How to measure and optimize the sustainability of complex (renewable) energy production pathways

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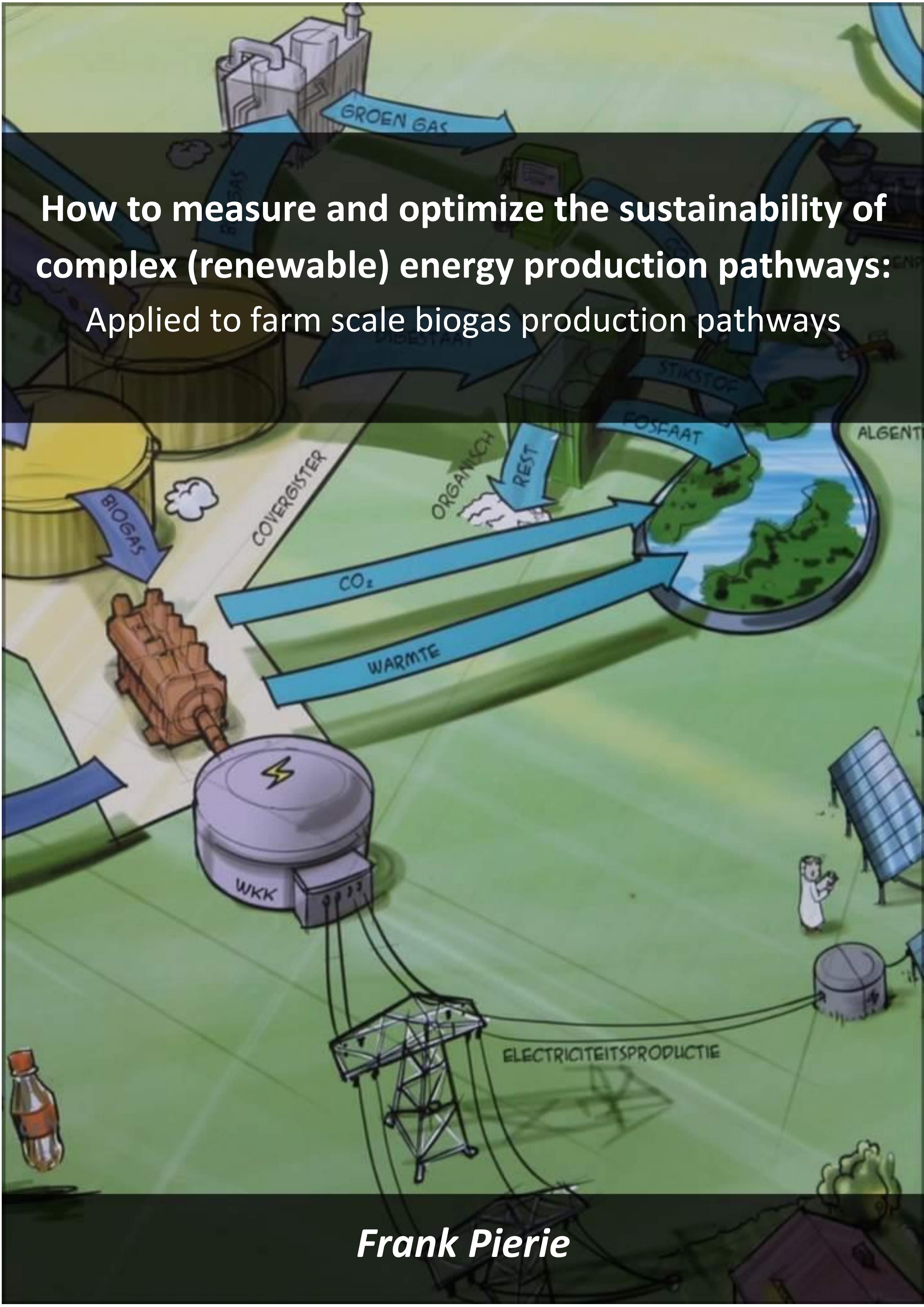
Applied to farm scale biogas production pathways



Frank Pierie

Example: Farm scale green gas production pathway, 140 Nm^3/hr green gas, Jelsum the Netherlands

Foto: HoSt Bioenergy Installations – www.host.nl

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Colophon

The research reported in this thesis was part of the Flexigas project, which was part financed by the municipality of Groningen, province of Groningen, the European Union, European Regional Development Fund, the Ministry of Economic Affairs, 'Pieken in de Delta' and the 'Samenwerkingsverband Noord Nederland', supported by Energy Valley.

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Doctoral Dissertation, University of Groningen, The Netherlands

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How to measure and optimize the sustainability of complex (renewable) energy production pathways:

Applied to farm-scale biogas production pathways

PhD thesis

to obtain the degree of PhD at the
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on the authority of the
Rector Magnificus Prof. E. Sterken
and in accordance with
the decision by the College of Deans.

This thesis will be defended in public on

Friday 5 October 2018 at 16:15 hours

By

Frank Pierie

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In Groningen

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PREFACE

Many challenges ahead

“Sustainability is not a goal, but a way of life”

“Here I stand after a long journey, which took me through every level of technical education in the Netherlands, only to see the world much clearer now. So many challenges lay ahead and hopefully sheer determination will prevail. I dedicate these achievements to my mother who is sadly not given the chance to share this moment with me and my father who supported me all these years with persistence, patience, and dedication beyond measure.”

The journey which led to this dissertation before you, started off with a strong personal belief that change is needed in the way we currently use our planet and co-exist with nature. To my personal opinion; “Sustainability is not a goal, but a way of life” and the longer we neglect this way of life the more future generations will suffer from the consequences. Within this context, and also to my personal opinion, the ones that have the opportunity, the knowledge, and the power to act also have the responsibility. This notion aforementioned, is not new and found its way into an important document in history: "But when a long train of abuses and usurpations, pursuing invariably the same Object evinces a design to reduce them under absolute Despotism, it is their right, it is their duty, to throw off such Government, and provide new Guards for their future security” (11th line 2nd paragraph US Declaration of Independence). Therefore, if we all cherish our children’s future, a full transition to non-polluting renewable and sustainable energies is needed to change our direction away from a worldwide energy and climatic crisis. Hence, we need to transcend towards a sustainable way of life. However knowing this; what is sustainability and how do you measure this? For, if we not know the direction we are supposed to be heading, how will we ever get there?

Additionally, we “the ones that have the opportunity, the knowledge, and the power to act“, also need to help the public to understand the problems we are facing and to judge the solutions which can help in solving these problems. As “The energy transition requires not only the generation of quantitative data but also the generation of visual imagination”. To do so, we must communicate! Not only with piles of paper in the shape of reports and articles, but also through lectures, discussion, examples, clarifications and any other method necessary to get this important message across. We must bring clear and correct information to the public for them to make the right decisions. Within this context I suggest to also read the comic “Farmer Frank” ending this thesis (see page 173).

My journey (PhD research) started (in July 2011) within the Flexigas project, which was facilitated by the Hanze University of Applied Sciences, with the main focus of my research on analyzing and optimizing the sustainability of farm-scale anaerobic digestion biogas installations. Within the Flexigas project, I was able to collaborate together with professional partners who helped me shape the ideas and research contained within the dissertation before you. Therefore, my thanks goes out to the Hanze University of Applied Sciences and the Flexigas project for giving me the time, space, and above all trust to follow the pursuit aforementioned. I will not try to name all involved during my PhD which gave me support feedback and new ideas, this, also to avoid the shame of forgetting someone. Instead I would like to focus on a few that had a profound impact on my research throughout my PhD. Starting with Prof. Henk Moll, who firstly pointed out this opportunity for a PhD. He guided me with patience and gave me the space needed to shape my own research. Under his wing I was able to develop my skills required for finalizing my PhD. As a second supervisor Dr. Rene Benders was always willing to help, his time, effort, and support “often behind the scenes” was invaluable for my progress. Students also had a profound impact on my research and in Christian van Someren I found a very professional and dedicated intern who helped me shape the base of my research. Dr. Jan Bekkering, together with Evert Jan Hengeveld, helped me to get started in the Flexigas project and in the field of biogas. Jan’s research shaped the foundation of my own research. Finally, Wim van Gemert provided me with inspiration on almost any renewable topic including biogas. Discussions with Wim, and also with Henk Moll, always helped me see the bigger picture regarding energy transition. Most importantly, I would like to thank my family and loved ones for the support needed outside of my promotion. Sometimes the most trivial things can give inspiration, alleviate stress, and give you the will to move forward when you yourself are at a standstill.

With sincerity,

Frank Pierie

“Our most basic common link is that we all inhabit this planet. We all breathe the same air. We all cherish our children's future. And we are all mortal” (John F. Kennedy).

AND

“Anyone who believes in indefinite growth in anything physical, on a physically finite planet, is either mad or an economist.”(Kenneth E. Boulding).

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LIST OF ABREVIATIONS

REPP	Renewable Energy Production Pathway
AD	Anaerobic digestion
CHP	Combined Heat and Power
oDM	Organic Dry Matter
FM	Fresh matter
MJ	Mega Joule (10^6 Joule)
GJ	Giga Joule (10^9 Joule)
TJ	Tera Joule (10^{12} Joule)
PJ	Peta Joule (10^{15} Joule)
kW	kiloWatt (10^3 Joule/second)
kWth	kiloWatt thermal (10^3 Joule/second)
kWe	kiloWatt electric (10^3 Joule/second)
MW	kiloWatt (10^6 Joule/second)
kWh	kiloWatt hour ($3.6*10^6$ Joule)
Mg	Mega gram (equivalent to metric tonne)
Tg	Tera gram (10^6 Mg)
PED	Primary Energy Demand
Nm^3	Normal cubic meter
[P]EROI	Process Energy Returned On Invested
GHG	Green House Gasses
GWP100	Global Warming Potential 100 year scale
$kgCO_2eq$	Kilograms of Carbon dioxide equivalent
Pt	Environmental impact in EcoPoint
LCI	Life Cycle Inventory
LCA	Life Cycle Analysis
aLCA	Attributed Life Cycle Analysis
cLCA	Consequential Life Cycle Analysis
MFA	Material Flow Analysis
MEFA	Material and Energy Flow Analysis

EBS	(Excel) Biogas Simulator
V&V	Verification and Validation
SI	Sustainable Indicator
NPV	Net Present Value
OPEX	Operational Expenses
CAPEX	Capital Expenses
NLS	Net Load Signal
NLDC	Net Load Demand Curve
EU	European Union
PESTEL	Political, Economic, Social, Technical, Environmental, and Legal

Chapter 1
INTRODUCTION

Optimizing the sustainability of complex, renewable energy production pathways, applied to farm-scale biogas production pathways

ABSTRACT

To avoid energy scarcity as well as climate change, a transition towards a sustainable society must be initiated. Within this context, governmental bodies and/or companies often note sustainability as an end goal, for instance as a green circular economy. However, if sustainability cannot be clearly defined as an end goal or measured uniformly and transparently, then the direction and progress towards this goal can only be roughly followed. A clear understanding of and a transparent, uniform measuring technique for sustainability are hence required for sustainable and circular (renewable) energy production pathways (REPPs), as society is asking for an integrated and understandable overview of the decision-making and planning process towards a future sustainable energy system. Therefore, within this dissertation, a new approach is proposed for measuring and optimizing the sustainability of REPPs; it is useful for the analysis, comparison, and optimization of REPP systems on all elements of sustainability. The new approach is applied and tested on a case based on farm-scale, anaerobic digestion (AD), biogas production pathways.

1.1. The need for a transition towards sustainable energy production

To avoid energy scarcity as well as climate change, substitutes for fossil energies are needed in the future. As fossils become less abundant, they are increasingly more difficult to mine, they become more expensive, and/or the effect of consumption becomes too disruptive to our way of life. However, the reality is that we live in an unsustainable, linear economy dominated by fossil energy, which will most likely not change in the foreseeable future [1]. Fossil sources currently (in 2016) account for over 81% of all energy used in the world [1], (Fig. 1.1). Also, energy demand worldwide is increasing extensively, and our main sources of energy are depleting rapidly. For every barrel of conventional oil being discovered, three are being consumed [2]. Furthermore, alternative fossil energy sources (e.g. shale oil, shale gas, and tar sands) are being implemented faster than renewables [1, 3, 4]. The International Energy Agency (IEA) is predicting a future scenario where fossils will still dominate the energy market by 60% in the most positive to 79% in the business-as-usual scenario for the year 2040 [1]. This would result in, amongst other things, additional greenhouse gas (GHG) emissions, which are key drivers of climate change.

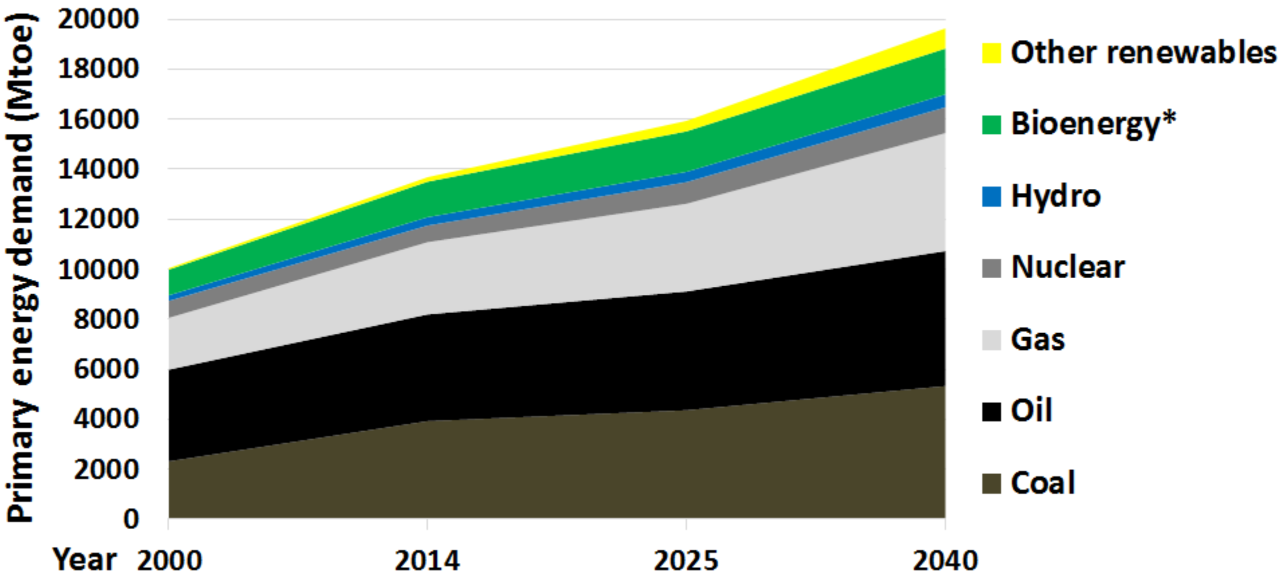

Fig. 1.1. Global energy demand by primal source [5]

* Includes the traditional use of biomass and the modern use of bioenergy.

1.1.1. Climate change as a key driver of change towards sustainable energy production

The facts that climate change is affecting the planet and that human activity is strongly affecting climate change have long been accepted within the scientific community [6, 7]. Every unit of fossil fuel consumed creates a net GHG increase, potentially adding to global warming, destabilizing natural processes, and endangering the earth's carrying capacity for advanced forms of life [8-10]. Many negative effects all over the planet have been linked to climate change, based on scientific research [10]. In Fig. 1.2, changes to the planet's ecosystems and the confidence of the link with climate change are indicated on a global map. Therefore, within the newly formed Paris agreement, focus is being placed on, inter alia, the following: **a long-term temperature goal (Art. 2)** of limiting global temperature increase to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees; **global peaking (Art. 4)** to reach global peaking of GHG emissions as soon as possible; and **sinks and reservoirs (Art. 5)** to conserve and enhance, as appropriate, the sinks and reservoirs of GHGs [11]. In line with the Paris agreement, the focus within the European Union (EU) has shifted toward, amongst other things, a circular economy [12, 13] and an energy transition towards renewable technologies [14-16], which together can be indicated as a green circular economy [15, 17]. Traditional economic systems are mostly designed in an open ended manner, with a low tendency to recycle [18]. The linear throughput flow model within traditional economics has dominated the overall development, causing serious environmental harm [13], whereas within a green circular economy, emphasis is placed on product, component, and material reuse; remanufacturing; refurbishment; repair; cascading and upgrading; as well as renewable energy utilization throughout the product value chain and cradle-to-cradle life cycle [12, 13, 19].

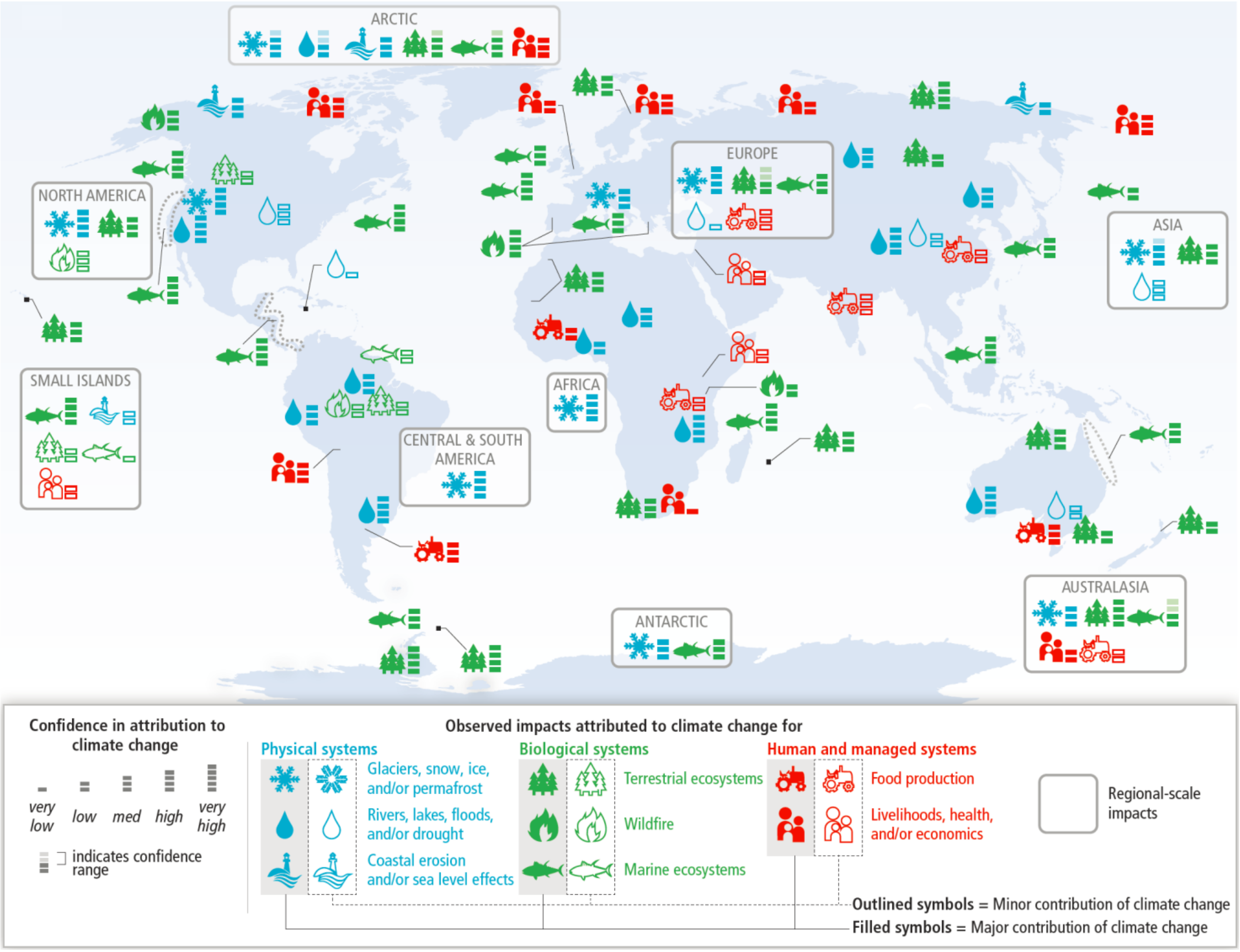

Fig. 1.2. Widespread impacts attributed to climate change based on the availability of scientific literature (since AR4) [10]

1.2. Definition of sustainability used within this dissertation

The green circular economy is often seen as a (fully) sustainable economy; however, this is not always the case. Sustainability is a difficult concept that contains many scopes and factors. In literature, definitions of sustainability are abundant and widespread. The Brundtland report provides the most popular notion of sustainability, namely "development that meets the needs of the present without compromising the ability of future generations to meet their needs" [20, 21]. Within the aforementioned concept, sustainability is introduced as a balance between the present and future needs regarding quality of life. After the Brundtland definition, a division formed into two directions: the so-called weak sustainability, which incorporates continued economic growth focused on the needs of humanity, and the so-called strong sustainability, which focuses on preserving nature and establishing balance [21]. A particular direction within the concept of strong sustainability is the triple-bottom line [22], which explains a hierarchal order wherein environmental quality (Planet) precedes social prosperity (People) and then economic prosperity (Profit) [22]. Without a functioning life support system, societies cannot thrive; without social structures and institutions, economies cannot flourish [21]. The foundation of life is essentially the ecological structure that surrounds us and the natural resources on the earth; to damage this in

CHAPTER 1: Introduction

any way, shape, or form will cause damage to the world's carrying capacity for a thriving future society and economy. Additional elements of sustainability are indicated in the PESTEL framework. *"The PESTEL framework primarily concerns six factors: political, economic, social, technical, environmental, and legal. As a structured way to organize environmental factors, PESTEL is used to analyze and map how the external environment influences an industry"* [23]. Within the aforementioned context, it can be argued that sustainability is a balance between the many stakes involved, some more important than others, summated in the triple bottom line concept by Elkington 1997, [22], and PESTEL.

1.3. Energy production pathways (EPPs) and renewable EPPs (REPPs)

Energy production pathways (EEPs) are a collection of physical processes with the end goal of producing energy for consumers, for instance in the form of electricity, heat, or chemical energy (e.g. gas or gasoline). These EPPs include all the steps needed, from mining and transport to conversion, in order to supply energy to the end consumer. Most EPPs are currently powered by fossil energy sources (e.g. coal, oil, and gas). In the future, these pathways will need to be replaced by EPPs using renewable energy sources (e.g. wind, solar, or biomass) to transform them into Renewable Energy Production Pathways or REPPs.

1.4. Introduction to the case used for the new approach

The role of natural gas within the Netherlands is currently being reviewed and scrutinized, as it has negative impacts on the location where it is extracted (e.g. province of Groningen) [24]. Additionally, natural gas is also a fossil resource that releases GHGs when combusted and will ultimately be depleted. Dependency on natural gas within the Netherlands is unfortunately high, as natural gas accounted for around 38% of the total energy use for the year 2016, with 24% used in industry and heating and 14% for electricity production. Demand for natural gas can be substituted through the use of renewable electricity production and electric heating systems (e.g. heat pumps and direct electric heating) or by reducing energy demand and increasing efficiency. However, a substantial demand for gas will remain in both industry and heat demand that cannot be fulfilled by other means [25, 26]. Within this context, biogas produced by anaerobic digestion (AD) can play an important role as a renewable and flexible energy carrier that is storable and which can be transformed into electricity or heat or upgraded to green gas (biogas upgraded to natural gas quality) [27]. Anaerobic digestion has been successfully implemented in the treatment of several biomass feedstocks, and it is already established as a reliable technology in Europe [28]. However, questions are being raised regarding the sustainability of AD biogas production and the availability of biomass fueling the system.

1.4.1. The choice for farm-scale AD

Within the Netherlands, a "Green deal" has been accepted, where the production of green gas is projected to increase from 0.1 billion Nm^3 (3.5 PJ) in the year 2016 to 3 billion Nm^3 (105 PJ) in the year 2030, replacing around 8% of the current natural gas use of 40 billion Nm^3/a (1404 PJ) [29]. Additionally, within the renewable energy goals of the Netherlands, a target of 40 PJ of locally produced bio-energy is included (e.g. biomass, green gas, and combined heat and power [CHP]) for the year 2020 [30]. However, with the intended increase of green gas production, the need for feedstocks will most likely increase as a result. The majority of the additional supply is expected to come from agricultural land, amongst other areas [31]. Therefore, questions can be raised regarding the achievability, efficiency, and sustainability of the biogas production pathway when utilizing large volumes of energy feedstocks and transporting them over longer distances. Furthermore, the increase in biomass demand can claim valuable arable land for cultivation [31] and/or affect biodiversity [32], thereby also raising the widespread debate regarding the use of food-quality biomass for energy production [33]. Within the aforementioned context, focus could be placed on alternative feedstocks that do not have other applications except as energy sources and that are locally available. However, biomass waste flows are often of a lower quality and quantity, and they are dispersed in availability (e.g. manure, harvest remains, and roadside or natural grass). When using local biomass availability, a decentralized production approach using smaller farm-scale installations might thus be preferable. Therefore, within this research, focus is placed on farm-scale biogas production using AD in an attempt to integrate the use of local biomass waste flows and renewable energy production within the farming process. In this regard, to aid in the achievement of the goals set in the Paris agreement, the following are important: gaining insight into the optimal use of the AD biogas production pathway and reducing environmental impacts on all elements.

