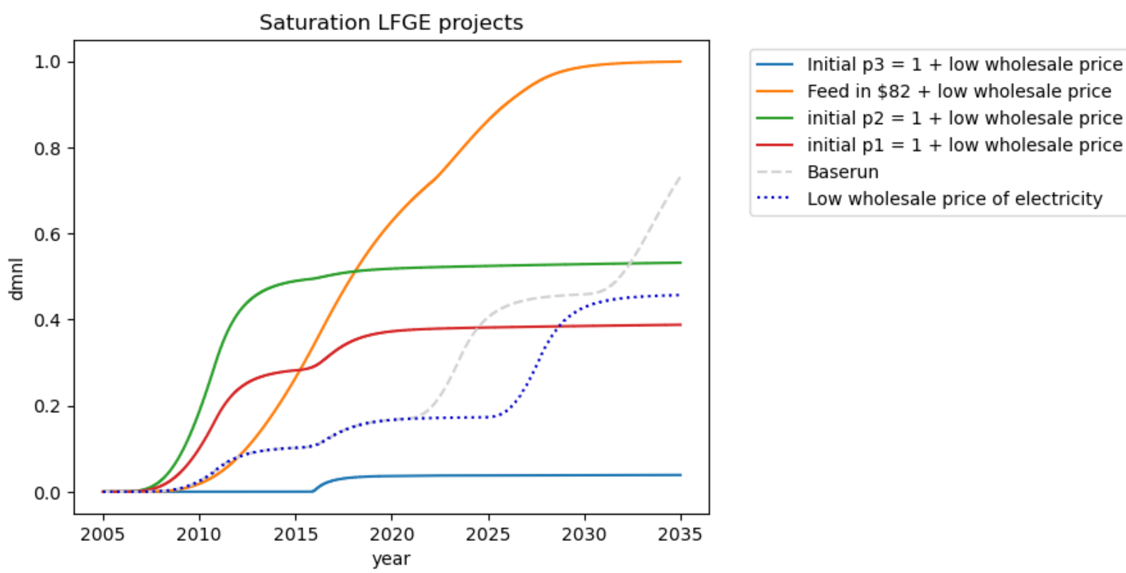

Figure 56. Effect policies in case of low wholesale price.

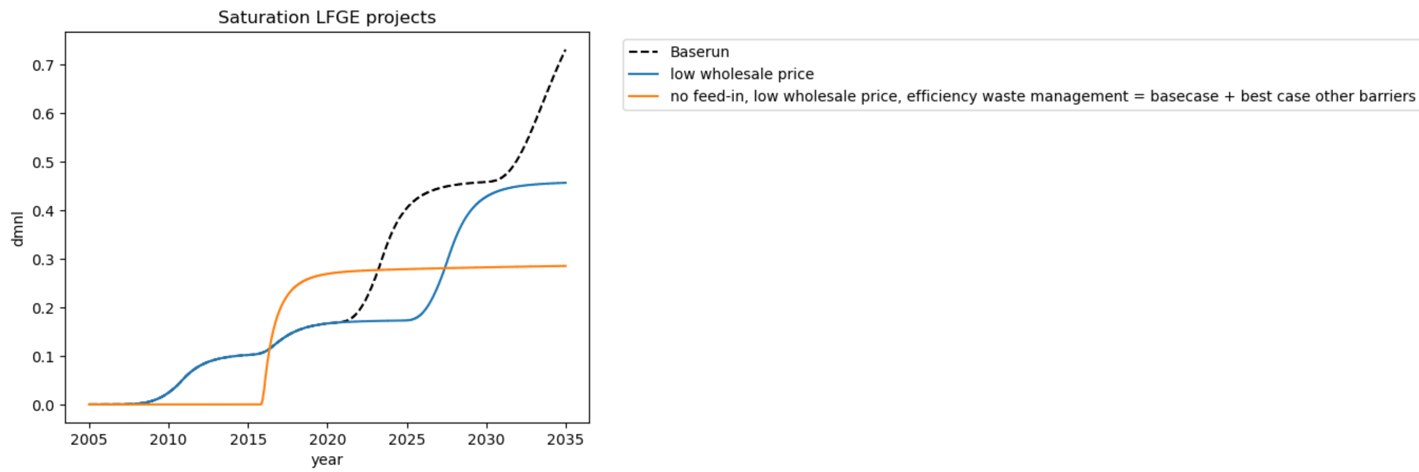

Figure 57. Effect best case barriers in case of low market price, inadequate feed-in tariff, and base case values for waste management.