1.4.2. Using the new approach for analyzing AD

To assess the sustainability of decentralized biogas production, the newly designed method for measuring the sustainability of REPPs will be applied to the renewable technology of farm-scale AD biogas production within the Netherlands, as part of the Flexigas project [34]. Within this research, the whole process from biomass through (co)digestion to biogas is referred to as *"the biogas production pathway"* (Fig. 1.3). A biogas production pathway is a complex REPP where the triple bottom line and green circular economy concepts intertwine, as the biogas production pathway contains a combination of energy, material, money flows (e.g. energy electricity, heat and gas, feedstocks, and green fertilizers), transport, and technical installations. A biogas production pathway hence contains most elements that influence sustainability, making it well suited for testing methods to measure and optimize sustainability.

1.4.3. Introduction to AD

Anaerobic digestion, a process by which microorganisms break down biodegradable material in the absence of oxygen, was applied for the first time in the treatment of wastewater. In 1881, a Frenchman named Mouras invented a crude version of a septic tank, which he named the "automatic scavenger" [35]. This concept was later improved by an Englishman, Cameron, in 1895. Then, in 1897, the local government of Exeter approved the treatment of the entire city's wastewater by septic tanks. Additionally, Cameron recognized the value of biogas, primarily a mix of methane and carbon dioxide, which was generated during sludge decomposition in the septic tanks, and some of the biogas was used for heating and lighting purposes at the disposal works [35]. Later on, the AD process was optimized for use in wastewater treatment, resulting in the systems we have today. In and around the 21st century, AD was rediscovered as a renewable source of biogas, produced on farms, amongst other places, using manure and co-substrates (e.g. maize and grass), (Fig. 1.3). Biogas can be seen as a *"flexible energy carrier"* that can be either stored in tanks, transformed into heat and electricity, or upgraded to higher-quality green gas and injected into the national gas grid [27]. Green gas is biogas that has been upgraded to natural gas quality. The digestion of biomass also leaves a residual material after biogas is extracted, called digestate, which can be used as fertilizer on agricultural land, if certified by the government, thereby reusing the nutrients in the digestate. This brings us back to the present, where renewable energy is gaining increasing attention as scientists keep stressing the importance of the energy transition. My research is part of this dialog, focusing on the sustainability of the farm-scale AD of biological materials.

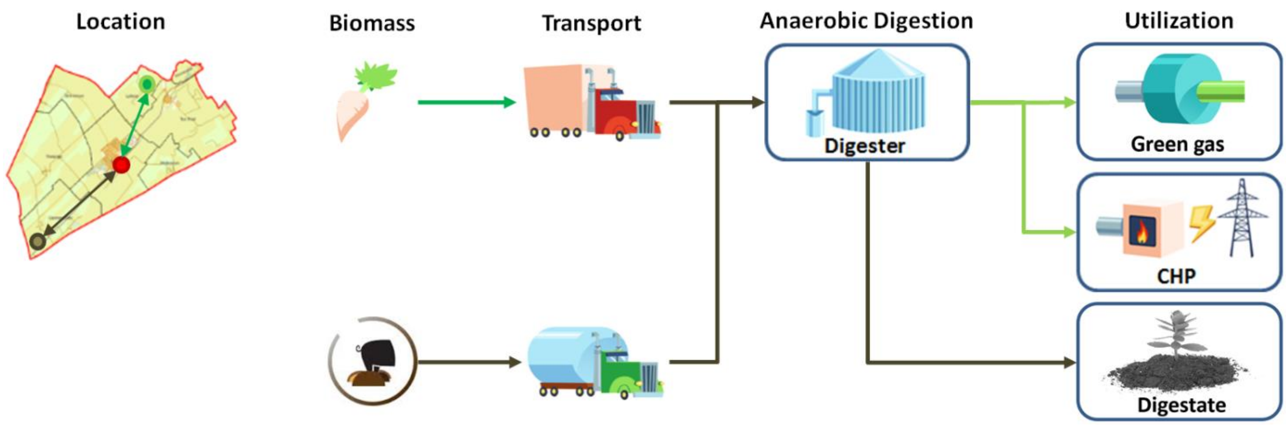

Fig. 1.3. Main components of the farm-scale biogas production pathway

1.5. Research problem

Governmental bodies and/or companies also often note sustainability as an end goal, for instance as a green circular economy. However, if sustainability cannot be clearly defined as an end goal or measured uniformly and transparently, then the direction and progress towards this goal can only be roughly followed [36]. The aforementioned circular economy concept is loosely based on a collection of ideas derived from other scientific fields (e.g. industrial ecology, industrial ecosystems, and industrial symbioses) [13]; therefore, it is lacking in a clear goal, focus, or methodology. Furthermore, when implementing the green circular economy (including renewable technologies), focus is often placed on single issue regulation (e.g. green energy production) and single technology integration (e.g. solar PV or wind), thereby losing focus on the broader picture (e.g. triple bottom line), with a high chance that "single factor" manipulation could result in a cumulative, negative overall gain regarding sustainability. Within this context, REPPs can be implemented for replacing fossils to lower resource depletion; however, another goal of reducing environmental impact (e.g. pollution and GHG emission reduction) might not be achieved. Per definition, renewable refers to the energy resource and not the process of extracting and refining the energy from this resource. The overall process of extracting energy from a renewable resource still often requires fossil input, which will have an impact on the environment and hence on the sustainability of the process. Also, other factors can influence the overall sustainability of a renewable resource; these can include the materials used, the production processes involved, and the (energy) system within which it is integrated [37]. Therefore, a clear understanding of and a transparent, uniform measuring technique for sustainability is required to be able to clearly indicate and communicate the goal and progress towards this goal. However, achieving the aforementioned will require a deep understanding of the different elements of sustainability, a transparent overview of the energy and material flows within a REPP, and a clear indication or expression of sustainability. Both frameworks (Elkington and PESTEL) indicate the presence of multiple main elements (or stakeholders) within sustainability; however, they do not quantify them for comparison, nor do they demand a clear method and structure for defining sustainability. Additionally, a clear understanding of the energy and material flows can also initiate transition from an open-ended economic system towards a circular one, where energy and material flows are reused, recycled, and/or upgraded (e.g. using industrial metabolism or the circular economy concept).

Main question:

How to measure and optimize the sustainability of complex (renewable) Energy Production Pathways; focused on farm-scale AD biogas production pathways?

1.6. Designing a new approach for measuring the sustainability of a REPP

Measuring the sustainability of a REPP can become the starting point for an optimization process, where renewable systems become more sustainable within the concept of the circular economy and according to both the triple bottom line and PESTEL. Therefore, in this dissertation, a method is described for measuring, expressing, and optimizing the sustainability of REPPs. The new approach is constructed from a synthesis of literature and practical information, which integrates physical, economic, and social indicators of sustainability into one set of comprehensive and comparable expressions (e.g. people, planet, profit, balance, and space), (Fig 1.4). This dissertation focuses on four main steps: design, planet, space, and profit (explained further in Section 1.6). Additionally, suggestions are made for three additional steps in the conclusion chapter.

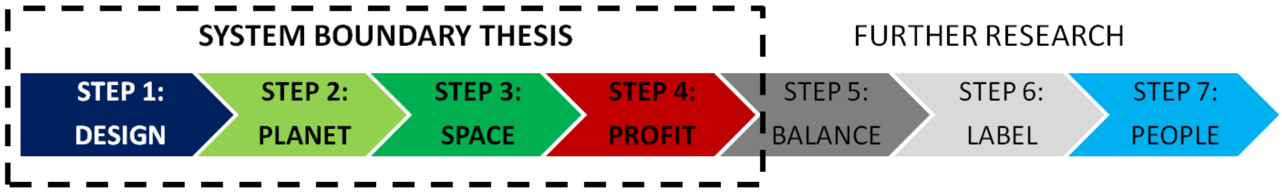

Fig. 1.4. Steps in measuring the sustainability of a REPP

1.6.1. The methods used within the new approach

Step in approach (Fig. 1.4)	Methods used
STEP 1: DESIGN Chapters 2, 3, and 4	Literature review on current methods for measuring sustainability of biogas production; creation of methodology (new approach) for optimizing farm-scale AD biogas production; construction and validation of a mathematical model for optimizing AD biogas production pathway in excel (Excel Biogas Simulator [EBS] model), based on the following methods: material and energy flow analysis (MEFA) and attributed life cycle analysis (aLCA).
STEP 2: PLANET Chapter 5	Literature review on the sustainability of AD biogas production, focused on a farm-scale process and multiple feedstocks; MEFA; aLCA; and mathematical modeling using the EBS model.
STEP 3: SPACE Chapter 6	Literature review on the availability of biomass waste feedstocks in the northern part of the Netherlands, MEFA, aLCA, and mathematical modeling using the EBS model.
STEP 4: PROFIT Chapter 7	Literature review on the economic costs of farm-scale AD biogas production and waste flow optimization, MEFA, aLCA, mathematical modeling (using the EBS model), and net present value (NPV) calculation.

1.7. Thesis structure

This dissertation discusses a new approach for determining the sustainability of a farm-scale AD biogas production pathway; this new approach can be used for generating and identifying sustainable solutions and for the optimization of REPPs. Overall, a new method for measuring sustainability is devised, conceptualized, modeled, validated, and applied to the renewable technology of farm-scale biogas production through the use of AD. The new approach consists of four main steps (Fig. 1.4 and 1.5), which are explained in this thesis, and a suggestion for three additional steps is explained in the conclusion.

Chapter 2 will discuss **STEP 1 DESIGN** in measuring the sustainability of a REPP (Fig. 1.5), using the published paper, “A new approach for measuring the environmental sustainability of renewable energy production systems: Focused on the modeling of green gas production pathways.” Within this chapter, the focus will be on the methodology and design of the REPP

Chapter 3 will describe the mathematical model used to calculate steps 2, 3, and 4 (PLANET, SPACE, and PROFIT), using part of the following conference proceeding: “The Development, Validation and Initial Results of an Integrated Model for Determining the Environmental Sustainability of Biogas Production Pathways”.

Chapter 4 will describe the integrated approach used for the validation of the EBS, using part of the following conference proceeding: “The Development, Validation and Initial Results of an Integrated Model for Determining the Environmental Sustainability of Biogas Production Pathways”.

Chapter 5 will discuss **STEP 2 PLANET** in measuring the sustainability of a REPP (Fig. 1.5), using the published paper, "Environmental and energy system analysis of bio-methane production pathways: A comparison between feedstocks and process optimizations."

Chapter 6 will discuss **STEP 3 SPACE** in measuring the sustainability of a REPP (Fig. 1.5), using the published paper, "Lessons from spatial and environmental assessment of energy potentials for Anaerobic digestion production systems applied to the Netherlands."

Chapter 7 will discuss **STEP 4 PROFIT** in measuring the sustainability of a REPP (Fig. 1.5), using the published paper, "Increasing sustainable farming practices through the use of anaerobic digestion and biomass processing."

In **Chapter 8**, the performed research within this dissertation will be culminated and concluded in an improved approach for designing, measuring, and optimizing the overall sustainability of renewable energy production systems. Furthermore, the results from this dissertation will be reflected.

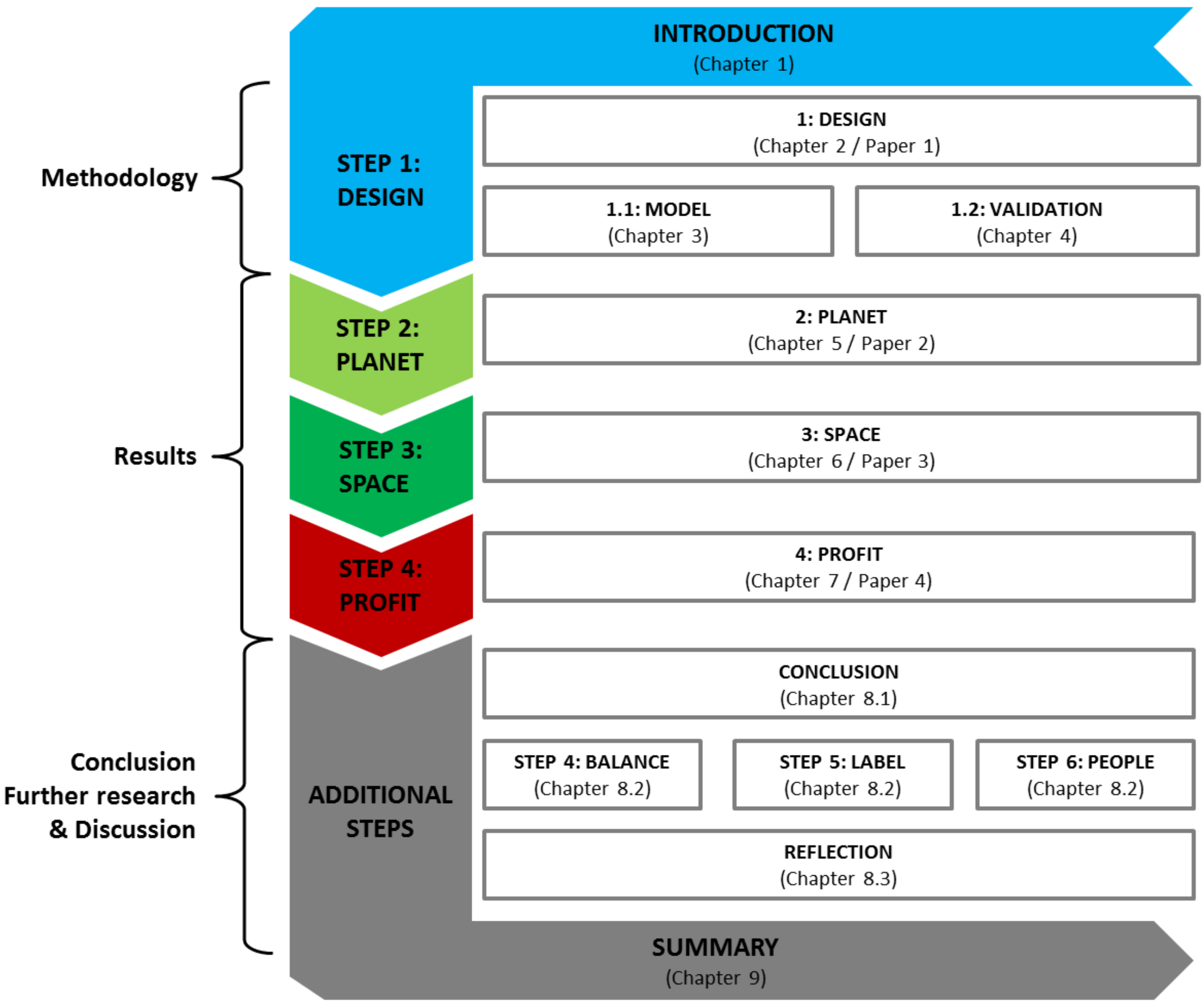

Fig. 1.5. Thesis structure with position of chapters used for creating the new approach and applying it to the case

Chapter 2
DESIGN: METHODOLOGY

A new approach for measuring the environmental sustainability of renewable energy production systems: focused on the modeling of green gas production pathways

ABSTRACT

A transparent and comparable understanding of the energy efficiency, carbon footprint, and environmental impacts of renewable resources are required in the decision making and planning process towards a more sustainable energy system. Therefore, a new approach is proposed for measuring the environmental sustainability of anaerobic digestion green gas production pathways. The approach is based on the industrial metabolism concept, and is expanded with three known methods. First, the Material Flow Analysis method is used to simulate the decentralized energy system. Second, the Material and Energy Flow Analysis method is used to determine the direct energy and material requirements. Finally, Life Cycle Analysis is used to calculate the indirect material and energy requirements, including the embodied energy of the components and required maintenance. Complexity will be handled through a modular approach, which allows for the simplification of the green gas production pathway while also allowing for easy modification in order to determine the environmental impacts for specific conditions and scenarios. Temporal dynamics will be introduced in the approach through the use of hourly intervals and yearly scenarios. The environmental sustainability of green gas production is expressed in (Process) Energy Returned on Energy Invested, Carbon Footprint, and EcoPoints. The proposed approach within this article can be used for generating and identifying sustainable solutions. By demanding a clear and structured material and energy flow analysis of the production pathway and clear expression for energy efficiency and environmental sustainability the analysis or model can become more transparent and therefore easier to interpret and compare. Hence, a clear ruler and measuring technique can aid in the decision making and planning process towards a more sustainable energy system.

Additional information chapter

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2.1. Introduction

The main benefits associated with renewable energy, for instance biogas production through anaerobic digestion, are the reduction of greenhouse gas emissions, environmental impact, and the use of fossil resources. Within this context, renewable resources are often seen as (fully) sustainable resources, which is not always the case. Per definition, renewable is referring to the energy resource and not the process of extracting and refining the energy from this resource. Often, the overall process of extracting energy from a renewable resource still requires fossil input, which will have an impact on the environment and therefore on the sustainability of the process. Also other factors can influence the overall environmental sustainability of a renewable resource, which can include materials used, the production processes involved, and the energy system it is integrated within [37]. Within this article when discussion sustainability, environmental sustainability is meant. The assessment of sustainability, regarding energy systems or renewable resources, has been applied within political decision making processes [38-40]. Within the literature aforementioned, sustainability is often only roughly measured giving more of an approximation in combination with other factors, which include economic and social indicators. However, the understanding of the efficiency, carbon footprint, and environmental impacts of renewable resources are required in the decision making and planning process towards a more sustainable energy system. To achieve this, sustainability must be accurately and reliably measurable and comparable [41]. Sustainability is a complex concept to quantify, containing many aspects that need to be meticulously measured in order to achieve accurate results. Within this context, a physical method for measuring sustainability appears to be the most scientifically accurate as it analysis physical energy and material flows [42].

Within current literature, the sustainability of biogas production pathways is often analyzed through the use of energy analysis and Life Cycle Assessment (LCA). Depending on the study, the focus can be on several feedstocks and biogas production pathways, variable transport distances, the biogas production process itself, and different end uses of biogas. Energy analysis studies identify and quantify all the energy and material inputs (e.g. cultivation, transport, processing) and outputs (e.g. biogas, green gas, electricity, heat) in a product's life cycle [27]. Results of these studies indicate either: Energy Input to Output Ratio [27]; Primary Energy Demand (PED) per functional unit [42]; or Primary Energy Input to Output Ratio (PEIO) [43]. The focus of the LCA approach lies in the analysis of environmental impacts of a product, a process, or a system [42]. Attributional LCA is applicable for understanding the environmental impacts directly associated with the life-cycle of a product using average data for each unit process. A consequential LCA approach seeks to describe the consequences of a decision taking marginal data for analysis [44]. Within LCA studies, results are given in a wide range of impact categories (e.g. climate change, ozone depletion, agricultural land occupation, etc.), which can add up to over twenty indicators or more [45, 46]. In measuring the environmental sustainability of biogas production systems the amount and types of indicators differ between studies, ranging from on average five [41, 42, 47-50], to ten [51, 52], up to eighteen [44, 46]. However, differences in methodological approaches and assumptions can have an effect on the final LCA results. A potential weakness of LCA is the large amount of data involved, the availability of that data, and the resource and time intensities of LCA [45]. Studies also tend to focus on specific fields within the biogas production pathway, e.g.

feedstocks, specific biogas technologies or specific biogas end uses [51]. This high level of detail and wide variability in both scope and indicators makes the interpretation and comparison of the various results difficult [51]. Also, the literature aforementioned often focuses on general average scenarios, providing low flexibility to design a specific biogas production pathway fitting a unique geographic location with dispersed availability of biomass and energy demand [53-55]. Furthermore, temporal influences (e.g. energy demand, intermittent renewable production, decentralized load balancing) from energy systems surrounding the biogas production pathway can also influence overall sustainability [37, 55, 56].

Within this context, what is lacking is a systematic method for generating and identifying sustainable solutions [57-59]. The transition towards renewable energy requires a clear and understandable insight into the environmental consequences of producing renewable energy [41, 58]. Therefore, measuring the sustainability of green gas production pathways will require an integrated systematic method, which addresses energy and LCA analysis, temporal dynamics and geographic diversity, and complexity. Furthermore, the results will need to be expressed in clear indicators. Overall, the understanding and accurate measurement of the environmental impacts of green gas production pathways are required to help the European Union in achieving the renewable energy and emission reduction goals, described in the EU energy directive and the EU roadmap 2050 [16, 60]. Therefore, we address this issue as part of the Flexigas project [34]. Within this article an integrated systematic method for determining the sustainability of a biogas or green gas production pathway is discussed, which can be used for generating and identifying sustainable solutions for energy production pathways. The approach offers; a structured approach during the analysis; a clear structure and transparent Life Cycle Inventory; a way for handling temporal dynamics; a clear functional unit and indicators for expressing the results; and comparability between analyses made. By demanding a clear and structured material and energy flow analysis of the production pathway and clear expression for energy efficiency and sustainability the analysis or model can become more transparent and therefore easier to interpret and compare. Within this article: First, the main rules of the new approach are described, creating a guideline for performing the analysis. Second, three clear and understandable units used to express sustainability and efficiency are discussed. The article is finalized in the discussion and conclusion wherein the integrated approach will be reflected upon.

2.2. The approach

The approach is constructed from a synthesis of literature and practical information. For the refinement of the approach a specific green gas production pathway is taken as an example. This pathway consists of the feedstocks manure, maize or grass, and anaerobic digestion in a small scale digester located on a farm which injects the biogas as upgraded green gas into the national gas grid as described in Bekkering et al. [61], (Fig. 2.1). Green gas is upgraded biogas to gas grid quality. A modular approach, where the pathway is divided in smaller parts, and Material and Energy Flow Analysis (MEFA) was used to shed light on the structure of green gas production pathways in order to accurately model them [62]. The new approach is built around the metabolism concept, defined by Ayres in 1988 as “the whole integrated collection of physical processes that convert raw materials and energy flows into a finished product” [63]. The concept indicates the presence of individual physical processes and different resource flows ranging from raw material and energy. The industrial metabolism concept will be expanded with new and existing methodologies to handle complexities, introduce temporal dynamics, account and quantify direct and indirect energy and material flows (including the embodied energy of the installations and maintenance). The system boundary for the energy and environmental system analysis should include all physical and identifiable flows needed to produce green gas. Within this section the modular approach is discussed first, after which the temporal dynamics are described, and finally, the structure of a single physical process is discussed which includes accounting the direct, indirect, and embodied energy and material flows.

2.2.1. The modular approach

The green gas production pathway is defined as a collective of physical processes working together to achieve a common goal (e.g. biogas or green gas production). These individual physical processes are called sub-modules and are assigned to groups that perform the same physical process called modules (Fig. 2.1). The green gas production pathways will be built up out of a succession of sub-modules in logical order forming a chain which, for instance, could result in the production pathway depicted in Fig. 2.1. Every sub-module in a module group can be interchanged with other sub-modules from the same module group. For example, transporting manure can be conducted both by tractor or tanker-truck according to Fig. 2.1; in this case transport is the module and tractor or truck transport are the sub-modules. The aforementioned approach will allow several arrangements of sub-modules to form different production pathways.

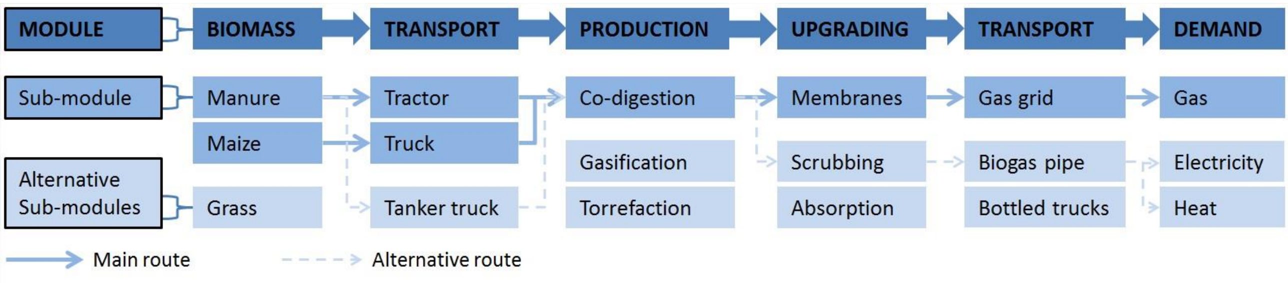

Fig. 2.1. The main modules and sub-modules used in an example green gas production pathway

In this line of reasoning standardization is very important, as all the sub-modules must first operate with the same units (e.g. distance (m), mass (kg) [64]), and also be placed correctly within the production pathway. If used correctly, the modular approach can help solve the problem indicated by Berglund, Börjesson stating that: “From a system analysis perspective, production systems for biogas are complex to study. The number of possible biogas systems is large due to the variety of available raw materials, digestion technologies and fields of application for the digestate and biogas produced” [27]. However, the diversity will depend on the database of sub-modules, which will need to be expanded in further literature research or by using case specific data. Overall, the modular approach can be used to design the optimum production pathway to suite particular cases, by changing, adding or removing individual sub-modules during the modeling (or planning) process.

2.2.2. Temporal dynamics

Green gas production pathways can encounter several temporal dynamic interactions which can influence sustainability. There are three main groups of dynamics with a temporal nature identified within the integrated approach; internal dynamic influences, within the green gas production pathway; external dynamic influences, originating in the energy system surrounding the Green gas production pathway; and long term dynamics which include technical and social change. For example:

1) Internal dynamics: Green gas production is dependent on current and future availability of biomass, which is not readily available at all locations, nor at arbitrary quality or quantity. Furthermore, the production of biogas from the anaerobic digestion process is based on complicated organic kinetics, which is susceptible to dynamic variability [65]. For example, changes in feed type, feed quantity and quality, feed timing, temperature and the process (e.g. mixing) can influence the overall biogas production of the digester over time. Also, during storage biomass can deteriorate over time.

2) External dynamics: When operating within an energy system green gas production pathways will encounter external dynamic variations in the shape of hourly fluctuations in energy demand. There are also seasonal fluctuations seen on a yearly basis, depending on the local influence of natural light and the outside temperature [66, 67]. Besides the variation in demand, there is also the likelihood of intermittent energy production. The most common intermittent sources are wind and solar PV, which both operate on weather patterns with hourly and seasonal fluctuations [37]. For example, fluctuations in demand or production can influence the output demand of the digester.

3) Long term dynamics: The technical lifetime of a green gas production pathway varies between twenty and thirty years exposing it to long-term dynamics which include technological change, improved efficiency, and social change. Over a longer time period demand for energy or prices of fossil energy sources may fluctuate [68] and the transition towards renewable energy production could increase the amount of intermittent production present in the decentralized smart energy system [16, 60].

Within the new approach dynamics are integrated through the use of hourly time intervals over a simulated year. One simulation will be the summation of hourly intervals over the course of one year. The use of hourly intervals and yearly scenarios will allow the use of different timescales: First, the short time scale will focus on an hourly basis; second, the mid time scale of one year will introduce seasonal variability; and finally, multiple scenarios of one year can be performed to include a longer timeframe. Overall, the aforementioned dynamic variability occurring during the lifetime of the green gas production pathway can be incorporated within the approach. During a simulation variables or flows can be altered per hourly interval through the use of time dependent variables. One year of hourly time-dependent variables will create a yearly dynamic pattern. Two types of patterns can be used, relative patterns and absolute patterns. A relative pattern indicates the percentage of the maximum flow available at every interval ranging between 0% and 100%. For instance, during the interval when cows are in the stable 100% of the manure produced is available for the digester, but during the interval when cows are grazing on the field 0% of the manure is available. The relative pattern can be placed directly after a fixed variable or flow to make it act dynamically. An absolute pattern indicates the actual value per interval (e.g. temperature, wind speed), which can be integrated in the formula calculating the variable or flow. The new approach is designed such that every variable or dataset within the model can be modelled with relative or absolute patterns.

2.2.3. The sub-module

Within each sub-module, one main physical process of the green gas production pathway is described (Fig. 2.1). Every sub-module will be capable of determining three environmental impact indicators; the efficiency in (Process) Energy Return on Investment or [P]EROI; the Carbon Footprint in Global Warming Potential 100 year scale or GWP100; and the Environmental impact in EcoPoints (these impact indicator will be discussed further in section 2.3). The summation of impact indicators from the sub-modules used in the scenario will determine the total efficiency and environmental impact of the green gas production pathway. To determine the aforementioned factors, each sub-module is separated into four levels; level one, the primary (mass) flow level (e.g. Biomass, biogas, digestate); level two, the direct energy and material level (e.g. electricity, heat, diesel); level three, the indirect energy and material level (e.g. production of electricity); and level four, the embodied energy level (e.g. production of the needed machinery). Each level will perform its own calculations (Fig. 2.2), level one and level two will be determined through the use of the MEFA methodology (explained in section 2.2.3.1 and 2.2.3.2), where level three and four will use the aLCA methodology (explained in section 2.2.3.3 and 2.2.3.4). Additionally, the first three levels in the sub-module will be linked together functioning as a cascade. Level one will deliver the input, through primary functional flows, for level two; and level two will provide input, through direct functional flows, for level three. This will allow dynamics in the higher level to influence the following levels, hence, transmitting the dynamic element downstream. Level four will work independently. In the following sections (2.2.3.1 to 2.2.3.4) the four levels in the sub-module will be discussed more explicitly using the structure depicted in Fig. 2.2.

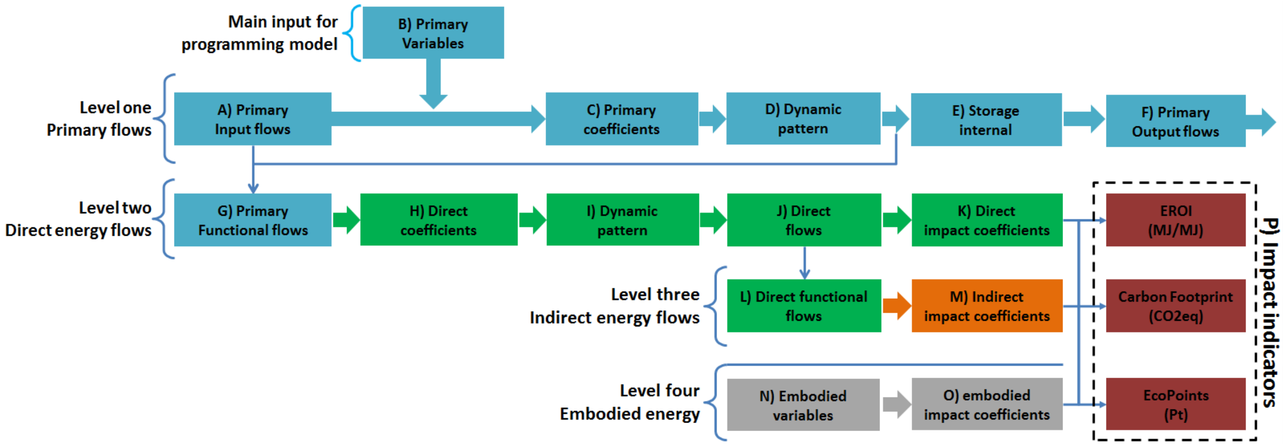

Fig. 2.2. Structure of a single sub-module based on dynamic MFA / MEFA / LCA

2.2.3.1. Level one: Primary flows

Within the metabolism concept primary mass flows are defined as raw materials (e.g., biomass, biogas, digestate and/or losses of the previous flows), which run through the green gas production pathway. The primary mass flows which run through a single sub-module are identified and quantified through the use of the Material Flow Analysis method (MFA), which is part of the overall Material and Energy Flow Analysis method (MEFA) [69], defined by Haberl and Weisz as:

> *"A physical environmental accounting approach that tracks the use of materials, reporting the flows in physical units of mass per time index and can conceptually be linked to economic accounting frameworks. This approach is ideally suited for accounting and quantifying material requirements and waste/emissions of production systems and can be used in comparative studies, given appropriate standardization. MFA can be applied to various scales and types of systems. Overall, the MEFA framework is an integrated toolkit to account for physical flows associated to socio-economic activities [62]."*

The MEFA framework is used for determining the primary flows and the direct energy and material flows described in section 2.2.3.2. Within this section the integration of the MFA method, which transform the primary input flows into the primary output flows is discussed (the letters in Fig. 2.2 coincide with the letters in the explanation).

A) Primary input flows: The primary flows entering each sub-module are determined by the primary output of previous sub-modules. For example, manure generated in a stable will become a primary input in a transport sub-module (Fig. 2.1).

B) Primary variables: Primary variables can be used to change the process conditions, for instance by changing the transport distance in the transport sub-module or the hydraulic retention time in the digester sub-module etc. Additionally, for sub-modules situated at the beginning of the green gas production pathway, the primary input is replaced with primary variables. For instance, within the manure sub-module a primary variable is used to indicate the number of cows in the stable, which is then used to determine the primary output (e.g. manure) given the correct data.

C) Primary coefficients: The transformation of the main input flows into the main output flows is calculated through the use of primary coefficients, which are given in units of output flow per unit of primary input flow or primary variable. Examples of primary coefficients include, manure production per cow or biogas production per unit of manure (Table 2.1). The coefficients used in the (entire) sub-module can be used effectively in combination with dynamic values and can be easily adapted or modified.

Table 2.1. Example of primary coefficients; biogas potential of manure per kg oDM

Biogas potential manure	Nm^3/Mg oDM	Source
Biogas potential	300.00	[61]
Methane content (CH_4)	180.00	[61]
Nitrogen (N_2)	6.00	[70]
Oxygen (O_2)	3.00	[70]
Ammonia (NH_3)	0.30	[70]
Hydrogen sulfide (H_2S)	0.03	[70]
Carbon dioxide (CO_2) (Remainder)	110.67	[70]

D) Dynamic pattern: Through the use of dynamic patterns the primary flows can be altered per time interval. Changing the primary flows can be achieved by using a relative or absolute pattern, as described in section 2.2.2. For instance, when the cows are outside manure production from the stable is 0%, when all cows are in the stable manure production is at 100%.

E) Storage: In almost every temporal dynamic system, some form of storage is included. Two types of storage will be integrated in the approach: internal storage which represents the buffers already present in many sub-modules (e.g. biogas storage in the top of the digester); and external storage or separate structures identified as an individual sub-module (e.g. maize storage in trench silos). Storage will be limited by the capacity of the storage sub-module. If surpassing the maximum capacity the flow entering the buffer must be redirected or discarded, for instance by adding storage capacity or flaring of surplus biogas production. Buffers are capable of absorbing dynamics in the green gas production pathway, stabilizing the system and changing the primary output of a sub-module, making them vital parts in highly dynamic systems.

F) Primary outputs flows: The output flows are the result of the aforementioned factors, which represent the physical process taking place in the sub-module. There are two main output flows, primary output flows and losses of the previous. For instance, the primary output flow (e.g. biogas) is calculated by multiplying the primary flow (e.g. manure) with the primary coefficients (e.g. biogas potential, Table 2.1) and the dynamic pattern if present. The main output flow (biogas) will continue through the green gas production pathway as a primary input in a subsequent sub-module (e.g. upgrading, combustion or storage, Fig. 2.1). Additionally, losses (e.g. biogas leakage) are accounted, which will also become an input (as primary functional flow) in the MEFA level, where they are added to the environmental impact indicators.

2.2.3.2. Level two: Direct energy and material flows

During the conversion process of raw materials towards a finished product, energy and materials are required in the form of direct energy and material flows. The direct energy and material flows (e.g. diesel, electricity, heat, fertilizer) needed for the physical processes in the sub-module are accounted for and quantified through the use of the Material and Energy Flow Analysis (MEFA). The MEFA method is a physical environmental accounting approach, part of the MFA/MEFA method, which tracks the use of materials and energy, reporting the flows in physical units of mass and energy per time index [62]. The MEFA concept is integrated into the sub-module using the following factors (the letters in Fig. 2.2 coincide with the letters in the explanation).

G) Primary functional flows: The main input of the MEFA level is the primary functional flow, which is selected from one of the primary flows in the MFA level (e.g. biomass, biogas, digestate or loss of the previous). The dynamic element in the primary level is transferred to the direct level through use of the primary functional flows. It is possible to select multiple primary functional flows in one single sub-module; this will also require multiple sets of direct coefficients and direct impact coefficients.

H) Direct coefficients: The direct energy and material flows are calculated through the use of direct coefficients, which are given per unit of primary functional flow. One example of a specific coefficient is diesel consumption per transported kilogram of manure through a pipeline, when using a tractor powered manure pump (Table 2.2).

Table 2.2. Example of direct coefficients; manure transport using a diesel powered pump

Transport manure	kg diesel /kg manure	Source
Diesel use per pumped kg manure	0.000035	[71-73]

I) Dynamic patterns: Through the use of dynamic patterns the direct energy and material flows can be altered per time interval. Dynamics in level two can include for instance, the heat needed for heating the digester, which is dependent on the outside temperature.

J) Direct flows: The direct material and energy flows are calculated by multiplying the direct coefficients with the primary functional flow and (if present) the dynamic pattern, resulting in the energy and material flows needed for the physical process taking place in the sub-module, for instance the flow of diesel needed for pumping a specific amount of manure.

K) Direct impact coefficients: The direct impact coefficients are used to calculate the final impact indicators. The impact coefficients are indicated per unit of direct flow. For instance, the direct energy, carbon footprint, and impact to the environment of diesel combustion is given per kg of diesel consumed (Table 2.3). The direct impacts are mostly calculated using the Attributed Life Cycle Analysis (aLCA) method, which will be explained in the following section.

Table 2.3. Example of direct impact coefficients; consumption of one kg of diesel through combustion

Diesel per kg combusted	Value	Unit	Source
Direct energy	43.1000	MJ/kg	[74]
Direct carbon footprint	3.2820	KgCO_2eq/kg	[74]
Direct environmental impact	0.0397	Pt/kg	[74]

P) Impact indicators: The main outputs will be indicated in the three chosen impact indicators and are calculated by multiplying the direct flow (e.g. diesel consumption pump) with the direct impact coefficients (Table 2.3).

2.2.3.3. LCA, level three: Indirect energy and material flows

Indirect energy and material flows are required for the production of the energy and material flows used during the physical conversion process, for instance the production of diesel for use in a tractor. These indirect energy and material flows are accounted and quantified through the use of the attributed Life Cycle Analysis (aLCA) method. The aLCA approach uses physical properties such as mass and energy to determine the environmental impact of the functional unit, described by Rehl as:

> *"The focus of the aLCA approach lies on the analysis of environmental impacts of a product, a process or a system. The aLCA approach uses physical properties such as mass, heating or economic value ratios of products to isolate the percentage share of resource demand and the emissions of pollutants from individual product flows" [42].*

The aLCA method specializes in the analysis of physical properties making it suitable for analyzing the direct flows and determining the impact indicators. The following main factors are used within the aLCA level (the letters in Fig. 2.2 coincide with the letters in the explanation).

L) Direct functional flows: The main inputs into the LCA level (Fig. 2.2) are the direct energy and material flows determined in the MEFA level, indicated in this level as direct functional flows (e.g. diesel used for pumping manure). The dynamic element in the direct level is transferred to the indirect energy and material level through use of the direct functional flows.

M) Indirect specific coefficients database: The sub-module will contain a datasets of indirect impact coefficients, one for each direct functional flow, to determine the impact indicators. The indirect impact coefficients are given per unit of direct functional flow. For instance, the indirect impact coefficients in Table 2.4 are consumed and emitted for producing and transporting 1 kg of diesel (direct functional unit).

Table 2.4. Example of indirect impact coefficients; production of one kg of diesel and delivery to consumer

Diesel per kg produced at consumer	Value	Unit	Source
Indirect energy	12.0000	MJ/kg	[75]
Indirect carbon footprint	0.6000	KgCO_2eq/kg	[75]
Indirect environmental impact	0.1800	Pt/kg	[75]

P) Impact indicators: The main outputs will be indicated in the three impact indicators, which are calculated by multiplying the direct functional flows (e.g. diesel used for pumping manure) with the indirect impact coefficients (Table 2.4).

2.2.3.4. LCA, level four: Embodied material and energy flows

The energy and material flows required for the construction, maintenance and deconstruction of the installations used in the sub-module, also called the embodied energy and material flows, are accounted and quantified through the use of the aLCA method (described in section 2.2.3.3). When the sub-module is used the impact indicators will be added to the scenario. Within the embodied energy level the dynamic element is not used. The following main factors are used within the embodied energy level (the letters in Fig. 2.2 coincide with the letters in the explanation).

N) Embodied variables: There are two main embodied variables of importance for determining the impact indicator, the size or power rating of the construction, and the technical lifespan of the specific installation. The size or power rating determines the needed amount of materials for the installation and therefore its total embodied impact. The total embodied impact of the installation is spread out evenly over its lifetime. Additionally, the overall lifespan of the whole installation is taken into account; if this is longer than that of the individual component, a number of them are required during the total lifespan of the installation.

O) Embodied impact coefficients: The embodied impact coefficients are used to calculate the final impact indicators. The embodied impact coefficients are indicated per unit of embodied variable. For instance, the embodied impact coefficients of a diesel powered manure pump are given in units per kW of mechanical power (Table 2.5).

Table 2.5. Example of embodied impact coefficients; embodied energy of manure pump per kW of Mechanical power

Embodied energy per kW	Value	Unit	Source
Embodied energy	6920.00	MJ/kW[a]	[75]
Embodied carbon footprint	518.00	KgCO_2eq/kW	[75]
Embodied environmental impact	150.00	Pt/kW	[75]

[a] Impact calculated back per kW of mechanical power manure pump

P) Impact indicators: The main outputs will be indicated in the three impact indicators, which are determined by multiplying the embodied impact coefficients with the size of the installation divided by the technical lifespan of the component times the amount of replacements required during the lifetime of the complete installation. For example the embodied impact of a diesel powered manure pump, will be determined by multiplying the embodied variable (e.g. the power rating of the pump) with the embodied impact coefficients (Table 2.5) dividing this by the lifetime of the component. Additionally, the amount of pumps needed in the total lifespan of the installation must be taken into account. The impact indicators will only be added to the scenario if the related sub-module is used in the simulation.

2.3. Environmental impact indicators

The resulting environmental sustainability will be expressed in three known indicators which correlate with the definition of “strong sustainability” [21], wherein environmental quality precedes social prosperity and then economic prosperity [21, 76]. The indicators used are; the (Process) Energy returned on Invested [P]EROI, indicating the efficiency of the chosen scenario; the carbon footprint (GWP100), indicating global warming potential; and the Eco Indicator ReCiPe 2008, indicating the overall environmental impact to the ecology, nature and human health. The three units will be expressed per Gigajoule of energy produced (e.g. kgCO_2eq/GJ). Taken together, these indicators will give a clear overall impression on the efficiency and sustainability of green gas production pathways. The indicators are elaborated in the following section.

2.3.1. Efficiency expressed in [P]EROI

Before, during and sometimes after the exploitation of an energy source, input is needed in the shape of energy, installations, maintenance, transport, storage etc., which will impact the overall efficiency of the energy source. To indicate the energy efficiency of a process the (Process) Energy Returned on Invested factor, or [P]EROI, will be used. [P]EROI is defined as the ratio between the energy obtained from a resource to the energy expended in the production and processing of a resource (The factor is based on the EROI theory [77]). To determine the [P]EROI factor for a green gas production pathway, both the process energy invested and the energy returned must to be defined. The process energy invested includes; the direct energy needed to transform the raw materials to a final product (e.g. green gas injected into the gas grid); the indirect energy needed to produce the direct energy and raw materials; and the embodied energy of the constructions including maintenance. Energy returned is defined as the useful energy delivered, which could be in the form of biogas, green gas, electricity or heat. Additionally, the dependence on fossil fuels can be included in the factor, by indicating the fossil share of the energy invested. Overall, the [P]EROI factor can help to indicate the most efficient use of the green gas production pathway within a dynamic system. The [P]EROI will be expressed in a single factor. When the [P]EROI of a resource is greater than one it can be classified as a net energy producer, meaning that more energy is obtained from the resource than is expended in processing it. When the [P]EROI is equal or less than one the resource in question will become an energy sink or net energy consumer (e.g. storage system), meaning that less energy is obtained than is expended [77]. In theory the threshold between energy producer and energy sink is set at one, however in practice this point is often higher due to uncertainties (e.g. 1.5 up to 3, [78]).

2.3.2. Carbon footprint expressed in GWP 100

One of the main reasons for developing renewable resources is the reduction of fossil anthropogenic greenhouse gas emissions into the atmosphere. Every unit of fossil fuel consumed creates a net greenhouse gas increase potentially adding to global warming, destabilizing natural processes and endangering the Earth’s carrying capacity for advanced forms of life [8, 9, 79].

However, there are many different types of greenhouse gasses present, all with their own greenhouse potentials and properties. To include most of them in a single score, the carbon footprint GWP100 scale is used [79]. The carbon footprint is expressed in carbon dioxide equivalents (CO_2eq) using the relevant 100-year global warming potential scale or GWP100, [79]. Within the approach the carbon footprint will be quantified as a net increase or decrease of GWP100. The biomass used in the green gas production pathway is assumed to be carbon neutral, as part of the organic carbon cycle, where carbon is trapped by photosynthesis and released through decomposition in a continuous cycle. The additional emissions originating from the cultivating and processing of the biomass are incorporated in the carbon footprint. There are two main net producers of GWP incorporated in the approach; first, carbon dioxide absorbed in biomass may be converted and emitted as a stronger greenhouse gas (e.g., methane), therefore increasing the overall GWP potential; second, use of fossil energy sources in the green gas production pathway will create anthropogenic emissions resulting in a net increase of GWP. The increase or decrease in GWP caused by the green gas production pathway is a simple and transparent ruler, making it comparable to other energy sources of fossil and renewable origin.

2.3.3. Environmental impact expressed EcoPoints

The overall impact on the environment will be expressed with the ReCiPe 2008 Eco indicator, used by the SimaPro model [80]. When following the ISO 14040 and 14044 generic frameworks, an LCA inventory usually results in a very long list of emissions, consumed resources and sometimes other items. The interpretation of this list is often complex and difficult to comprehend. The ReCiPe LCIA procedure method is designed to help with this interpretation through the use of the Eco indicator. "An indicator" is an overall expression of total load on the environment (as currently understood in science), based on the damage-oriented approach. The indicator uses weighting factors wherein damage is brought into perspective and is made comparable to other types of damage [74]. The following explanation is used for the ReCiPe 2008 indicator.

> *"ReCiPe uses an environmental mechanism as the basis for the modelling. An environmental mechanism can be seen as a series of effects that together can create a certain level of damage to for instance, human health or ecosystems. For instance, for climate change we know that a number of substances, increases the radiative forcing, this means heat is prevented from being radiated from the earth to space. As a result, more energy is trapped on earth, and temperature increases. As a result of this we can expect changes in habitats for living organisms, and as a result of this species may go extinct. In ReCiPe eighteen midpoint indicators are calculated, and three (more uncertain) endpoint indicators are calculated. The motivation to calculate the endpoint indicators, is that the large numbers of midpoint indicators are very difficult to interpret, partially as there are too many, partially because they have a very abstract meaning. The indicators at the endpoint level are intended to facilitate easier interpretation, as there are only three, and they have a more understandable meaning [74]."*

Overall, the three impact categories (human health, ecosystems, resource depletion) are brought together into a single score through the use of damage models and normalization. Hence, ReCiPe 2012 indicator method provides a representation of the total environmental load exerted on human health, the ecology of the planet and resource depletion.

2.4. Discussion

The aim of this study is to create an integrated approach capable of combining energy and environmental system analysis, temporal dynamic and geographical diversity, which can be used for measuring the sustainability of green gas production pathways operating in specific geographic locations. The approach is a new and untested method for determining the overall environmental sustainability of green gas production pathways. Although the separate methods used in the approach are proven in literature, this new approach itself will need validation when used. In future research the new approach will be used in a model, where validation and sensitivity analysis will be conducted to validate the integrity of the integrated approach and model. Within the new approach the carbon balance of the biomass is assumed neutral, where the carbon is contained within a continuous cycle of biomass to carbon dioxide and back to biomass again. The ReCiPe indicator methodology (used for determining the EcoPoint) is still evolving, with research progressing in the field of environmental impacts, meaning that there are possible uncertainties with this indicator which new research could dispute. Finally, to express the efficiency and environmental impact, three specific impact categories are chosen in order to give an overview and gain more transparency. However, they cannot give detailed information regarding specific environmental impacts (e.g. acidification). This article is part of a research line within the Flexigas project, which is working towards economic and *sustainable* integration of biogas into the future national and decentralized energy system. However, this particular line of research is not focused on the economic analysis of the aforementioned green gas production pathways; this would be an important addition to the proposed line of research.

2.5. Conclusion

The sustainability of green gas production through anaerobic digestion has been well documented and researched. However, the wide variability in both scope and approach makes the interpretation of the various results difficult. A solution could be found within an integrated approach for measuring the sustainability of green gas production pathways including clear indicators for sustainability. Therefore, a new approach is proposed for measuring the sustainability of green gas production pathways, which can determine the overall environmental sustainability. The approach combines Material and Energy Flow Analysis, Energy and Environmental System Analysis including LCA, and temporal dynamics, in order to gain more insight into the sustainability of green gas production pathways. The new approach is based on the industrial metabolism concept, and is expanded with three known methods. First, the Material Flow Analysis method is used to simulate the decentralized energy system. Second, the Material and Energy Flow Analysis method is used to determine the direct energy and material requirements. Finally, the Life Cycle Analysis is used to calculate the indirect material and energy requirements, including the embodied energy of the components and required maintenance.