Appendix I.2 Comparison barriers in base case

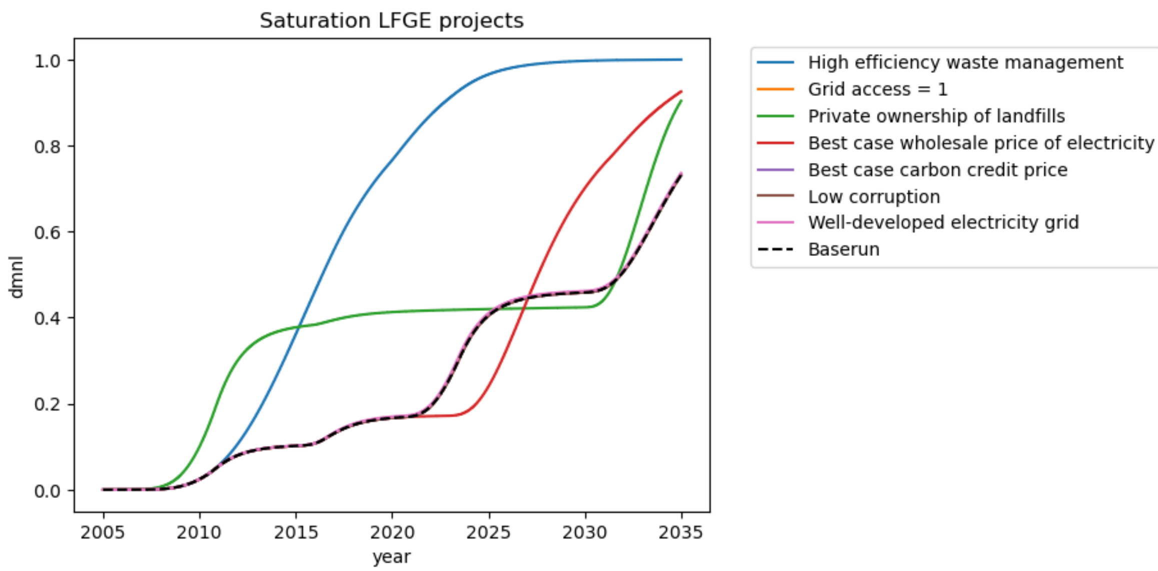

Figure 58. Best cases of barriers compared to the base case

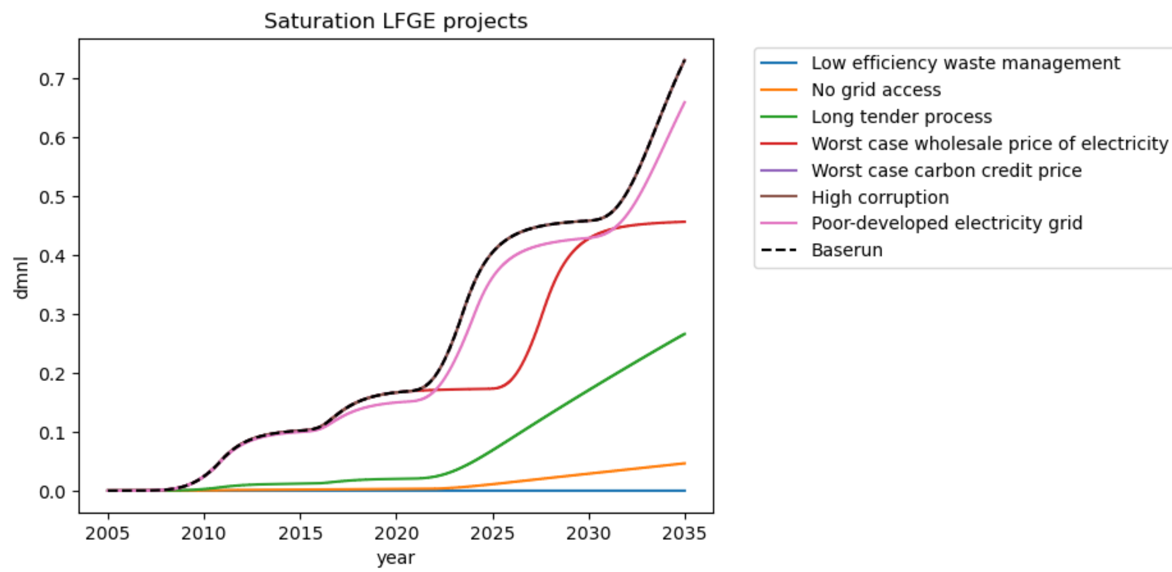

Figure 59. Worst cases barriers compared to base case.

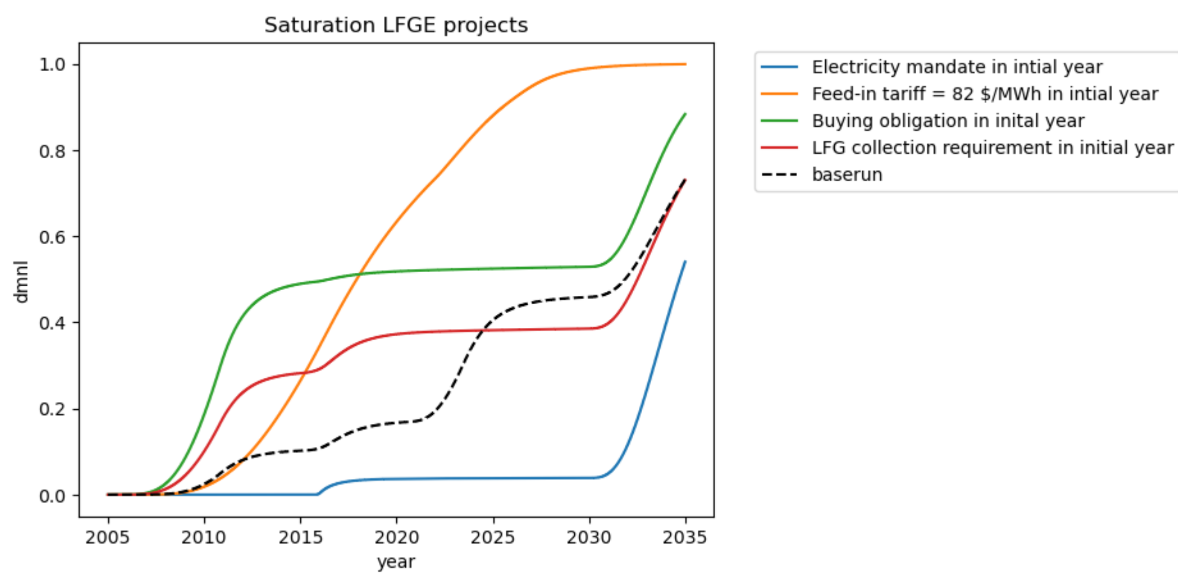

Figure 60. Best cases of policies in initial year compared to the base case.