Complexity will be handled through a modular approach, which allows the simplification of the green gas production pathway while also allowing for easy modification in order to determine the impacts for specific conditions and scenarios. Temporal dynamics will be introduced in the approach through the use of hourly intervals and yearly scenarios. The sustainability of green gas production is expressed in (Process) Energy Returned on Energy Invested, Carbon Footprint, and EcoPoints. The proposed approach within this article can be used in energy and environmental system analysis and models for the analysis of green gas production pathways. By demanding a clear and structured material and energy flow analysis of the production pathway and clear expression for energy efficiency and sustainability the analysis or model can become more transparent and therefore easier to interpret. The understanding of the absolute energy and environmental impacts of renewable resources are required to help the European Union in achieving the renewable energy and emission reduction goals, described in the EU energy directive and the EU roadmap 2050 [16, 60]. Furthermore, the knowledge gained from applying the new approach can increase the efficiency and sustainability, of green gas as a renewable resource. Hopefully, this article will also provoke further discussion on the subject of modeling complex energy systems, as society is asking for an integrated and understandable overview in the decision making and planning process towards a more sustainable energy system.

Chapter 3

DESIGN: MODELING TOOL

The BioGas Simulator: modeling the sustainability of biogas production pathways operating on AD

ABSTRACT

Within this article, the use, operation and structure of a model for the environmental assessment of anaerobic biogas production pathways is discussed. The (Excel) BioGas Simulator (EBS) model is capable of calculating the economic cost, energy efficiency, carbon footprint, and environmental sustainability of small (farm)-scale anaerobic digestion (AD) biogas production pathways (2,000 up to 50,000 Mg/a of biomass input). The results from the model are expressed in four main indicators: the economic cost in net present value (NPV) and (economic) payback period, the efficiency in (process) energy returned on invested (PEROI), the carbon footprint in the global warming potential 100-year scale (GWP100), and the environmental impact in EcoPoints. The expression of sustainability in four clear indicators offers an understandable reference for comparison with other scenarios, and it allows for the research of several aspects of the biogas production pathway. The EBS model is constructed around a clear methodology, comprised of the industrial metabolism concept, modular approach, energy and material flow analysis (MEFA), life cycle analysis (LCA), and NPV analysis. The modular approach separates the biogas production pathway into individual physical processes, which makes the model more transparent, flexible in use, and programmable with different settings. Overall, the EBS model can help to shed light on the sustainability of specific biogas production pathways and to indicate options for improvement.

Additional information chapter

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3.1. Introduction

Biogas production through the use of anaerobic digestion (AD) is a promising method for producing a renewable and flexible energy carrier [27, 44, 81]. However, biogas is often seen as a (fully) sustainable resource. By definition, renewable refers to the energy resource (e.g. the yearly renewal of biomass) and not the process of producing and extracting the usable energy from this resource. These processes still often require fossil input, which will affect the costs, efficiency, emissions, and environmental impact of the complete process and therefore on overall sustainability [27, 58]. Within this context, the efficiency and sustainability of AD biogas production pathways are greatly influenced by the types of biomass used [27], the design of the installation, and the use or allocation of the AD process and final products or waste flows. A full life-cycle-based understanding regarding the impact of AD biogas production pathways is thus required for a sustainable integration of AD within the future (energy) system.

Therefore, in the Flexigas project [34], an Excel-based model is developed from a synthesis of existing methods, literature, and practical information, specifically for creating more insight into the sustainability of AD biogas production pathways. The model is called the (Excel) BioGas Simulator (EBS) model, and it is constructed around a clear methodology, comprised of the industrial metabolism concept, modular approach, energy and material flow analysis (MEFA), attributed life cycle analysis (aLCA), and economic net present value (NPV) analysis. In the EBS model, the biogas production pathway is defined as a collection of physical processes working together to achieve a common goal (e.g. biogas and green gas or heat and power production). This modular approach allows for the simplification of the biogas production pathway while also allowing for easy modification in order to determine the impacts of biogas production for specific conditions. Therefore, EBS model is flexible, and it can be easily modified or expanded to model case-specific scenarios. The results from the model are expressed in four main indicators: the economic cost in NPV and (economic) payback period, the efficiency in (process) energy returned on invested ([P]EROI), the carbon footprint in the global warming potential 100-year scale (GWP100), and the environmental impact in EcoPoints. The signal of sustainability in four clear indicators provides an understandable reference for comparison with other scenarios, and it enables the research of several aspects of the biogas production pathway.

A full life-cycle-based understanding of farm-scale AD will yield valuable information on the overall sustainability of the process, and it can be the starting point for an optimization process on sustainability not only for the AD process itself but also for the (energy) system within which it is integrated. In this article, the main methodology and structure of the model are discussed first, followed by the overall structure of the model, and finally, the overall function and operation of the EBS model are discussed. This article can be used as a fast guide for programming the EBS model.

3.2. Methodology

The method used in the EBS model is based on “A new approach for measuring the environmental sustainability of renewable energy production systems” Pierie et al., 2016 [36], which combines the industrial metabolism concept, the modular approach, MEFA [62], energy and environmental system analysis [27], aLCA, and economic NPV analysis in order to gain insight into the cost, energy efficiency, carbon footprint, and environmental sustainability of biogas production pathways [36]. The overall sustainability within the model defined as "strong sustainability" wherein environmental quality precedes social prosperity, and then economic prosperity [21, 76] will be determined using the aLCA methodology, which utilizes physical properties such as mass and energy to determine the environmental impact of the functional unit [42] (e.g. m, s, or kg). The LCA analysis is undertaken in accordance with European guidance and ISO / NEN 14040 to 14044. The environmental impacts were obtained through the use of the SimaPro v8.0 (2013), utilizing the Eco Invent database v3.0 (2013) as endpoints.

3.3. Expressions

The economic performance will be expressed in NPV and (economic) payback period to indicate the possible profitability over the economic and technical lifespan of a biogas production pathway. The process energy efficiency, carbon footprint, and environmental sustainability of the biogas production pathway will be expressed by three indicators per GJ of energy produced. The first one is (process) energy returned on energy invested ([P]EROI), which is defined as the ratio between the energy obtained from a resource to the energy expended in the production and processing of a resource. This factor is based on the EROI theory [77]. The second indicator is the carbon footprint, expressed in carbon dioxide equivalents (CO2eq) using the GWP100 [79]. Finally, the third indicator, namely, the overall impact on the environment, is expressed by the ReCiPe 2008 Eco indicator, used by the SimaPro model [80, 82]. The expressions are described in Pierie et al., 2016 Section 3 [36].

3.3.1. System boundaries

The system boundaries of the model are set within the regulatory domain of the Netherlands; therefore, only biomass types that are approved for use by the Dutch government are included in the databases [83]. Also, technologies predominantly available within the Netherlands (and Germany) are used in the model. The model starts with the input of feedstocks and ends with the injection of green gas in the gas grid, electricity in the electricity grid, heat in a heat network, and the use of digestate as an organic fertilizer. All costs involved regarding feedstocks, energy, and machinery are taken into account, and costs regarding overhead (e.g. labor) are included in a specific NPV calculation. Energy and material use and their environmental impacts are taken into account when they are in service of the biogas production pathway (e.g. production, processing, and transport), (Fig. 3.1). Offset regarding the replacement of current waste treatment chains can be considered within the model. Additionally, internal energy production through the use of a combined heat and power (CHP) unit and fuel replacement with green gas can also be utilized in the model. Losses of material flows will be taken into account, including losses of feedstock, biogas, and digestate, which originate from leakages, spills, or the degradation of biomass during storage. Emissions caused by these losses will be included. Finally, offsets of mineral and fossil fertilizers, with upgraded digestate as a substitute, can also be included in the model.

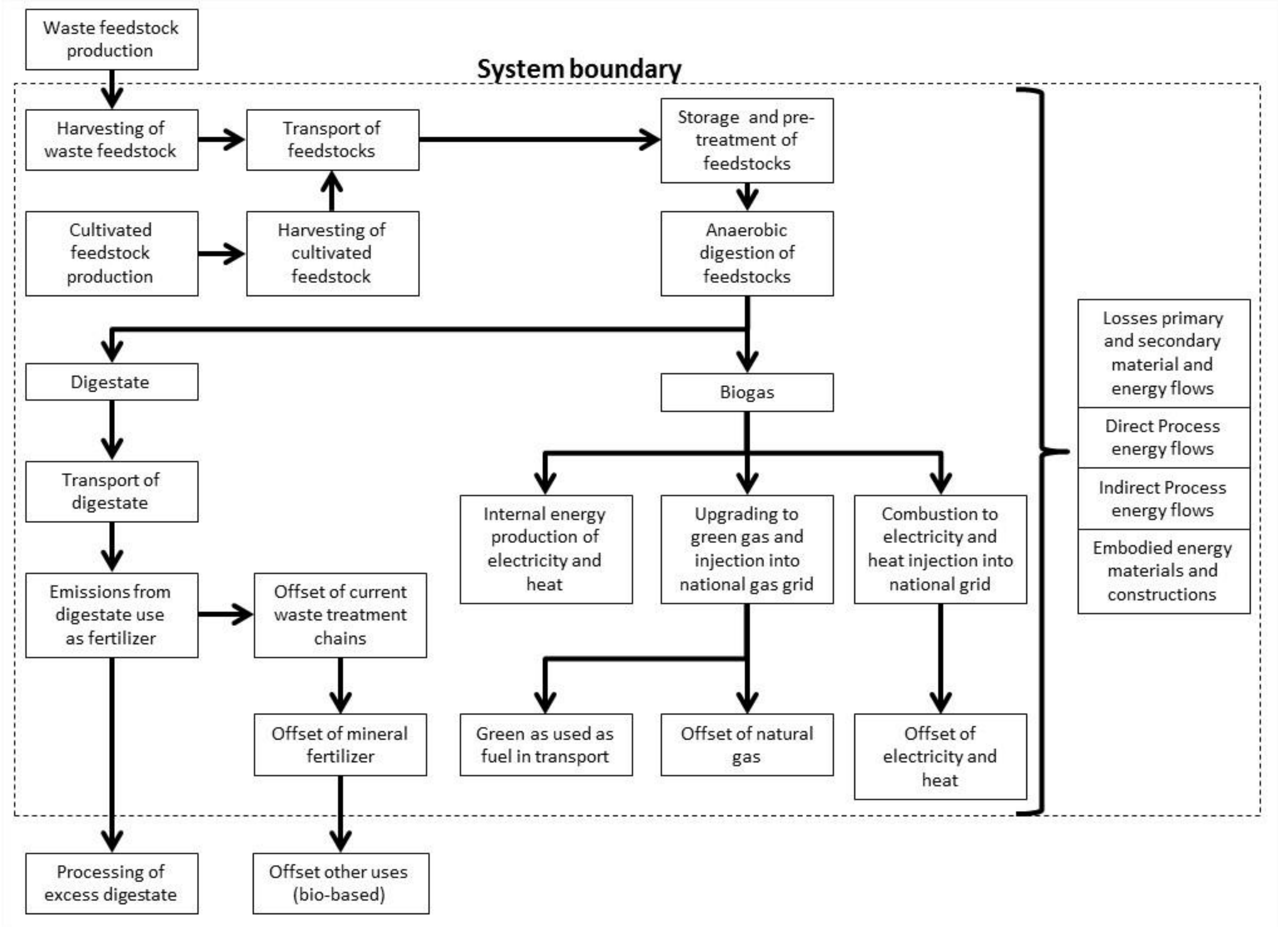

Fig. 3.1. System boundaries of biogas production and end use included in LCA

3.3.2. Use of the International System of Units

The consequent use of units is of importance within the calculations of the EBS model; when integrating new data or expanding calculations, they must be expressed in the same units. Within the EBS model, the International System of Units is utilized (e.g. distance [m], mass [(kg]). However, different variations of the standard units can be used for simplifying the value (e.g. 1,000 g = 1 kg), (Table 3.1). It is important to keep this in mind when using the EBS model, as the difference between the SI unit for mass (g) and the variation used in the model (Mg) is 1 million, which will have a significant effect on the outcomes of the model.

Table 3.1. Main units used in model [64]

SI unit description	SI unit	Variation used in model
Main unit for mass	g	Mg / tonne
Main unit for distance	m	Km
Main unit for temperature	K	C (Celsius)
Main unit for time	s	hr (hour) or a (year)
Main unit for amount of substance	Moll	kMoll
Main unit for amount of energy	J	kJ, MJ, GJ or kWh, MWh
Main unit for currency (Europe)	€ (Euro)	€ (Euro) k€, M€

3.3.3. Modular approach

Within the modular approach, the AD biogas production pathway is defined as a collection of physical processes working together to achieve a common goal (e.g. biogas or green gas production) [36]. These individual physical processes are called sub-modules, and they are assigned to groups, called modules, that perform the same physical process (Fig. 3.2). The AD biogas production pathway will be built from a succession of sub-modules, in logical order, forming a chain that, for instance, could result in the green gas production chain depicted in Fig. 3.2. The aforementioned approach will allow several arrangements of sub-modules to form different production pathways. In a later stage of the measuring and optimization process, the modular approach can be used to design the optimum production pathway to suit particular cases by changing, adding, or removing individual sub-modules during the modeling (or planning) process.

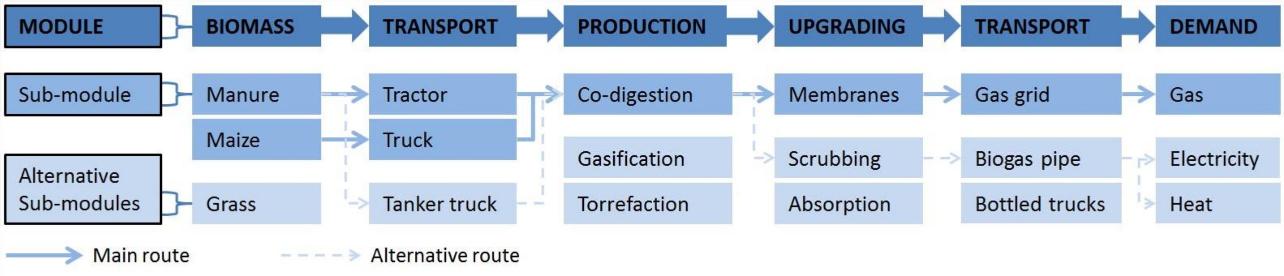

Fig. 3.2. The main modules and sub-modules used in an example green gas production pathway

Sub-modules will act as individual models where one or more main physical processes are described (Fig. 3.3). Every sub-module will be capable of determining the expression for that particular physical process. To determine the expressions, each sub-module is separated into four levels: level one, the primary (mass) flow level; level two, the direct energy and material level; level three, the indirect energy and material level; and level four, the embodied energy level. Primary mass flows are defined as raw materials (e.g. biomass, biogas, digestate, and/or losses of the previous flows) that run through the system; direct energy flows are used during the conversion process of raw materials into a finished product (e.g. diesel, electricity, heat, or fertilizer); indirect energy and material flows are required for the production of direct energy and material flows (e.g. the production of diesel); and embodied energy and material flows are required for the construction, maintenance, and deconstruction of the installations used for processing the primary flows (e.g. digester). Each level will be described through the use of an existing method that will perform its own calculations (Fig. 3.3). Sub-modules will share primary flows (e.g. biomass), as the output of one sub-module becomes the input for the next (e.g. transport to co-digester), (Fig. 3.2). For a full explanation of the approach described in this section, see Pierie et al., 2016 [36] (Section 2).

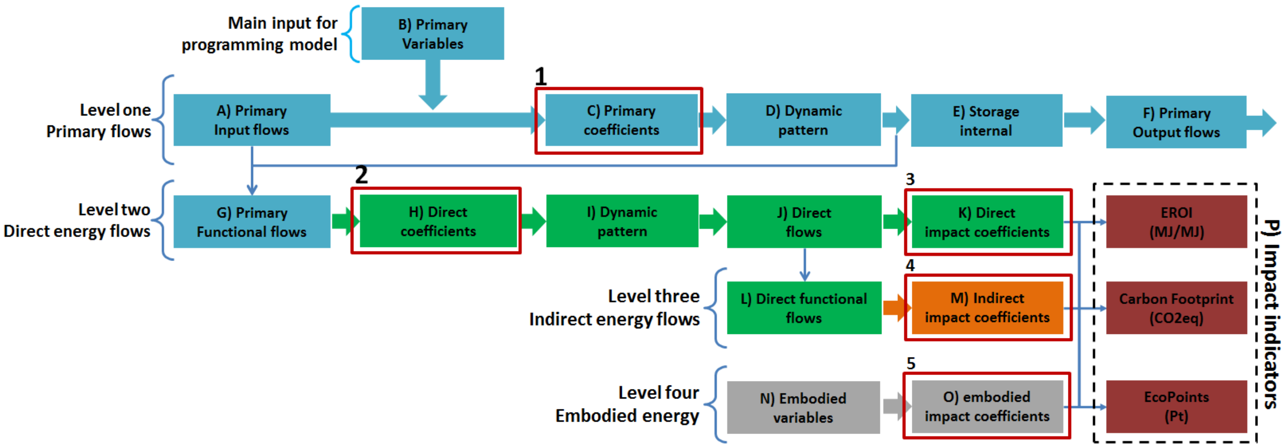

Fig. 3.3. The layout of an individual sub-module and the (numbered) location of the databases therein

3.4. The main components of the EBS model

The main components of the EBS model are indicated in the main layout sheet (Fig. 3.4), which represents the collection of sub-modules in the modular approach working together to achieve energy production [36]. To navigate through the large number of sub-modules, a hyperlink navigation structure is implemented, where clicking on the sub-module icon will direct one to this sub-module. The modular system makes the model flexible in use and programmable with different settings. Furthermore, the model is built up out of layers of complexity to increase the accessibility of the model. The biogas production pathway contains all the needed sub-modules to produce either green gas (with Groningen gas quality) injected into the national gas grid or CHP, with power injected into the national grid and heat used for the biogas production pathway and local heat networks. Also, digestate handling is included in the model, where the digestate can either be used as fertilizer or upgraded to replace fossil fertilizers. The sub-modules making up the EBS model are grouped into the following main components for processing the biomass: liquid biomass sources (including bypass), solid biomass sources, an AD digestion system, an upgrader system to green gas, CHP systems, digestate handling, and a backup heating system (Fig. 3.4). Additionally, a cooperative farming reference case is included for determining the environmental impact of farming without the use of AD on the farm. The main components will be discussed in this section.

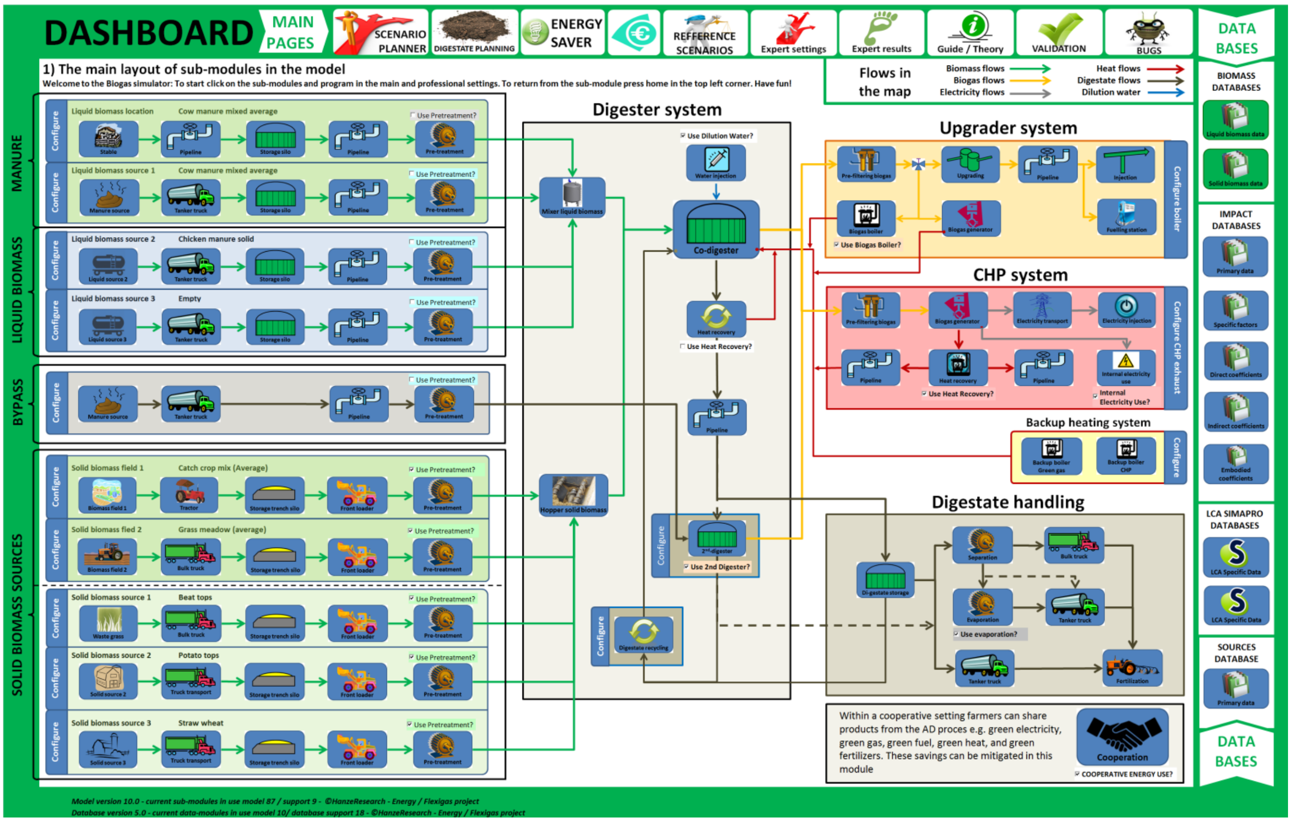

Fig. 3.4. The main layout (for MEFA) of the biogas production pathway in the EBS model

3.4.1. Liquid biomass inputs

The model contains two main types of biomass input, namely, liquid and solid. The distinction between the two types of feedstock input reflects the different equipment needed to process either liquids or solids. Within liquid feedstocks, a distinction is made between manure substrates and other substrates (Fig. 3.4). According to Dutch regulation for co-digestion, at least 50% of the feedstock needs to be a manure substrate [83]. In the EBS model, one of the manure substrates originates from the stable where the digester is located, and the other manure substrate originates from a source (e.g. another stable or farm), (Fig. 3.8 nr. 2). Two additional liquid substrates can be programmed in (e.g. glycerin or municipal organic waste). For all feedstocks, transport and storage can be included from the source to the digester system (Fig. 3.8 nr. 3). The transport of liquids will mostly be in the form of either tanker trucks or pipe transport. Also, pretreatment is included that can screen the feedstock for debris, pretreat the feedstock for better biogas yields, and/or pasteurize the feedstock to kill harmful bacteria or other organisms. Additionally, there is a manure bypass input (Fig. 3.8 nr. 2) where manure can be directly pumped into the second digester (Fig. 3.4). This additional feature can increase manure utilization in locations with an abundance of manure without compromising the feedstock ratio in the main digester. The transport distance of the additional manure can be indicated in the model (Fig. 3.8 nr. 3).

3.4.2. Solid biomass inputs

With solid feedstocks, the distinction is made between production on the farm and receiving biomass from a source. Two fields, which are adjacent to the digester site where the farmer can grow energy crops, are included in the model (Fig. 3.4). Besides this, three solid substrates can be used (e.g. onions, grass, and catch or cover crops), which originate from other farms or production locations (e.g. factories or waste management), (Fig. 3.8 nr. 2). As with liquid sources, transport, storage, and pretreatment can be taken into account before the feedstock enters the digester system (Fig. 3.8 nr. 3). Transport for solid feedstocks will mostly be in the form of bulk truck transport, front loaders, and walking floor or screw systems.

3.4.3. Digester system

The digester system is built around a main co-digester tank, which is based on a round concrete tank design with a flexible roof to hold biogas (Fig. 3.4). To produce biogas, feedstocks are forced into the digester and then stirred and heated. The retention time in the digester is, on average, 30 days at mesophilic temperature, with a water content of 80% in the digester. Water injection can be taken into account to keep the water content at a level that will allow for stirring. The biogas production from the digester is based on theoretical values, indicated per feedstock type (e.g. biogas and methane production per Mg of organic dry matter [oDM]), which are multiplied by the mass flow of feedstocks moved in the digester tank. The amount of digestate and the content of the specific nutrients in the digestate are calculated from the total input of feedstocks minus the biogas production. For this calculation, molar mass equations are used, and nutrients are taken into account for later use as fertilizers. There is an added option, called bypass, where manure can be inserted into the second digester directly. The digester is stirred using electricity either from the national grid or produced on-site. The heat needed for the process is supplied by on-site sources (e.g. a biogas boiler or CHP unit) or, if required, through the use of a backup natural gas boiler. Additionally, a second digester can be switched on, where the digestate from the first digester is stored to extract the last remaining biogas (Fig. 3.4). There is also the option to recuperate heat from the digestate, through the use of a heat exchanger or a heat pump system, to heat the digester. The digester is programmed in the model as a linear expandable installation, meaning that the size and consequent expressions will automatically adjust within the range of the model. This is achieved through the use of relative factors. For example, dividing the cost of a known digester by the volume will create a relative factor in cost per volume. If the needed volume of the co-digester is known, then the cost of the digester installation can be calculated. The same aforementioned method will be used to calculate the expressions of most installations in the model.

3.4.4. Upgrader system

Biogas can be upgraded to natural gas quality, such as green gas, through the use of an upgrader system (Fig. 3.4). Before entering the upgrader, the biogas is filtered using active carbon to remove hydrogen sulfide and other pollutants, which can hinder and damage the upgrading process and equipment. Part of the biogas after filtering is redirected to the biogas boiler, which provides the heat needed in the biogas production pathway. The upgrader principle within the EBS model is based on a membrane system, which uses highly selective membranes to separate methane from carbon dioxide and trace gasses (e.g. oxygen and nitrogen) [84]. The energy use of the green gas upgrading and injection system is mainly in the form of electricity, and it is used for compression. The green gas produced will be injected into the national gas grid at intermediate pressure (8 bar) to ensure that the total production of green gas can be absorbed the whole year round. Gas pipes can be incorporated for transporting the green gas from the production site to the injection station.

3.4.5. Combined heat and power system

Biogas can be combusted in a CHP unit (Fig. 3.4) to produce electricity and heat. Before entering the CHP unit, the biogas is filtered using active carbon to remove hydrogen sulfide and other pollutants, which can damage the engine. The electricity produced by the CHP unit is transported to the national electricity grid. Before injection, electricity can be extracted for internal use. Furthermore, the construction of electrical infrastructure for transporting the electricity to the grid can be included, and the heat from the CHP unit can be distributed to a local heat network. Transport in the form of heat pipes can be included, and part of the heat can be redirected to the biogas production chain to fulfill the internal heat demand.

3.4.6. Backup heating system

To supply heat to the biogas production system when either the biogas boiler or CHP unit are down or insufficient, a backup system is included (Fig. 3.4). The backup system comprises a high-efficiency boiler operating on natural gas from the national gas grid. The backup boilers will automatically activate when the biogas boiler or the internal heat production from the CHP is insufficient or switched off. Impacts of the backup system, including fuel use and the construction of the system, are incorporated into the results.

3.4.7. Digestate handling system

After biogas is extracted from the feedstocks, a substance called digestate remains, which is pumped into a large storage tank (or, if selected, into the second digester), (Fig. 3.4). Digestate contains high levels of nutrients and organic materials that are useful as fertilizer. It can be used directly as a fertilizer, comparable to manure, or it can be processed to contain more of a specific nutrient, comparable to fossil fertilizers. In the EBS model, the digestate can be separated into a thick and thin fraction (Fig. 3.4). On the one hand, the thick fraction is rich in organic material and phosphorus, and it is often preferred as a fertilizer for the cultivation of crops. The low water content of around 50% makes the thick fraction solid and therefore transportable as solid bulk material. On the other hand, the thin fraction contains a high nitrogen fraction and most of the water; it is preferred by dairy farmers as fertilizer for grass fields. The thin fraction, being 90% water, is a liquid, which needs to be transported in tanker trucks. To improve on the quality of the thin fraction, a reversed osmosis option is added to the EBS model, where a large part of the water is removed through the use of high-pressure membrane separation (Fig. 3.4). Due to the many options available for digestate processing and use, a special digestate planner is constructed within the EBS model (Section 3.7.2).

3.5. Mitigation pathways

Using the AD process can replace current processes or practices of biomass handling. When impacts are avoided within the AD system (e.g. fossil fuel use or methane emissions), compared to the replaced processes or practices, they can be mitigated. Three current processes or practices are included in the EBS model for mitigation, namely, storage of manure in ventilated tanks and admission of manure to the field, mowing of road side grasses, and decay of leftover organic material (e.g. beat tops) on the field. Through mitigation, the emissions and environmental impact of these current waste treatment pathways can be subtracted from the overall emissions and environmental impact of the AD biogas production chain when providing the same function (Fig. 3.5). The three current processes or practices mitigated are discussed in this section.

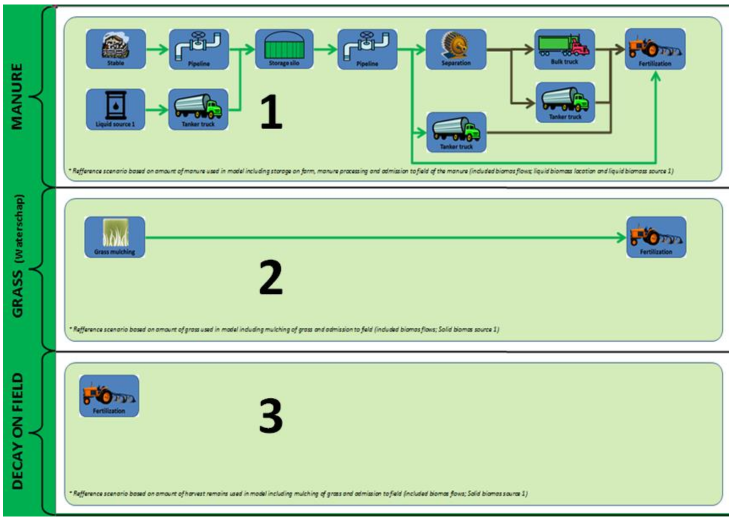

Fig. 3.5. The MEFA of the current waste treatment scenarios

3.5.1. The manure waste treatment pathways

An AD system can replace manure storage in closed tanks on a farm. Within this practice, the manure is collected year round from the stables (or from manure sources) and stored in a sealed tank (Fig. 3.5 nr. 1). However, emissions still occur from this sealed tank in the form of methane or nitrogen oxides, as it is ventilated by the outside air. Furthermore, when the manure is dispersed over the field as fertilizer, additional emissions will occur. When AD is used, part of the emissions from storage can be avoided, for instance by using the methane to produce energy and transform it into carbon dioxide. Furthermore, processed digestate has lower emissions when applied to the field.

3.5.2. The roadside grass waste treatment pathways

Road side or natural grass management (for some organizations) is currently based on mowing and directly mulching the grass into a fertilizer, which is then left on the field. When plant remains are left on the field, emissions will result from decay. Using the grasses in a biogas production pathway will avoid these specific emissions and replace them with emissions from the application of digestate on the field; the latter emissions are, on average, lower (Fig. 3.5 nr. 2). This difference can be accounted for and then mitigated within the EBS model.

3.5.3. The composting scenario

Biomass composting is based on leaving organic material or harvest remains on the field after harvesting the most important part of the plant. Examples of harvest remains are tops and roots from sugar beets, potato plants, or straw from grains. Leaving these remains on the field or ploughing them into the soil will result in emissions from decay (Fig. 3.5 nr. 3). Similarly to the previous scenario, using the harvest remains in a biogas production pathway will prevent these specific emissions and replace them with emissions from both the biogas production process and the application of digestate on the field. The latter emissions are also, on average, lower. This difference can be accounted for and then mitigated within the EBS model.

3.6. Databases

Within the EBS model, all the data used from either literature or practice are stored in databases. The databases are constructed in such a way that they can be expanded with new information, or incorrect information can be altered. A reference and/or remarks can also be added for every data entry. Furthermore, the databases are directly linked to the sub-modules, meaning that if used values in the database are changed, for instance with better data, then the values in the sub-modules will automatically change as well. The databases are grouped into five main sections, based on the main calculation method used in the model [36]. The location and use of the databases are linked to the structure and layout of the sub-module (Fig. 3.3). This section will describe the databases used in the model (encircled with red boxes in Fig. 3.3).

3.6.1. Primary coefficients databases

The primary coefficients database consists of the primary database and the biomass databases (Fig. 3.3 nr. 1). The latter databases consist of a liquid feedstock database and a solid feedstock database.

3.5.1.1. The primary database

The primary database contains a selection of the physical properties of primary energy and material flows (e.g. biomass, biogas, methane, and water) used in the model. These physical properties include, for instance, density, heating values, specific energy, and molar mass (Table 3.2). These primary data are mostly used to calculate the primary flows within sub-modules (Fig. 3.3 nr. 1).

Table 3.2. Example of methane gas in the primary database

Main properties methane gas			
Energy content	**39.00**	MJ/Nm3	http://en.wikipedia.org/wiki/Methane
Density	**0.72**	kg/Nm3	

3.5.1.2. Liquid feedstock database

The liquid feedstock database houses all of the manure types, including the solid manures (e.g. cow, pig, and chicken manures) and some additional liquid feedstocks (e.g. municipal organic waste, Ecofrit, and glycerin). The biogas and methane potentials, the nutrients in the feedstock, the yield per hectare or animal, and the impacts for collection or cultivation are important values indicated for every feedstock (Table 3.3). The database is primarily used for calculating primary flows (e.g. biogas and digestate), (Fig. 3.3 nr. 1). Additionally, the ingredients or nutrients are indicated per kg of biomass type (Table 3.3), which will determine the nutrients in the digestate after biogas is extracted. The nutrients can be reused as fertilizer on the field. Furthermore, all values in this database can be changed when better or different data are available.

Table 3.3. Example of manure in liquid biomass database

Cows										
Cows	**Cow manure mixed average**			**Ingredients per kg**			**Biogas potential per kg oDM**			**Sources**
Cows	Liquid cow urine mixed with solid cow manure (f			oDM	0.0640	kg/kg M	Biogas	0.3500	Nm3/kg	KWIN-V 2013-2014 for content manure
Cows	Production per cow	18,120	kg/yr	DM	0.0210	kg/kg M	CH4	0.1800	Nm3/kg	SimaPro EcoInvent database, 2013
Cows	oDM Content	6.40%	%	Nitrogen	0.0041	kg/kg M	N2	0.0060	Nm3/kg	
Cows	Density	1005	kg/m3	Phosphate	0.0015	kg/kg M	O2	0.0030	Nm3/kg	
Cows	Methane content	60%	%	Potassium	0.0058	kg/kg M	NH3	0.0003	Nm3/kg	
Cows	Energy Content		MJ/kg	Magnesium	0.0012	kg/kg M	H2S	0.0000	Nm3/kg	
Cows				Sodium	0.0007	kg/kg M	CO2	0.1607	Nm3/kg	
Cows				Water	0.9017	kg/kg M				
Cows										
Cows										

3.5.1.3. Solid feedstock database

The solid feedstock database houses all of the solid feedstock types (e.g. maize, grass, catch crops, and onions) and some additional solid feedstocks (e.g. agricultural or industrial organic waste). The biogas and methane potentials, the nutrients in the feedstock, the yield per hectare, and the impacts for collection or cultivation are important values indicated for every feedstock (Table 3.4). The database is primarily used for calculating primary flows (e.g. biogas and digestate), (Fig. 3.4 nr. 1). Additionally, the ingredients or nutrients are indicated per kg of biomass type (Table 3.4), which will determine the nutrients in the digestate after biogas is extracted. The nutrients can be reused as fertilizer on the field, and all values in this database can be changed when better or different data are available.

Table 3.4. Example of energy maize in solid biomass database

Maize										
Maize	**Maize (average)**			**Ingredients maize per kg**			**Biogas potential maize per kg oDM**			
Maize	Maize source Bekkering model			oDM	0.3000	kg/kg M	Biogas	0.6060	Nm3/kg	**Poschl, Ward et al., 2010.**
Maize	Production ha (whet mass)	45,000	kg/ha.yr	DM	0.0450	kg/kg M	CH4	0.3224	Nm3/kg	SimaPro EcoInvent database, 2013
Maize	oDM Content	30%	%	Nitrogen	0.0046	kg/kg M	N2	0.0120	Nm3/kg	
Maize	Density	460	kg/m3	Phosphate	0.0019	kg/kg M	O2	0.0060	Nm3/kg	
Maize	Methane content	53%	%	Potassium	0.0055	kg/kg M	NH3	0.0006	Nm3/kg	
Maize				Magnesium	0.0000	kg/kg M	H2S	0.0001	Nm3/kg	
Maize				Sodium	0.0000	kg/kg M	CO2	0.2650	Nm3/kg	
Maize	Energy Content		MJ/kg	Water	0.6430	kg/kg M				
Maize										
Maize										

3.6.2. Direct coefficients database

The direct coefficients database contains data primarily used for the calculation of direct energy flows (e.g. electricity, diesel, heat, and natural gas), (Fig. 3.3 nr. 2), for example the amount of electricity needed to pump a fixed amount (e.g. 1 kg or 1 m^3) of manure (Table 3.5). With the flow of manure known, the flow of electricity needed to pump the manure can be determined. The database contains values for all the processes in the model (e.g. transport, pumping, mixing, and heating). All values in this database can be changed.

Table 3.5. Example of electric manure transport through the use of a pump in the specific database

Transport manure displacement pump electric			
Electricity use	**0.0007**	MJ/kg	Edze trading: http://www.drijfmesttechniek.nl/mestpompen/
Heat use	**0.0000**	MJ/kg	

3.6.3. Direct impact coefficients database

The direct impact coefficients database contains data for calculating the direct impact factors (e.g. costs, [P]EROI, carbon footprint, and EcoPoints) of a direct energy and material flow (Fig. 3.3 nr. 3), for example the direct impact of diesel use when combusted (Table 3.6). These impacts are calculated through the use of the aLCA method, the SimaPro model, and the EcoInvent database [75]. All values in this database can be changed.

Table 3.6. The direct impact factors of 1kg of diesel used trough combustion

Energy carriers			
Diesel, 1kg {CH}, at consumer			
CAPEX	**€ 0.00**	€/kg	
OPEX	**€ 1.46**	€/kg	http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLnl&PA=81
Direct Energy	**43.1000**	MJ/kg	SimaPro EcoInvent database, 2013
Direct CO2eq	**3.2820**	kgCO2eq/kg	
Direct EcoPoints	**0.0397**	Pt/kg	

3.6.4. Indirect impact coefficients database

The indirect database contains indirect, specific coefficients, which are used in the indirect flow sections of the sub-modules (Fig. 3.3 nr. 4). They are mainly used to calculate the indirect impact factors of the direct energy and material flows. Indirect impacts of, for instance, diesel include the whole process from extraction and refining up to transport to the end consumer (Table 3.7). These impacts are calculated through the use of the aLCA method, he SimaPro model, and the EcoInvent database [75]. All values in this database can be changed.

Table 3.7. The indirect impact factors of 1kg of diesel production and transport to local storage

Diesel, 1kg {CH}, at consumer			
CAPEX	**€ 0.00**	€/kg	
OPEX	**€ 0.00**	€/kg	
Indirect Energy	**13.5000**	MJ/kg	SimaPro EcoInvent database, 2013
Indirect CO2eq	**0.5670**	kgCO2eq/kg	
Indirect EcoPoint	**0.1960**	Pt/kg	

3.6.5. Embodied impact coefficients databases

The embodied database contains embodied, specific coefficients, which are used in the embodied flow sections of the sub-modules, for calculating the impact factors of installations present in the sub-module (Fig. 3.3 nr. 5). The embodied impact assessment includes the cost of construction (the capital expenses [CAPEX]), the materials and energy used during construction, and deconstruction during end of life (Table 3.8). These impacts are calculated through the use of the aLCA method, the SimaPro model, and the EcoInvent database [75]. All values in this database can be changed.

Table 3.8. The indirect impact coefficients of 1m^3 of solid biomass storage in a trench silo

Solid biomass storage, concrete trench silo, 1m3 {NL}, at consumer			
Costs	60.33	€/m3	Estimate
Direct Energy	458.52	MJ/m3	SimaPro EcoInvent database, 2013
Direct CO2eq	169.83	kgCO2eq/m3	Bosch beton (https://www.mijnsleufsilo.nl/)
Direct EcoPoints	46.46	Pt/m3	

3.6.5.1. Life cycle database

The life-cycle-specific databases are comprised of two individual databases. One database contains all the values and variables used in the SimaPro model to calculate the indirect, specific coefficients found in the indirect impact coefficient databases (Section 3.6.4). The other database contains all the values and variables used in the SimaPro model to calculate the embodied, specific coefficients found in the embodied database (Section 3.6.5). Most of the values used in the indirect and embodied databases are retrieved as a result of the SimaPro model working on the Eco Invent database [75]. The data contained in the LCA databases represent the values used in the SimaPro model to calculate the specific indirect or embodied values (e.g. the environmental impact of a trench silo), (Table 3.9). Additionally, for some constructions in the biogas production pathway (e.g. trench silo), the construction drawing is included in the LCA database to provide the user with an impression of the installation (Fig. 3.6). This allows other researchers to reproduce every value in the model (if using the same version of SimaPro).

Main design | Side wall 18X SL200R | Ground plate 44X 2000x2000

Fig. 3.6. The design of a trench silo for storing solid feedstock

Source: http://www.boschbeton.nl/Agrarisch_en_Groenvoorziening/Configurator

Table 3.9. The values programmed into the SimaPro model for calculating the embodied impact factors of a trench silo

Solid biomass storage, concrete trench silo, 3315m3 {NL}, at consumer			Remarks			
Costs (Euros)		€/unit	Filled in by Frank Pierie			
Embodied energy (Cumulative energy demand V1.08)	1520000	MJ	2014-05-27 Checked by Frank Pierie			
Carbon footprint (IPCC 2007 GWP 100a)	563000	kgCO2eq				
Impact environment (Recipe Endpoint (E))	154000	Pt				
1) Assembly			**Transport**			
Material (SimaPro)	**Factor**	**Unit**	**Transport type (SimaPro)**	**(km)**	**(ton.km)**	**Remark**
Concrete block {GLO}| market for | Alloc Def, U	168599.20	kg	Included	0	0.00	Concrete plate sidewalls
Concrete, sole plate and foundation {GLO}| market for | Alloc Def, U	441823.20	kg	Included	0	0.00	Foundation of concrete plates (is 185.64 m3 concrete)
PVC pipe E	686.40	kg	Transport, freight, lorry 16-32 metric ton, EURO4 {G	100	68.64	Pipes used for dewatering
Cement mortar {GLO}| market for | Alloc Def, U	100.00	kg	Included	0	0.00	Kit between the concrete slabs
Sand {GLO}| market for | Alloc Def, U	503717.76	kg	Included	0	0.00	Sand used for foundation
Gravel, crushed {GLO} | market for | Alloc Def, U	356952.96	kg	Included	0	0.00	Gravel used for foundation
Process (SimaPro)	**Factor**	**Unit**	**Transport type (SimaPro)**	**(km)**	**(ton.km)**	**Remark**
Excavator, hydraulic digger {GLO} | market for | Alloc Def, U	1233.96	m3		0	0.00	
Totals	1471879.5200	kg	Transport total	100	68.6400	
2) Maintenance			**Transport**			
Material (SimaPro)	**Factor**	**Unit**	**Transport type (SimaPro)**	**(km)**	**(ton.km)**	**Remark**
Concrete block {GLO}| market for | Alloc Def, U	16859.92	kg	Included	0	0.00	Maintenance
Concrete, sole plate and foundation {GLO}| market for | Alloc Def, U	44182.32	kg	Included	0	0.00	Maintenance (is 18.564 m3 concrete)
PVC pipe E	68.64	kg	Transport, freight, lorry 16-32 metric ton, EURO4 {G	100	6.86	Maintenance
Cement mortar {GLO}| market for | Alloc Def, U	10.00	kg	Included	0	0.00	Maintenance
Process (SimaPro)	**Factor**	**Unit**	**Transport type (SimaPro)**	**(km)**	**(ton.km)**	**Remark**
Excavator, hydraulic digger {GLO} | market for | Alloc Def, U	123.40	m3		0	0.00	Maintenance
Totals	61120.8800	kg	Transport total	100	6.8640	
3) Life Cycle			**Transport**			
Material (SimaPro)	**Factor**	**Unit**	**Transport type (SimaPro)**	**(km)**	**(ton.km)**	**Remark**
Process (SimaPro)	**Factor**	**Unit**	**Transport type (SimaPro)**	**(km)**	**(ton.km)**	**Remark**
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO} | market for | Alloc Def, U	1471879.52	kg	Included	0	0.00	Transport to end user
Transport, freight, lorry 16-32 metric ton, EURO4 {GLO} | market for | Alloc Def, U	61120.88	kg	Included	0	0.00	Transport to end user
Totals	1533000.4000	kg	Transport total	0	0.0000	
4) End of life			**Transport**			
Material discarded (SimaPro)	**Factor**	**Unit**	**Transport type (SimaPro)**	**(km)**	**(ton.km)**	**Remark**
Waste (waste scenario) {NL} | treatment of waste | Alloc Def, (Silo assembly)	611208.8000	kg	Transport, freight, lorry 16-32 metric ton, EURO4 {G	50	30560.44	Disposal
Waste (waste scenario) {NL} | treatment of waste | Alloc Def, (Maintenance)	61120.8800	kg	Transport, freight, lorry 16-32 metric ton, EURO4 {G	50	3056.04	Disposal
Totals	672329.6800	kg	Transport total	100	33616.4840	

3.7. Working with the EBS model

The EBS model can be operated by a specialist in the field of biogas production. The model has been constructed in such a way that its use is fairly comprehensible and understandable. However, when exploring behind the main sheets, the model will become exponentially more complex. The main pages for operating the model are indicated in the top bar of the dashboard (Fig. 3.7). These will be discussed in this section.

Fig. 3.7. The main sheets in the model

3.7.1. The scenario planner

The main input sheet in the model is called the scenario planner, and it is divided into six main sections (Fig. 3.8). The most important settings can be altered in this sheet, and the main results are also indicated therein. Within the model, the economic and technical lifespan of the complete biogas production pathway can be indicated (Fig. 3.8 nr. 1). The economic lifetime will influence the write-off period of the installation, and the technical lifetime will indicate the maintenance and number of replacement parts needed. Four liquid and five solid biomass flows and their amounts can be selected (Fig. 3.8 nr. 2). When clicking on the box (containing the name of the biomass), a drop-down table will appear, depicting the feedstocks present in the database, which can then be selected. The amounts of biomass are mostly indicated in tonne (Mg) per year. However, there are two exceptions: for the farm where the biogas system is located, the number of cows can be filled in to determine the local availability of manure, and for the same farm, an amount of hectares can be filled in for growing energy crops locally (e.g. maize). Transport

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distances can be indicated for all the feedstocks programmed in the model per feedstock type. Most biomass types are transported by truck or tractor; however, manures from the farm and digestate can also be transported by pipeline (Fig. 3.8 nr. 3). For upgrading, the transport distance of green gas to the injection station can be changed (Fig. 3.8 nr. 4), and for the CHP unit, the electric efficiency of the engine, the heat use for district heating, and the transport distance of heat towards the district heating system can be altered (Fig. 3.8 nr. 4). The total mass of feedstock and the ratios in percentages are graphically indicated for a whole year. Additionally, there is a graph that indicates the ratio between manure and feedstocks (Fig. 3.8 nr. 5). In the Netherlands, regulation states that on a yearly base, at least 50% of the total input in the digester must be comprised of manure. The other 50% can be made up of other feedstocks (e.g. maize or grass).

The primary results expressed in the four main indicators (discussed in Section 3.2.1) are graphically indicated for comparison between green gas and CHP with the reference of natural gas and grey electricity (Fig. 3.8 nr. 6). The efficiencies are given in [P]EROI, the emissions are given in GWP100, and the environmental impact is given in Pt or EcoPoints. These expressions are described in Pierie et al., 2016 [36]. The economic costs are indicated within the economic section of the model (Section 3.7.6). Overall, the "scenario planner" can already be used to perform a quick and dirty analysis of biogas production pathways, which will provide an indication of overall impact and efficiency. However, when more specific details are needed, users will need to delve deeper into the model.

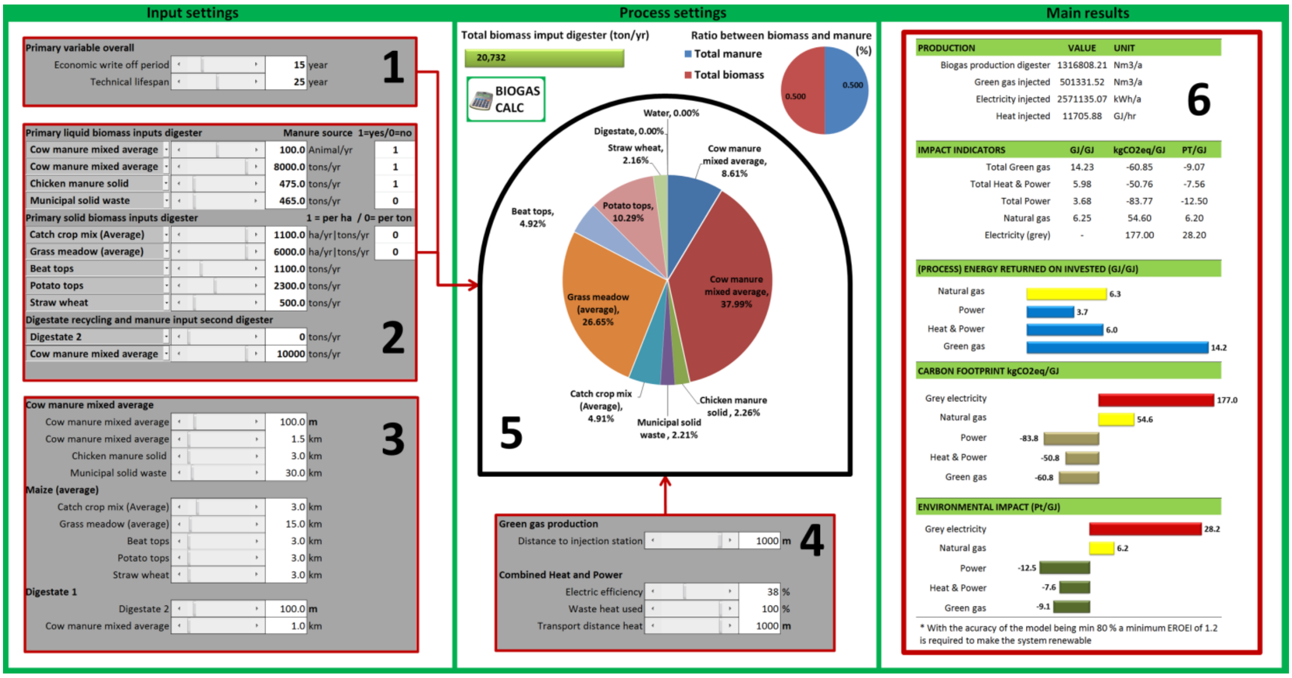

Fig. 3.8. The main scenario planner within the EBS model

3.7.2. Digestate planner

Digestate is what remains after the biogas is extracted from the feedstock. If the feedstocks are cleared by regulation for use as fertilizer, then the digestate can be used as fertilizer on agricultural fields. There are several ways in which to do this: digestate can be used directly as fertilizer, or it can be separated into a liquid "thin" and a solid "thick" fraction. Additionally, the thin fraction can be upgraded. The handling of digestate can be planned in "the digestate planner" section per fraction (Fig. 3.9). The percentage of manure separated into a thin and thick fraction can be indicated in the model (Fig. 3.9 nr. 1), along with the per fraction amount used to displace fossil fertilizer (Fig. 3.9 nr. 2). If, for instance, half of the fossil fertilizer normally used on the farm is replaced with one of the fractions, then the impact of 50% fossil fertilizer will be mitigated in the biogas production chain. Furthermore, the amount of fraction used on the farm (or other locations) can be indicated. Also, the fraction can be sold in two of the locations (Fig. 3.9 nr. 2). Transport distances to locations can be included per location (Fig. 3.9 nr. 3). Finally, when a fraction is not utilized at any location, it has to be discarded and processed at a special facility. The costs of waste disposal are included, and the transport distance to this facility can be indicated (Fig. 3.9 nr. 3).

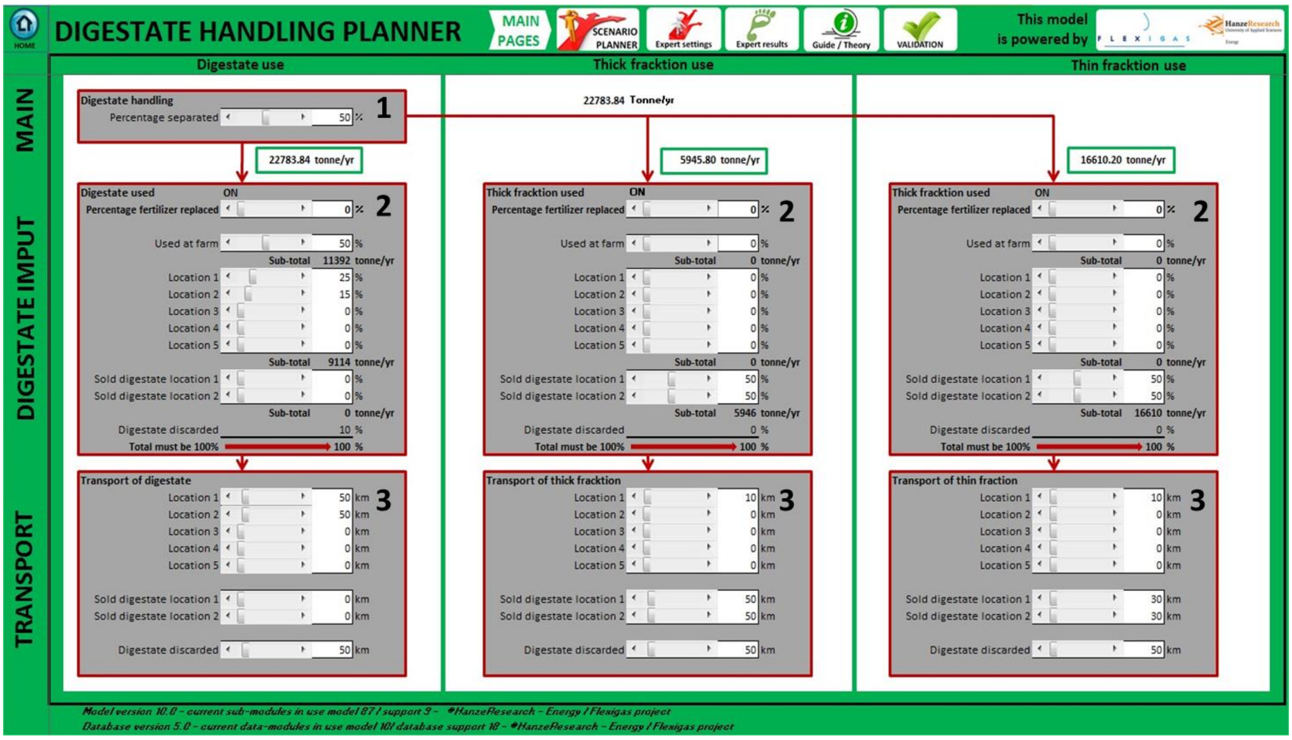

Fig. 3.9. The digestate handling scenario planner within the EBS model

3.7.3. Energy saver

The EBS model also allows one to utilize several chain optimization options within the "energy saver." These options can optimize the expressions of the AD biogas production process. The EBS model currently has four optimization options (Fig. 3.10). Within the green gas production pathway, internal energy production (through the use of a CHP unit) can be enabled, which will produce the needed electricity and heat for the process (Fig. 3.10 nr. 1). The unit can be programmed on both electric output and heat output (Fig. 3.10 nr. 1); an overproduction of electricity will be sold on the grid, whereas an overproduction of heat will be discarded to the environment. The effects of internal energy production are indicated in a table, which can help to optimize the system (Fig. 3.10 nr. 5). Within the model, three current management systems can be mitigated, namely, manure storage (Section 3.5.1), grass management (Section 3.5.2), and harvest remains (Section 3.5.3), and the mitigation of each functional unit (e.g. [P]EROI, GWP 100, and EcoPoints) can be adapted individually (Fig. 3.10 nr. 2). For instance, in the scenarios, the mitigation of energy is normally switched off, whereas the mitigation for carbon footprint and

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environmental impact is mostly switched on. The effect of mitigation is depicted in a table for comparison (Fig. 3.10 nr. 6). Furthermore, fuel used for transporting the feedstock can be replaced with green gas. The mitigation of each functional unit (e.g. [P]EROI, GWP 100, and EcoPoints) can be adapted individually or as a group (Fig. 3.10 nr. 3). For instance, if half of the trucks run on green gas, then half of the impact for every functional unit can be mitigated. The effect of fuel replacement is depicted in a table for comparison (Fig. 3.10 nr. 6). The green gas used as fuel for the trucks is not injected into the gas grid as it is converted into fuel beforehand. Additionally, there is an option to reduce the heat energy required by the digester tank (Fig. 3.10 nr. 6), thereby simulating improved insulation or installations. The resulting effects can be observed in both the output of optimization and the main results, which are included in the energy saver (Fig. 3.10 nr. 7 and 8).

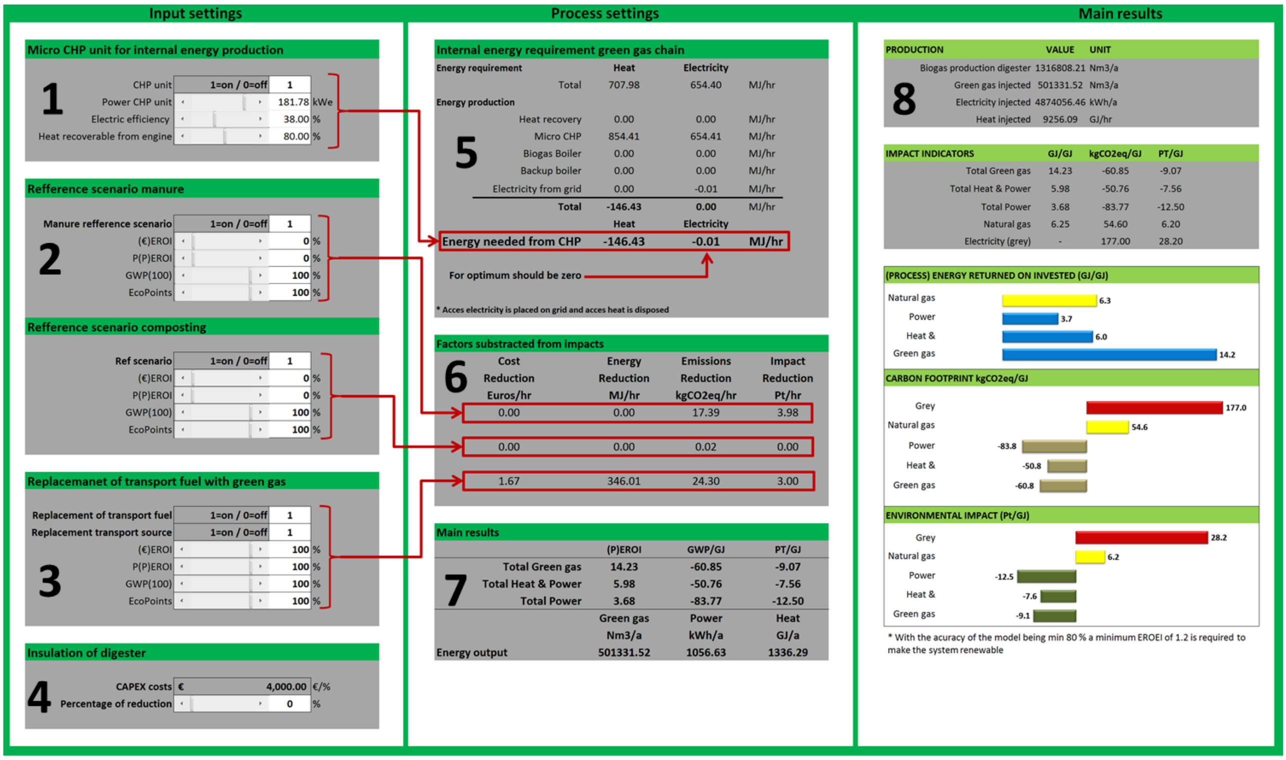

Fig. 3.10. The energy saver within the EBS model

3.7.4. Expert settings

Variables that are not present in the main input sheets can be traced back in the expert setting section. A default setting, which can reset all variables to default, is included in the expert settings (Fig 3.11). A minimum and maximum value and a source of the information can also be added to these expert settings. Specific variables can be tweaked in this section; however, this is only recommended for expert users.

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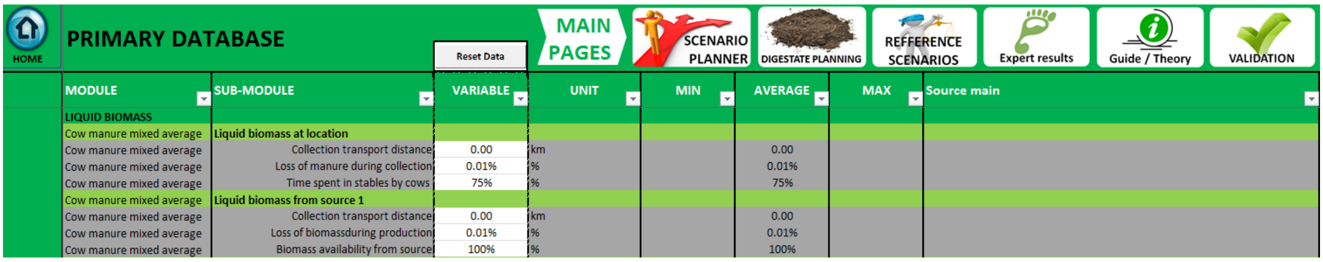

Fig. 3.11. The professional settings within the EBS model

3.7.5. Model results

Within the results section of the model, further insight—in addition to the results already indicated in the scenario planner (Fig. 3.12 nr. 3)—is provided regarding the following aspects of the biogas production chain: the input of the specific feedstock in tonnes (Mg) per year (Fig. 3.12 nr. 1); the energy requirements per main process (Fig. 3.12 nr. 2) of the complete pathway; the amount of biogas produced per feedstock used per hour (Fig. 3.12 nr. 5); the amount of green gas produced in Nm^3 and the balance between energy input and output (Fig. 3.12 nr. 6); the produced heat and power in MJ and the balance between energy input and output (Fig. 3.12 nr. 7); the emissions (Fig. 3.12 nr. 8) and environmental impacts (Fig. 3.12 nr. 9) indicated per main process of the biogas production pathway; and the mass distribution of the digestate output in digestate, thin fraction, and thick fraction produced (Fig. 3.12 nr. 10). Additionally, the range of yearly feedstock input, where the model is validated for use, is indicated (Fig. 3.12 nr. 11).

Fig. 3.12. The expert results within the EBS model

3.7.6. Economic cost analysis NPV

The economic costs of the programmed biogas production pathway can be analyzed in the economic scenario planner. The cost calculations in the model are based on an NPV cost analysis and a payback period analysis over a technical lifespan of 25 years. The main capital expenses (CAPEX) and operational expenses (OPEX)—in the form of costs of energy, e.g., electricity or gas—are derived from the model (Fig. 3.13 nr. 1), and additional CAPEX costs can also be included therein (Fig. 3.13 nr. 2). Revenues and subsidies can be programmed into the model (Fig. 3.13 nr. 3), while main economic variables (e.g. inflation, interest etc.) can be altered to fit the current situation (Fig. 3.13 nr. 4), and main operational costs outside of the biogas production pathway can be selected per business case (Fig. 3.13 nr. 5). Furthermore, a scrap value can be indicated for the installation after its technical lifetime (Fig. 3.13 nr. 6). Additionally, labor costs not indicated in the overall operation and management can be included (Fig. 3.13 nr. 7). For the programmed business case, the main economic expressions include NPV and payback period (Fig. 3.13 nr. 8), with an additional explanation on expenditure, depreciation, income, and operational costs. The results for the green gas (Fig. 3.13 nr. 9) and CHP (Fig. 3.13 nr. 10) utilization pathways are indicated separately.

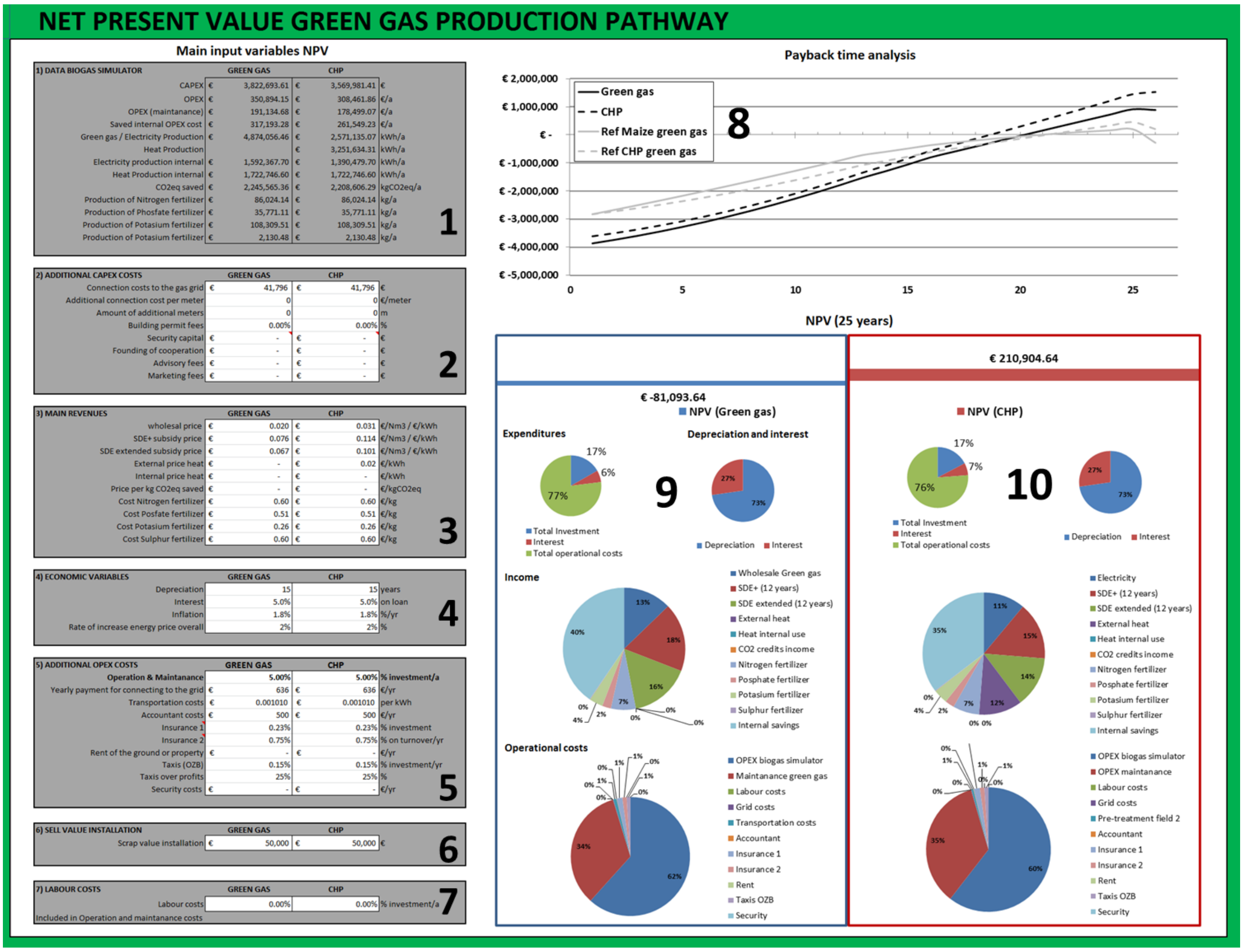

Fig. 3.13. The economic cost planner within the EBS model

3.7.7. Configuration of sub-modules in EBS model

The sub-modules are the main building blocks of the EBS model, and every sub-module is modeled in an individual Excel sheet (Fig 3.14). The layout of every sub-module is similar and follows the preset structure indicated in Fig. 3.3. This makes the structure of the EBS model more transparent and the individual sub-modules reusable for other similar processes. The main components within a single sub-module are as follows (Fig 3.14): the main variables used in the calculation of the specific sub-module (Fig. 3.14 nr. 1); the main impacts per expression (e.g. costs, [P]EROI, carbon footprint, and EcoPoints) resulting from all energy and material flows used in the sub-module (Fig. 3.14 nr. 2); the main positive impacts per expression, resulting from all green energy and material flows (e.g. green gas, electricity, and heat production) produced in the sub-module and possible mitigation (e.g. replacing natural gas with green gas will save emissions when used, thereby creating positive impacts that can be mitigated), (Fig. 3.14 nr. 3); the primary flows entering and leaving the sub-module (e.g. biomass or biogas), (Fig. 3.14 nr. 4); the direct energy and material flows needed for the processing of the primary flows(e.g. electricity or diesel), (Fig. 3.14 nr. 5); the indirect energy and material flows (Fig. 3.14 nr. 6), which are needed for the production of the direct material and energy flows; and the embodied material and energy flows (Fig. 3.14 nr. 7), which calculate the impact factors of the infrastructure used in this sub-module. Positive impacts on the expressions are avoided impacts when mitigated.

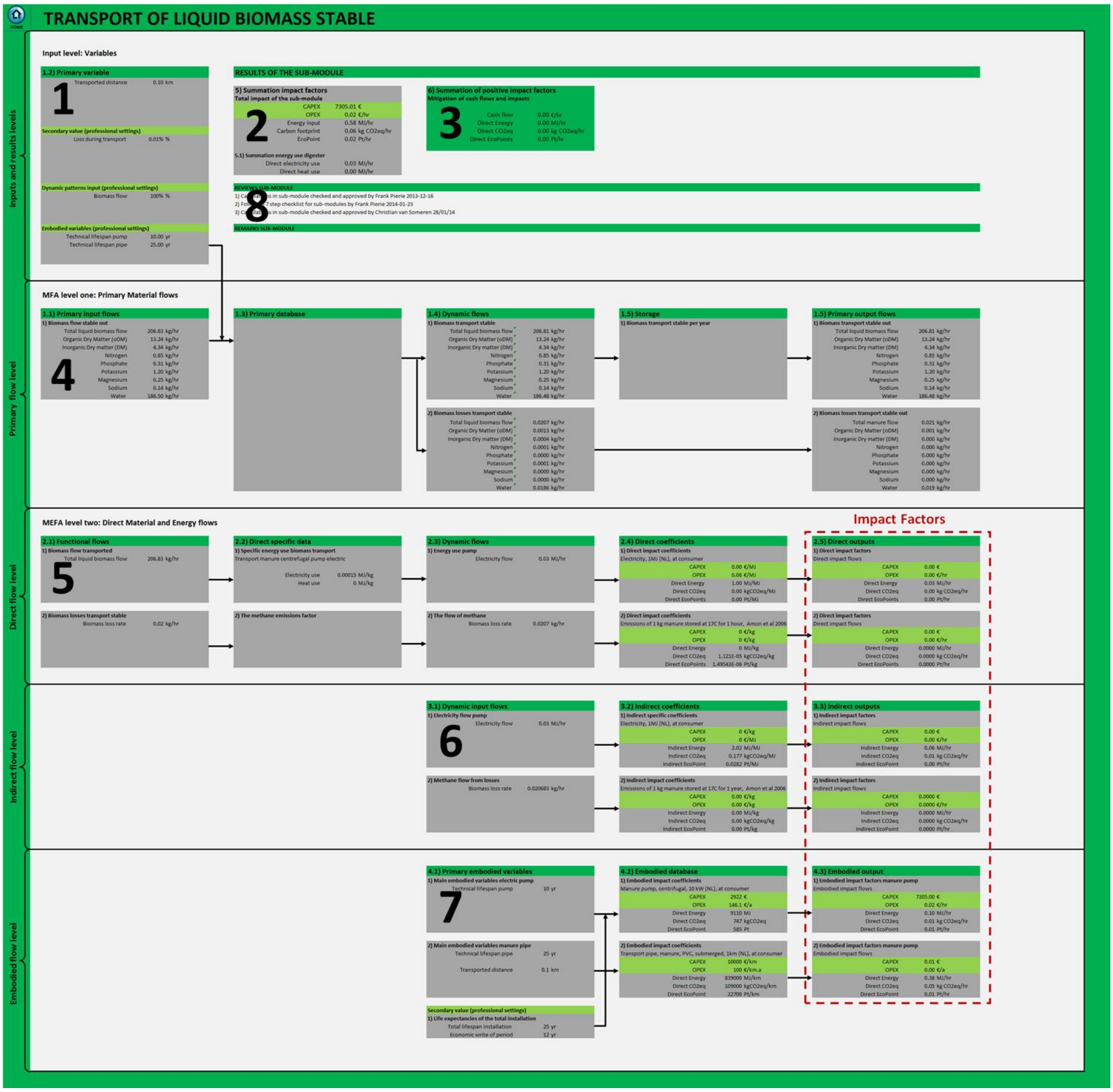

Fig. 3.14. Overview of a single sub-module —in this case, a front loader transport— within the EBS model

3.8. Discussion

The EBS model is intended to help to determine the best possible and the most efficient and sustainable use of biogas for specific geographic locations. Validation and sensitivity analyses are conducted to validate the integrity of the EBS model (Chapter 4). However, biogas production pathways are complex, containing several factors and variables that must be taken into account. The accuracy of the model will depend strongly on the quantity and quality of the data it contains, from both literature and practice. Therefore, all of the main data used in the new model can be altered to include new developments or additional datasets. To express the efficiency and environmental impact, three specific impact factors are chosen to provide an overview and to gain more transparency. However, they cannot offer detailed information regarding specific environmental impacts (e.g. acidification). The current version of the model with the multiple variable input levels can only be handled by an expert in the field of modeling and biogas systems.

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Therefore, one should always consult an expert when using the model for advice or research. Through the use of the EBS model, in expert hands, knowledge can be communicated to society, where it can help to decrease uncertainties in the development and realization of renewable and sustainable decentralized AD biogas production pathways.

3.9. Conclusion

Within this article, the use, operation, and structure of a model for the environmental assessment of anaerobic biogas production pathways is discussed. The EBS model is capable of calculating the economic cost, energy efficiency, carbon footprint, and environmental sustainability of small (farm)-scale AD biogas production pathways (2,000 up to 50,000 Mg/a of biomass input). The results from the model are expressed in four main indicators: the economic cost in NPV and (economic) payback period, the efficiency in [P]EROI, the carbon footprint in GWP100, and the environmental impact in EcoPoints. The EBS model is constructed around a clear methodology, comprised of the industrial metabolism concept, the modular approach, a material and energy flow analysis (MEFA), a life cycle analysis (LCA), and an economic NPV analysis. The modular approach separates the biogas production pathway into individual physical processes, which makes the model more transparent, flexible in use, and programmable with different settings. The Excel-based EBS model is a collection of sub-modules, which model the process steps needed to produce biogas, and every sub-module used in the biogas production pathway is described in a separate tab in the model. Individual sub-modules can be added or removed, activated or deactivated, and/or rearranged to suit the modeler's preferences. To navigate through the large amount of sub-modules, a hyperlink navigation structure was implemented based on pictures that form an MEFA of the biogas production pathway (Fig. 3.4). The most important variables are indicated in the scenario planner, where liquid and solid biomass substrates can be programmed in with subsequent transport distances. In the digestate planner, particular scenarios can be specified for digestate handling, including transport, upgrading, processing of excess digestate, and selling of digestate products. In the energy saver, additional options can be controlled for internal energy production, mitigation, the use of green fuel, and the reduction of heat requirements in the process. In the economic planner, cost-related values are indicated for performing economic scenarios. The main calculation of the EBS model is based on several databases containing the values (e.g. heat use per kg of manure) used for determining the four main expressions. All the values in the databases can be changed if new and more accurate data are available. The modular approach makes the model flexible in use and programmable with different settings, which allows for the research of several aspects of the biogas production pathway, including the sustainability of biomass feedstocks; the effect of chain optimization through internal energy production, green gas as transport fuel, and the mitigation of current waste management pathways; and the sustainability of the biogas production pathway as a whole. Furthermore, the signal of sustainability in four clear indicators provides an understandable reference for comparison with other scenarios. Overall, the EBS model can help to both shed light on the sustainability of specific biogas production pathways and indicate options for improvement.

Chapter 4
DESIGN: VALIDATION

An integrated approach for the validation of energy and environmental system analysis models: used in the validation of the Flexigas Excel BioGas model

ABSTRACT

Verification and validation (V&V) is an essential step in the completion of computational models. Therefore, within this article, a review of validation techniques used in the V&V of the (Excel) BioGas simulator (EBS) model has been performed. The V&V process can indicate the value and accuracy of the EBS model, which calculates the environmental impact of anaerobic digestion (AD) biogas production pathways. Through the use of the method described within this article, inconsistencies in the model are resolved, the strengths and weaknesses of the model are found, and the concept of the model is tested and strengthened. The V&V process not only improves the model itself, but also helps modelers to widen their focus and scope. Therefore, this article can also be used in the V&V process of similar models. The main result from the V&V process indicates that the EBS model is valid with added scientific value and sufficient accuracy; however, the EBS model should be considered as an expert model, only to be used by expert users.

Additional information chapter

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Title in proceedings: The development, validation, and initial results of an integrated model for determining the environmental sustainability of biogas production pathways

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4.1. Introduction

The Flexigas project researches the integration of biogas produced from anaerobic digestion (AD) within decentralized smart energy systems [34]. One goal of the project is the development of "a BioGas Simulator," a tool that can be used for modeling the energy efficiency and environmental sustainability of complex energy production pathways (EPPs). For this purpose, a specific model was created, called the (Excel) Biogas Simulator (EBS) model. The Excel-based EBS model is capable of calculating the economic cost, energy efficiency, carbon footprint, and environmental sustainability of small (farm)-scale AD biogas production pathways with a biomass input of 2,000 up to 50,000 Mg/a. Within exact science, models are often used for complex calculations. Variables in the model are changed for different scenarios to observe the effect on the results, thereby allowing for scientific analysis. However, before the results from a model can be deemed trustworthy (or not), the model must first be verified and validated [85]. The process helps to strengthen the model by resolving mistakes in the model, and it brings to light the model's strengths and weaknesses. Furthermore, verification and validation (V&V) also helps to test and strengthen the conceptual model and research goals behind it. Therefore, the V&V of a newly created model is a vital part of the process towards a trustworthy model.

However, validation in itself is not a solid science; "Validity, in its generic form, refers to measuring what we think we are measuring or, in the case of models, representing what we think we are representing" [85]. In the literature, the definition of V&V is not settled, as there are still differences among studies [85]. Overall, a model is considered to be valid for a set of experimental conditions if its accuracy is within an acceptable range, which is the amount of accuracy required for the model's intended purpose [86]. In this context, it is important to remember that "A model should be developed for a specific purpose (or application) and its validity determined with respect to that purpose" [86]. Theoretically, a model should represent exactly the physical system it models. In the V&V of physical systems, there is "ground truth" against which the as-built system can be measured: "it can either fly so far or it can't, it weighs less than X or it doesn't, and so on" [85]. However, "it is often too costly and time consuming to determine that the model is absolutely valid over the complete domain of its intended applicability or describes the ground truth. Instead, tests and evaluations are conducted until sufficient confidence is obtained that a model can be considered valid for its intended application" [86].

There is an abundance of literature available describing the process of validation [85-93]; however, this literature and the variety of options make it difficult to select a specific V&V method for the EBS model, which leads to the main question: how does one verify and validate the EBS model, such that the accuracy of the models intended purpose is within an acceptable range? Therefore, in this article, a review was performed on validation literature to select the most viable V&V method for the EBS model [85-93]. The review concluded that most articles had notions and ideas of how to perform a V&V; however, they lacked a clear method to follow, with the exception of Balci et al. [88] and Sargent [86]. Balci et al. described a list of golden rules that are helpful in the validation process, and Sargent described a list of topics or validation techniques to use within the V&V process of simulation models. The latter is specifically of interest for the validation and verification of the EBS model due to the detailed description that Sargent provides per technique. Therefore, the developed V&V method described within this article is derived from Sargent, 2013

[86]. Overall, the V&V process can indicate the value and accuracy of the EBS model and therefore add to scientific understanding regarding the sustainability of biogas production. The V&V method designed specifically for the EBS model is discussed in the method section; then, the results from the V&V process performed on the EBS are discussed in the result section. Finally, the results are reviewed and summarized in the discussion and conclusion sections.

4.2. Methodology

The model will be validated through the use of a question list containing validation techniques—retrieved from Sargent, 2013 [86]—selected specifically for the validation of the EBS model. The focus points are separated into two main sections. First, the validation will focus on the goal of the model in order to determine whether the correct model was built for answering the main research questions (*Did I build the right thing?*). Second, the model itself will be verified, through a testing structure, to estimate transparency and correctness among other things (*Did I build the thing right?*). The V&V process will be performed with the help of multiple verification techniques that address the concept, the overall model, or a particular area of the model.

4.2.1. Definition of Validation and Verification

In this article, validation confirms that the realized system complies with stakeholder requirements (the right system was built). It is defined as the “substantiation that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model” [86]. Verification confirms that all elements of the system meet technical requirements (the product was built right) [85]. It is defined as “ensuring that the computer program, the computerized model, and its implementation are correct” [86].

4.2.2. Expected accuracy of the model

Most models can be placed along a “continuum of objectivity” (Fig. 4.1a), where physical models are often more objective, and theoretical models more abstract [85]. The V&V process and techniques can be determined according to the position of the model within this “continuum of objectivity.” When considering the V&V of theory-based models, however, the option of verifying against ground truth (i.e., historic data collected from a real system) is often not available to modelers [85]. Within the aforementioned context, the EBS model, being a physical model, can be compared on many aspects, ranging from the factual aspects (e.g. compared to the ground truth Fig. 4.1a), to the conceptual aspects (e.g. opinion by experts or face Fig. 4.2).

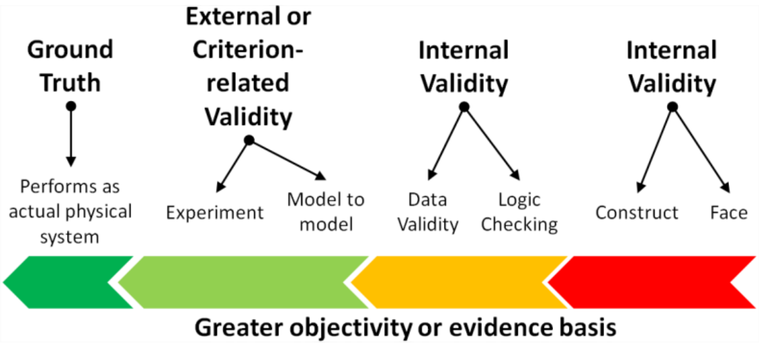

Fig. 4.1a. The ground truth principle within V&V [85]

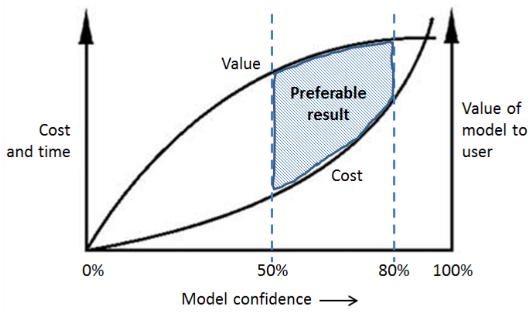

Fig. 4.1b. Effort reward graph for V&V [86]

There is a link between accuracy and the development time required. In this context, the goal is to retain the highest accuracy with the lowest time requirements (Fig. 4.1b). Therefore, for the fact-based comparison, the preferred accuracy of the EBS model should be at least 80% for the basic calculations and around 80% for the economic calculations (Fig. 4.1b). However, for the primary calculation (e.g. biogas, green gas, or heat and power production), accuracy is expected to be in the range of 95% to 99%. Accuracy levels will be mainly expressed in the percentage difference between the reference models and the EBS model. These should then not exceed 20% for the model to maintain its 80% accuracy. For the conceptual validation, however, the accuracy of 80% is difficult to quantify. Therefore, additional theoretical explanations are required.

4.2.3. Validation of concept: Did I build the right thing?

The first step in the overall V&V process will be to focus on the problem entity (Fig. 4.2) and the conceptual model. When building a model, it is important to keep in mind that most models have the purpose of providing answers to complex issues. From this perspective, it is important to start with the right question and then verify it. In short, the following question must be asked: did I build the right model? To validate this, the concept must comply with the following statements:

1) The model adds to scientific understanding or to societal benefit.
2) The model refers to clear answers that can be provided through modeling.
3) The model is reviewed (e.g. literature review) and verified by experts in the field (e.g. professors or researchers).

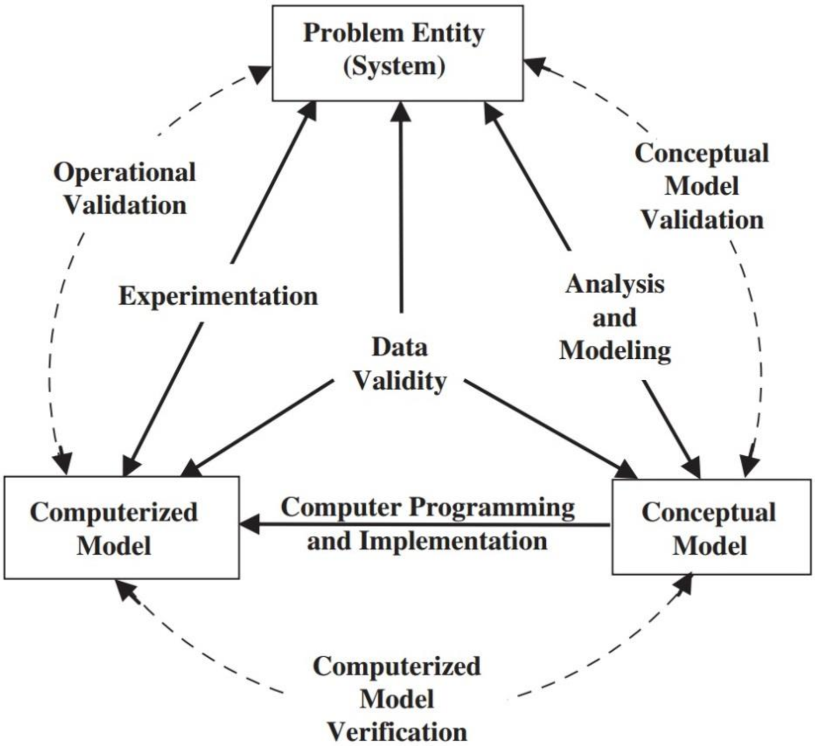

Fig. 4.2. Main list of subjects used in the V&V process [86]

4.2.4. Model verification: Did I build the thing right?

This section discusses the V&V techniques selected for the EBS model. Most of the techniques described here are found in literature, although some may be described slightly differently to specifically fit the EBS model. The V&V techniques can be used either subjectively or objectively. By subjectively, we mean the modeler and experts in the field employ common reasoning, and by objectively, we refer to the use of some type of mathematical procedure or statistical test, for example hypothesis tests or confidence intervals [86]. The V&V process utilizes a combination of techniques, which can be used to verify individual components within the model and the complete model. The following list of verification techniques is retrieved from Sargent, 2013 [86] for use in this article and in the V&V process of the EBS model:

(A) Comparison to other models: Various results (e.g. outputs) of the simulation model being validated are compared to the results of other (valid) models. For example, simple cases of a simulation model are compared to known results of analytic models, and the simulation model is compared to other validated simulation models.

(B) Data relationship correctness: Data relationship correctness requires data to have the proper values regarding relationships that occur within a certain type of data and between and among different types of data. For example, a question related to data relationship correctness would be, are the values of data collected on a system or model correct for some known relationship within some type of data such as an inventory balance relationship or a dollar relationship?

(C) Event validity: The "events" of occurrences of the simulation model are compared to those of the real system to determine whether they are similar. For example, the number of fires in a fire department simulation is compared to the actual number of fires.

(E) Extreme condition test: The model structure and outputs should be plausible for any extreme and unlikely combination of levels of factors in the system. For example, if in-process inventories are zero, then production output should usually be zero.

(F) Face validity: Individuals who are knowledgeable about the system are asked whether the model and/or its behavior are reasonable. For example, they are asked whether the logic in the conceptual model correct and whether the model's input–output relationships are reasonable.

(G) Internal validity: Several replications (runs) of a stochastic model are made to determine the amount of (internal) stochastic variability in the model. A large amount of variability among the replications may cause the model's results to be questionable, and if this variability is typical of the problem entity, then it may question the appropriateness of the policy or system being studied.

(H) Parameter variability–sensitivity analysis: This technique consists of changing parameters in the model to determine the effect on the model's behavior or output. The same relationships should occur in the model as in the real system. This technique can be used qualitatively (directions only of outputs) and quantitatively (both directions and [precise] magnitudes of outputs). Those parameters that are deemed sensitive because of significant changes in the model's behavior or output should be made sufficiently accurate prior to using the model. (This may require iterations in model development.)

(I) Structured walkthrough: The model under review is formally presented, usually by the developer, to a peer group to determine the entity's correctness. An example is a formal review of computer code by the code developer explaining the code, line by line, to a set of peers to determine the code's correctness.

(J) Trace: The behavior of a specific type of entity in a model is traced (followed) through the model to determine whether the model's logic is correct and if the necessary accuracy is obtained. (Most current simulation software provides for trace capability, thereby making the use of traces relatively simple.)

4.3. Results

The list of V&V techniques mentioned in the methods (Sections 4.2.3 and 4.2.4) will be used to validate the EBS model. The results from the V&V process will be discussed in the following sections.

4.3.1. Model validation: did I build the right thing?

To determine whether the right model was built, the verification of the concept method is applied (described in Section 4.2.3) to the EBS model. The overall results indicate that the validated model adds to scientific understanding and helps to answer the main questions stated in the line of research for which the model is constructed. The model is based on existing literature and methods, and experts from the field, who were addressed for the V&V of the EBS model, agree that the right model was built for the main question posed, which asks, *How to model and measure the sustainability of (renewable) EPPs, focused on farm-scale AD biogas production?* In the following section, this result is explained in more detail.

4.3.1.1. Adding to scientific understanding or to social benefit

The EBS model combines energy and environmental system analysis, geographic modeling, and temporal dynamic load modeling to gain more insight into biogas production pathways. The discussed model in this article can expand current knowledge on the energy efficiency and environmental sustainability of biogas production pathways operating within a decentralized smart energy system. The EBS model can also help in designing a tailor-made AD biogas production pathway for a specific geographic location, thereby increasing the efficiency and sustainability of biogas as a renewable resource. Furthermore, a full life-cycle-based understanding of the absolute energy and environmental impact of biogas and green gas production pathways can help governments to form proper policies that effectively support the EU in achieving renewable energy and emission reduction goals, as described in the EU energy directive and the EU roadmap 2050 [16, 60].

4.3.1.2. Refer to clear answers which can be provided through modeling

The EBS model is based on the industrial metabolism concept, and it is expanded with three known methods: the material flow analysis (MFA) method, which is used to simulate the decentralized energy system; the material and energy flow analysis (MEFA) method, which is used to determine the direct energy and material requirements; and the life cycle analysis (LCA), which is used to calculate the indirect material and energy requirements, including the embodied energy of the components and required maintenance. The resulting efficiency and environmental impact calculated in the EBS model will be expressed in three known indicators, which correlate with the definition of “strong sustainability” [21], wherein environmental quality precedes social prosperity which precedes economic prosperity [21, 76]. The indicators used are the (process) energy returned on invested ([P]EROI), indicating the efficiency of the chosen scenario in energy invested in the process divided by energy produced by the same process [77]; the carbon footprint (GWP100), indicating global warming potential in kgCO2-equivelant per GJ of produced energy [79]; and the Eco Indicator 99, indicating the overall environmental impact on the ecology, nature, and human health using the ReCiPe indicator [94] given in Pt per GJ of produced energy. Taken together, these indicators will provide a clear overall impression of the efficiency and sustainability of biogas production pathways functioning within dynamic systems, and they can help to answer the main question and main goal stated, namely, how to measure the sustainability of complex EPPs. The combined method described in this section, which forms the base of the EBS model, is integrated into a scientific article, which has been accepted in a peer-reviewed journal [36], adding an additional review by experts.

4.3.1.3. Review by experts

A group of reviewers was selected, made up of specialists in the field of modeling and biogas systems and in the field of energy transition. To receive feedback on a wide range of subjects regarding the model, a mixed review group is chosen on all aspects (Table 4.1).

Table 4.1. The participating reviewers for the EBS model

Name	Organization	Position
Wim van Gemert PhD. MSc.	Hanze University	Leading lector Hanze University—Energy
Jan Bekkering MSc.	Hanze University	PhD. Researcher on the topic of modeling biogas
Evert Jan Hengeveld MSc.	Hanze University	PhD. Researcher on the topic of modeling biogas
Wen Liu PhD. MSc.	Hanze University	Researcher and specialist in EnergyPlan model
Henk Moll Prof. PhD. MSc.	RuG—IVEM	Professor on subject Energy and Environmental Sciences
René Benders PhD. MSc.	RuG—IVEM	Researcher and designer of several energy models
Gideon Laugs MSc.	RuG—IVEM	PhD. Researcher of decentralized storage modeling
Johan Holstein MSc.	DNVGL	Safety expert in the field of gas

The reviewing process began with an opening session, during which the EBS model was explained to the reviewers. The inner workings, the formulas, and the used variables were explained through the use of a structured walk-through of the EBS model. At the end of the workshop, the reviewers were sent home with a version of the model and an assignment containing explanatory documents and a questionnaire. Within this questionnaire, the reviewer was asked to grade the model as either sufficient or insufficient for use. After the reviewing process, the group reconvened in a final walk-through session, where feedback, remarks, and improvement options were discussed. At the end of the session, the verdict was given regarding the validity of the EBS model. The group of reviewers concluded that the right model was built for answering the stated research questions (Section 4.3.1), and the group acknowledged the use of correct literature and methods (Sections 4.3.1.2. and 4.3.1.3.). Furthermore, according to the reviewers, the model will add to scientific understanding when used correctly (Section 4.3.1.1.). However, the model's layout and use are too complex for non-expert users; therefore, the EBS model should only be used under supervision of one of its creators until a sufficient level of expertise is reached. Overall, the review session helped to strengthen the model. During both sessions, many corrections where made, and adaptions were devised and put in place, including a more transparent interface. The classification of the model "as only usable by experts" was kept due to the overall complexity of the variables and outcomes of the model.

4.3.2. Model verification: Did I build the thing right?

To indicate whether the model was built correctly, the V&V method (described in Section 4.2.4) is applied to the EBS model. Overall, the results indicate that the model and the used database were built correctly. Statistical verification, validation tests, and experts from the field indicated that the right model was built and that it is within the accuracy level set (at 80% accuracy of the model). In the following section, this result is explained in more detail.

4.3.2.1. Comparison to other models

During this V&V phase, the EBS model was compared to the Bekkering et al. model [95], which focuses on the economic aspects of farm-scale AD biogas production. The Bekkering et al. model has been verified against the Weidenaar model [96], and calculation from ECN for subsidization schemes in the Netherlands [97], The Bekkering et al., model has produced several articles [61, 98-

100]. The Bekkering et al. model contains the same calculations for biogas production and biogas upgrading to green gas as the EBS model, with indicators for economic cost, energy efficiency, and carbon footprint. Therefore, both models have common outputs in biogas and green gas production, cost per Nm3 of green gas, and energy efficiency and carbon footprint of green gas production. To compare both models, a comparison scenario was created, based on a co-digestion system of manure (50% fresh matter [FM]) and maize (50% FM). The main variables for biogas production were kept the same (Table 4.2) in both models, and losses of biomass and biogas were switched off, excluding the biogas loss from the digester. However, professional settings between the models differ (e.g. losses of biomass during processing).

Table 4.2. Main inputs comparison scenario models

Main variables	**Value**	**Unit**
Economic depreciation period	12	Years
Technical lifespan installation	25	Years
Electricity price	0.14	€/kWh
Operating hours per year	8760	h/a
Total transport distances	0	km
Losses of biogas from digester	1	%
Manure input	9000	Mg/year FM
Organic dry matter manure	8	%
Biogas potential of manure	310	Nm^3/Mg.oDM
Methane potential of manure	180	Nm^3/Mg.oDM
Cost of the manure	-15	€/Mg
Maize input	9000	Mg/year FM
Organic dry matter maize	31.5	%
Biogas potential of maize	620	Nm^3/Mg.oDM
Methane potential of maize	330	Nm^3/Mg.oDM
Cost of the maize	35	€/Mg

*Transport was not indicated in the scenarios. The price for the biomass is the same in both models

The comparison of the two models indicates that the EBS model performs sufficiently when looking at the primary calculations of biogas and green gas production and the costs of green gas. The difference in biogas production between the models is around 0.74%, which can be found in the professional settings and margins or rounding of numbers (Table 4.3). The costs differ by 3.58%, which is also within an acceptable level (Table 4.3). However, when examining the energy efficiency and carbon footprint, the values differ significantly—around 32% for energy efficiency and 39% for the carbon footprint (Table 4.3). The Bekkering et al. model does not utilize an LCA for the calculation of energy efficiency and carbon footprint; therefore, discrepancies can be expected, as the system boundaries of the EBS model take into account more impacts (e.g. indirect energy production and embodied energy). Within this context, the Jan Bekkering et al. model cannot be used for the verification of environmental indicators.

Table 4.3. Outcomes comparison scenario both models

Outcome	Unit	Bekkering et al, model	EBS model
Biogas production	Nm3/h	226	223.9 [a]
Green gas production	Nm3/h	135.0	134.0 [a]
Costs	€ct/Nm^3 green gas	75.3	78.0 [a]
Efficiency	[P]EROI	3.9	2.6
Carbon footprint	kgCO2eq/GJ (GWP100)	29.6	41.1 [b]

[a] The use of the internal biogas boiler for heating the digester is not included

[b] Emissions when using a biogas boiler for heating the digester

4.3.2.2. Data relationship correctness

In this section, the database of the EBS model will be compared to peer-reviewed literature. Most of the values and variables (around 90%) used in the EBS model are based on either peer-reviewed literature, reports, or practical data [101]. However, there is still a large variation between the values and variables used in literature. Within the model, most of the values and variables, when multiple sources are available, are based on averages of the total range. There are cases when only one source from the literature is present; the use of this number depends on the quality of the source. Additionally, the model itself is constructed in such a way that all important variables can be altered, for instance when new and better data are presented. All values used in the model are also fitted with a source. Besides the data themselves, the correlation between the data, namely, the calculations, are all performed through a standard modeling methodology accepted in a peer-reviewed journal, described in Pierie et al., 2016 [36].

4.3.2.3. Event validity

In this section, the EBS model will be verified against an actual biogas facility situated at the Dairy Campus near the city of Leeuwarden, the Netherlands. The facility consists of two digester units and two CHP units; the digesters were owned by the University of Wageningen. During operation, the biomass inputs and electricity production were recorded. The outcomes of the EBS model will be compared in two cases with data from the WUR digesters: (A) the primary biogas production calculated by the WUR digesters input will be verified against the biogas production of the EBS model, and (B) the measured power output of the CHP units from the WUR digesters will be compared to the EBS model.

(A) The WUR biogas input sheet comparison: In this comparison, the theoretical biogas potential calculated by the employees of the WUR digesters in Leeuwarden for the year 2011 will be compared to the EBS model, which was programmed with the same values (Table 4.4).

Table 4.4. Main variables WUR digester and EBS model

Main variables	Value	Unit		
Average methane content	58.07	%		
Theoretical efficiency CHP unit	35	%		
Loss of biogas	0	%		
	Biomass input	**Organic fraction**	**Biogas potential**	**Biogas potential**
Feedstocks digester	Mg/a	oDM (% of FM)	m3/Mg.FM	m3/Mg.oDM
Dairy cow manure	7107.4	6%	20	333.3
Solid manure	2442.7	33%	70	212.1
Maize field	1917.3	34%	175	514.7
Organic waste flows	531.9	62%	700	1129.0
Maize source	433.2	45%	300	666.7
Unions and onion peels	550.7	20%	60	300.0
Ecofrit	3179.5	20%	500	500.0
Digestate reuse	505.4	20%	5	25.0

The theoretical output of the calculation sheet is comparable with the outcome of the model using the same input parameters, with a difference of 0.35% (Table 4.5). However, when assessing the actually measured power production of the CHP unit of the WUR digester, the production is 31.03% less than that of the EBS model (Table 4.5). Therefore, the use of theoretical values in the input sheet might not reflect the actual process taking place in the biogas production pathway.

Table 4.5. Main outputs from the comparison scenario

Outcome	Unit	WUR data sheet	EBS model
Biogas production	Nm^3/hr	171.7	171.1
Methane	Nm^3/hr	99.7	99.4
Electricity production total	MJ/hr	862.0	1249.9
Electricity exported	MJ/hr	746.2	1155.7

(B) The WUR CHP comparison: From the previous verification, it became clear that the theoretical production of the biogas plants, as calculated by Dairy Campus, does not fully comply with the measured outcome of the CHP units (Table 4.5). The overall efficiency of the CHP unit given by Dairy Campus is 35%; however, the biogas production calculated in the previous verification implies that the efficiency of that unit only reaches 25%. This discrepancy might be found in the losses of the system during the AD biogas production process, including losses of biomass during transport, storage, and loading; losses of biogas during storage or transport to the engine; and a lower efficiency of the engine due to less than optimal operation. To test the EBS model on accuracy, the same case is used (Table 4.4), including the aforementioned losses, along with the preset values present in the model (which include internal use and losses). The results indicate a difference of approximately 14.66% between the EBS model and the measured electricity production at Dairy Campus, which is within the 20% accuracy range of the model (Table 4.6). The difference between the real case scenario of the WUR and the EBS model can result from many factors (e.g. lower biogas yields biomass, internal electricity consumption, lower CHP unit efficiency, or more internal losses). If, for instance, the CHP efficiency is set to 31% in the EBS model (which is not uncommon as average operational efficiency [102]), then the net electricity production becomes similar to the output of the WUR digester.

Table 4.6. Main outputs WUR CHP comparison

Outcome	Unit	WUR data sheet	EBS model
Net production CHP unit	MJ/hr	746.24	855.7
Efficiency CHP unit	%	?	35.0
Biogas production	Nm3/hr	?	119.0
Methane production	Nm3/hr	?	68.4

4.3.2.4. Extreme condition test

During the zero tests, all the inputs within the EBS model are set to zero, and all the main outputs of the EBS model indicate zero (0) or are divided by zero during the zero tests. Also, when individual sub-modules are turned to zero, they will not influence the outcome of the model. There is an exception: machinery installed in the biogas production pathway that is not used will have embodied impact, as embodied energy is present in the system. Within the model, there is the possibility of turning the embodied energy off if the machinery is not installed in the scenario. Furthermore, there are some cases where the model indicates a divide by zero fault; this can be expected, as all values, including, for example, efficiency of the CHP unit or all biomass flows, are zero as well.

4.3.2.5. Face validity

During the face validity phase, a group of experts in the field of modeling, biogas production, and energy transition was selected (Table 4.1) and assigned the task of reviewing the model. The reviewers followed a program that resulted in a written review report and a final remark, which is either "inadequate" or "adequate." The reviewers concluded that the model can fulfill its intended purpose of analyzing the environmental impact of biogas production chains. The structure used in the model is logical and transparent, thereby strengthening the trustworthiness of the model. The model can also help in creating a better scientific understanding of the sustainability of biogas production. However, the calculations are still numerous and not always clear, both of which make exact verification difficult. The complexity of the topic and the multiple level inputs needed in the model make it usable only by experts. While the outputs are understandable and logical, the EcoPoint system will need better explanation. The reviewers advised integrating an NPV cost calculation into the model for a more complete and comparable outcome. Finally, all reviewers agreed on the fact that the model can be used for its intended purpose.

4.3.2.6. Internal validity

Internal validity is analyzed through the use of two different techniques: (A) an internal comparison of calculation, and (B) a sensitivity analysis of the main parameters.

(A) Internal comparison of scenarios: Within the EBS model, there are multiple calculation pathways that use the same variables and inputs and calculate the same outputs. This property, of multiple similar calculation pathways, can be used for internal verification of the model. Therefore, for V&V purposes, the pathways are preset to calculate the same scenario. Cow manure with energy maize and cow manure with grass are the two biomass input scenarios chosen for this comparison (Table 4.7). The results from these pathways using the same biomass inputs can be compared with each other, as the outcome should be similar. This approach also covers the validation step called trace—for every scenario made, the calculation pathway is traced when compared to other scenarios. Furthermore, discrepancies between scenarios are mostly solved using trace.

Table 4.7. Input internal comparison scenario maize

Products used	Manure + Maize	Manure + Grass	Unit
Dairy cow manure mixed farm	367	367	Cows/a
Dairy cow manure mixed source	5000	5000	Mg/a
Maize from field	116.5		ha/a
Maize from source	5250		Mg/a
Grass from field		368	ha/a
Grass from source		5250	Mg/a

The method of comparison together with trace proved to be useful for the validation process of the model, and it brought to light several programming mistakes. Overall, the calculation pathways within the model are aligned through the use of an internal comparison of scenarios (Fig. 4.3). However, transport in results 1 and 2 (Fig. 4.3) were not similar; this dissimilarity was traced back to the programmed transport distance in the model and the type of transport (e.g. tractor or truck).

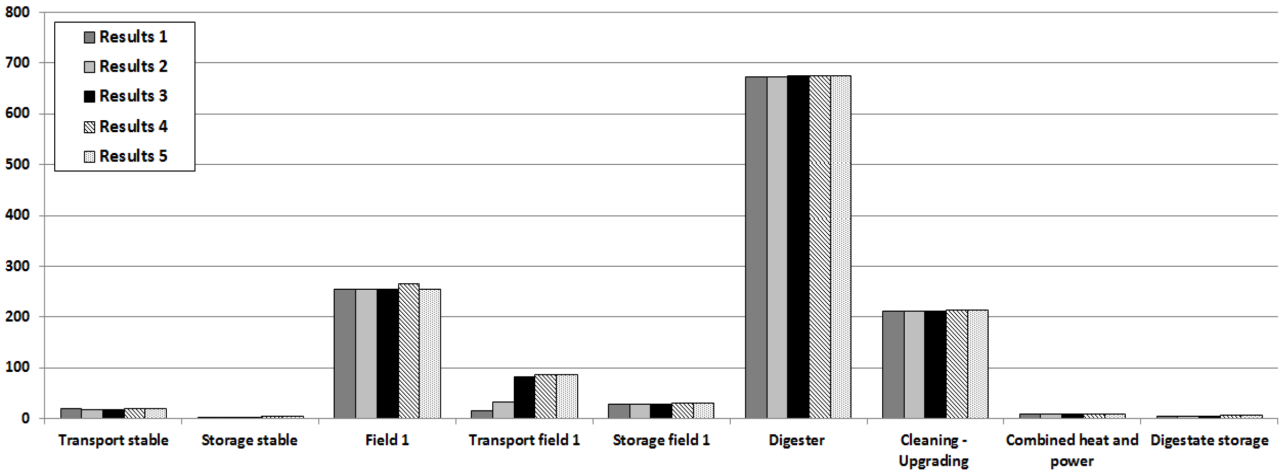

Fig. 4.3. Results from the internal comparison scenario with manure and energy maize

(B) Output sensitivity analysis: Within the EBS model, the outputs (e.g. efficiency, emissions, and environmental impact) are given per unit of produced energy, for example GJ, which could be in the form of electricity and heat or green gas injected into the grid. Therefore, the outputs from the model, for example the [P]EROI factor, over the projected range of biomass input are expected to be relatively similar per GJ of produced energy. Within this context, the main input, namely, biomass, will be varied from a minimum of 250 Mg per year up to a maximum of 50,000 Mg per year with steps of 250 Mg. During the analysis, all other variables are kept constant, and the biomass mix will be fixed at 50% manure and 50% maize. When looking at the output indicator, namely, [P]EROI, similar results with only a gradually incremental increase or decrease are expected over the biomass input range.

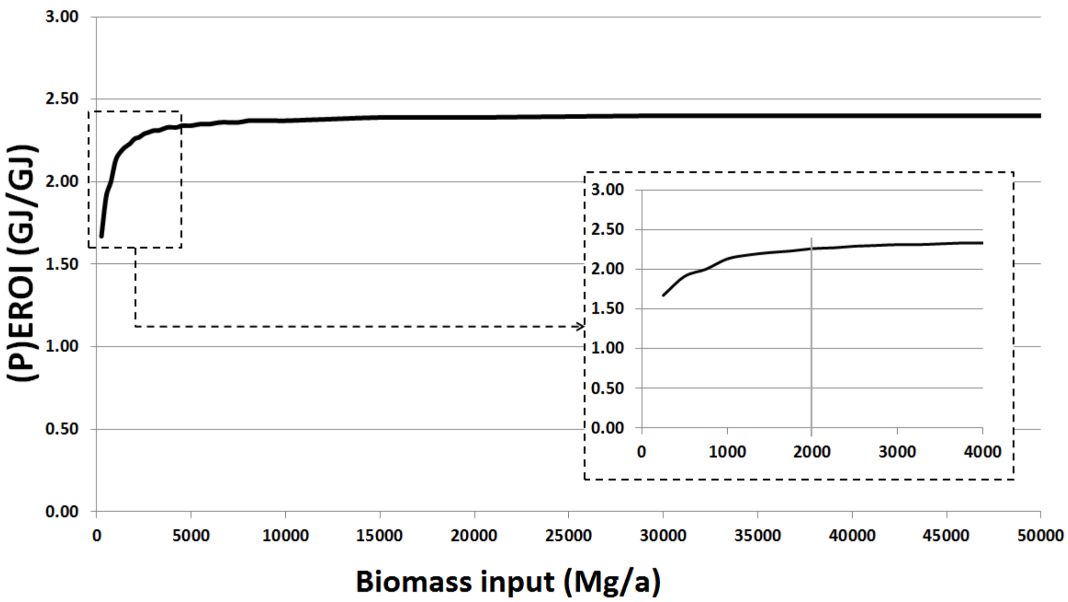

Fig. 4.4. The [P]EROI outputs of the model over a projected biomass input range of 50% manure and 50% maize

The EBS model is highly stable in a large part of the biomass input range, with a small incline starting from an input of 2,000 Mg/a (Fig. 4.4). An explanation for the small incremental incline (from 2,000 to 50,000 Mg/a) might be found in the economy of scale, where larger installations become more efficient. However, when looking at the biomass input below 2,000 Mg per year, the indirect and embodied impacts have a large impact on the end result, for example [P]EROI. Therefore, the accuracy of the model cannot be guaranteed below a yearly biomass input of 2,000 Mg/a. From the 2,000 Mg/a input range upwards, the factors increase gently, and within that range, the model is trustworthy. However, beyond the range of 50,000 Mg/a of biomass input per year, the behavior is not measured, making this the maximum value for the model, which is beyond the scale of most AD farm digester systems.

4.3.2.7. Parameter variability (sensitivity analysis)

Within the EBS model, the most sensitive parameters were indicated empirically through the use of a sensitivity analysis. By keeping all variables constant, except for one, the sensitivity of this specific variable can be determined. The sensitivity analysis performed on the EBS indicates great sensitivity in biogas potential, oDM content in biomass, and biomass yields from fields. These parameters are highly variable and depend greatly on local conditions and specific types of biomass, among other things. Table 4.8 depicts the most dominant variables in the model that are often linked to the biomass source. Biomass quality and quantity unfortunately varies per growing season, location, field quality, and harvest date and time, among other things, making biomass already sensitive by itself. Averages are often used, which include many samples; however, even these vary within literature [101].

Table 4.8. Most dominant variables in EBS model

Biomass variables	**Impact on expressions**
Yield of biomass from a certain area	Medium to Low [a]
Organic matter ratio	High
Biogas content of the biomass type	High
Methane content within the produced biogas	High
Costs of the biomass	High
Biogas production process	Impact in model
Energy use digester (heat and electricity)	High
Efficiency upgrader	High
Efficiency CHP unit	High
Remainder	Impact in model
Total biomass input in model	Low to high [b]
Transport	Low to medium

[a] Depends on use of own fields in model.

[b] Below a threshold yearly input of biomass per year (2000 Mg/year) the model becomes inaccurate

4.3.2.8. Structured walkthrough

During the final session of the review process, a walkthrough session was organized with the reviewers (Table 4.1). During this session, the model was discussed, and improvement points as well as limitations of the model were noted. The result of the session indicated that this model can be a useful tool in the hands of experienced professionals. The model is built correctly and can add to scientific understanding; however, to do so, it must be used professionally and responsibly.

4.3.2.9. Trace

During the internal V&V phase (discussed in Section 4.3.2.6), a trace of biomass inputs was performed. As already discussed, the model contains several calculation pathways capable of calculating the same scenarios. When the comparison scenarios were programmed into the model per calculation pathway, the results were traced and also compared to other calculation pathways in the model. At every control point during the trace, the intermittent results were checked and also compared with the other calculation pathways.

4.4. Discussion

Within this article, the review process of the EBS model is discussed. To ensure a correct and trustworthy model, several V&V techniques are used. During this phase, many mistakes and errors were detected and corrected in the model. The internal validation method aligned with several calculation pathways in the model such that the outcomes were similar. The comparison with external models (which are already validated themselves) and a case study of a biogas system demonstrated that the main mass flow calculations of biomass and biogas production are in the same range. Furthermore, the economic calculations in the model (not being the primary goal) are in the same range as well. The aforementioned also confirms the usability of the V&V method proposed in this article. However, the V&V process discussed in this article cannot guarantee a 100% accurate model, since the complexity of the model makes it difficult to remove all mistakes. Through the comparison with other models and their results, a projected accuracy of 80% can be expected. Within this article, the model with its current calculations and dataset has been verified. However, the model depends heavily on information retrieved from literature, where some values have great influence on the final result. Most of the literature-based values used in the EBS model are programmed as changeable parameters, and changing these parameters will shift the responsibility of selecting these values to the user. When doing so, the user is expected to be an expert capable of determining which values are trustworthy and which ones are not. There is hence a principle difference between the validation of the model, the data used in the model, and the use of the model for making scenarios. Additionally, the accuracy of the model can only be guaranteed for a specific range of yearly biomass inputs; it is demonstrated that indirect and embodied values have too much influence on the final outcome below this range. Additionally, the model also contains new and untested methods and calculations that focus on the sustainability of biogas production, which is difficult to validate due to a lack of comparable literature and models. The calculations are verified using the internal validation method; however, the methodology and chosen formulas can only be verified partly by literature. Furthermore, the core data used in the model are based on a well-known scientific database of environmental impacts (e.g. EcoInvent database [103]). Overall, the V&V process that was used on the EBS model indicated no discrepancies in its intended purpose, namely, to analyze the sustainability and efficiency of farm-scale biogas installations. From the results in this article, the model is classified as adequate for use through both validation techniques and expert review. The results from the model can now be used to improve scientific understanding regarding the sustainability of biogas production through AD in farm-scale biogas installations.

4.5. Conclusion

The V&V method constructed and applied to validate the EBS model, based on a simple model development process [86], is a useful tool for improving the quality of physical calculation models. Through the use of the V&V method, mistakes in the model were resolved, the strengths and weaknesses of the model were found, and the concept of the model was tested and strengthened. Going through the V&V process not only helps the model, but it also enables the researchers to widen their focus and scope, thereby helping them to perform a correct V&V and re-evaluate the function and goal of their model. Apart from the use of common sense when interpreting results, the validation of a model is of significant importance. A model that has not been validated can potentially yield inaccurate or even incorrect results, which could have been prevented by a V&V process. The V&V method researched, constructed, and applied in this article can be a guide for the validation of models with a similar goal and context. The main results from the V&V process in this article indicate that the EBS model is valid and is ready for use in determining the energy efficiency, carbon footprint, and sustainability of farm-scale biogas production pathways based on AD. This V&V method resolved several problems in the model and strengthened the concept. The results presented in this article classify the EBS model as adequate for use through both V&V techniques and expert review. The model, however, is considered to be an expert model, and the outputs can only be trusted when the model is used by expert users. When used by experts in a proper and responsible manner, the model can be capable of adding to scientific understanding regarding the sustainability of biogas production.

Chapter 5

PLANET

Environmental and energy system analysis of bio-methane production pathways: a comparison between feedstocks and process optimizations

ABSTRACT

The energy efficiency and sustainability of an anaerobic green gas production pathway was evaluated, taking into account five biomass feedstocks, optimization of the green gas production pathway, replacement of current waste management pathways by mitigation, and transport of the feedstocks. Sustainability is expressed by three main factors: efficiency in (Process) Energy Returned On Invested [P]EROI, carbon footprint in Global Warming Potential GWP(100), and environmental impact in EcoPoints. The green gas production pathway operates on a mass fraction of 50% feedstock with 50% manure. The sustainability of the analyzed feedstocks differs substantially, favoring biomass waste flows over, the specially cultivated energy crop, maize. The use of optimization, in the shape of internal energy production, green gas powered trucks, and mitigation can significantly improve the sustainability for all feedstocks, but favors waste materials. Results indicate a possible improvement from an average [P]EROI for all feedstocks of 2.3 up to an average of 7.0 GJ/GJ. The carbon footprint can potentially be reduced from an average of 40 down to 18 kgCO_2eq/GJ. The environmental impact can potentially be reduced from an average of 5.6 down to 1.8 Pt/GJ. Internal energy production proved to be the most effective optimization. However, the use of optimization aforementioned will result in les green gas injected into the gas grid as it is partially consumed internally. Overall, the feedstock straw was the most energy efficient, where the feedstock harvest remains proved to be the most environmentally sustainable. Furthermore, transport distances of all feedstocks should not exceed 150 kilometers or emissions and environmental impacts will surpass those of natural gas, used as a reference. Using green gas as a fuel can increase the acceptable transportation range to over 300 km. Within the context aforementioned and from an energy efficiency and sustainable point of view, the anaerobic digestion process should be utilized for processing locally available waste feedstocks with the added advantage of producing energy, which should first be used internally for powering the green gas production process.

Additional information chapter

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5.1. Introduction

Concerns over climate change, resource depletion, and a worsening environmental health indicate the need for a full transition to non-polluting renewable energies. Therefore, the European Union has enforced strict targets for renewable integration and the reduction of emissions [16, 60]. One potential renewable energy resource is green gas production through anaerobic digestion (AD). Benefits associated with green gas production include the reduction of greenhouse gas emissions, environmental impact and the use of fossil resources. Anaerobic digestion is a promising method for producing a renewable and flexible energy carrier, which is storable and can be transformed into electricity and/or heat or can be upgraded to green gas [27]. However, renewable energy production processes like AD are often seen as (fully) sustainable, which is not always the case. Per definition, renewable is referring to the energy resource (e.g. biomass) and not the process of extracting and refining the energy from this resource. Often, the overall process of extracting energy from a renewable resource may still require fossil input, which will have an impact on the environment and therefore on the sustainability of the process [27, 42]. Within this context, understanding the efficiency, carbon footprint, and environmental impacts of AD is required in the decision making and planning process in order to ensure a more sustainable production process.

Mono-digestion and co-digestion processes have been thoroughly researched based on feedstock type, energy balance and environmental impact. Depending on the study, the focus can be on specific feedstocks, mixtures of feedstocks, different biogas production pathways, variable transport distances, the biogas production process itself, and different end uses for biogas. Energy analysis studies identify and quantify all the energy and material inputs (e.g. cultivation, transport, processing) and outputs (e.g. biogas, green gas, electricity, heat) in a product's life cycle [27, 58]. Studies indicate that the energy input needed within anaerobic digestion processes varies between 10% to 65% of the energy output [27, 42, 43]. A large share of this energy input is often provided by fossil energy (e.g. cultivation, transport, pumping, mixing, heating, filtering, and cleaning) [42, 104]. The focus of the LCA approach lies in the analysis of environmental impacts of a product, a process or a system [42, 58]. LCA results are often given in a wide range of impact categories (e.g. climate change, ozone depletion, agricultural land occupation, etc.) [58], which can add up to over twenty indicators [45, 46]. Overall, studies indicate that the choice of feedstocks, technologies and the operational values of AD pathways (e.g. feedstock, transport, process) have a large influence on the environmental impact [41, 42, 46-52, 104]. Within this context, it is important that the design of a production pathways and the location of the facilities is chosen wisely [47]. When, for instance, a green gas production pathway is not properly designed and managed; more primary energy could be invested into the production process than is finally obtained [27]; emissions and environmental impacts might become similar to or even surpass current fossil resources for similar uses [48].

Both energy analysis and LCA give a focused view into the sustainability of the biogas production process. However, the wide variability in both scope and approach makes the interpretation of the various results difficult [51, 58]. Also, a reference with current fossil energy use is often missing in the studies, making comparison difficult. Additionally, within many LCA studies the energy returned on invested is not included. Furthermore, many of the studies aforementioned do not focus on possible improvement in the AD process regarding sustainability. The next logical step should be to focus on integrating several feedstocks and process optimization within an LCA analysis, expressed in clear indicators of sustainability, and compared to a fossil reference scenario. Therefore, within this article an anaerobic digestion process producing green gas operating on either energy maize, roadside grass, catch crops, harvest remains, or straw is analyzed on environmental sustainability. Optimization of the green gas production pathway is included in the shape of internal electricity and heat production through the use of a small Combined Heat and Power Unit (CHP) and green gas powered transport of the feedstocks. Also, the effects of variable transport ranges of the feedstocks are included. Sustainability is expressed in three main factors: efficiency in (Process) Energy Returned On Invested, carbon footprint in Global Warming Potential GWP(100), and environmental impact in EcoPoints. The reference scenario will be based on natural gas production and consumption in the Netherlands. Overall, this study can provide a comprehensive overview regarding the sustainability of several feedstocks and green gas production pathways including potential optimization. Furthermore, this study can also shed light on the optimum use of the anaerobic digestion process as a green gas production system from a sustainably vantage point, which can help increase the efficiency and sustainability of the national energy system by utilizing green gas from anaerobic digestion as an integral renewable energy resource.

5.2. Methods

In the following section the methods used during the formation of the results are described.

5.2.1. The biogas simulator

Within this research the BioGas simulator is used to model the green gas production pathway. This model operates on a new approach, described in Pierie et al. [36], based on the industrial metabolism concept, which combines Material and Energy Flow Analysis [62], Energy and Environmental System Analysis [27], temporal dynamics, a modular design and Attributed Life Cycle Analysis, in order to gain more insight into the efficiency and sustainability of green gas production pathways. Within this model the green gas production pathway is defined as a collective of physical processes working together to achieve a common goal (e.g. biogas, green gas or heat and power production). This modular approach allows the simplification of the green gas production pathway while also allowing for easy modification in order to determine the impacts of green gas production for specific conditions and scenarios.

5.2.2. aLCA methodology

Within this research the Attributed Life Cycle Analysis (aLCA) method is used. The aLCA approach uses physical properties such as mass and energy to determine the environmental impact of the functional unit [42] and is performed in accordance with European guidance and ISO / NEN 14040 to 14044. The environmental impacts were obtained from SimaPro v8.0 model (2013) utilizing the Eco Invent database v3.0 (2013) in the shape of endpoints. In this article sustainability is defined as “strong sustainability” [21], wherein environmental quality precedes social prosperity and then economic prosperity [21, 76].

5.2.3. System boundary

The system boundaries (Fig. 5.1) within this research are set within the regulatory domain of the Netherlands. Regulation within the Netherlands states that feedstocks must be present on a pre specified list if the digestate is allowed to be used as fertilizer and only 50% of the biomass input can come from crops and/or vegetation (e.g. energy maize, roadside grass, catch crops or harvest remains); the other 50% should originate from manure sources (e.g. Cow, Pig manure). Environmental impacts are taken into account when they are in service of the green gas production pathway (e.g. production, processing, and transport). For instance, the impact of manure production (e.g. farming) is not taken into account but the effort of transporting the manure into the digester is taken into account. The same holds true for roadside grass, harvest remains and other waste products, with the addition of harvesting. In the case of catch crops, seeding and harvesting is taken into account. For energy maize the entire production process is taken into account when it is specifically cultivated for use as feedstock in the digester. Furthermore, energy and material use in service of the green gas production pathway will also be taken into account. For instance, regarding electricity consumption from the grid, both a direct impact of consumption and the indirect impact of producing and transporting the electricity will be included. The digestate is returned to the source of biomass to close the nutrient cycle, which includes use of 50% of the digestate on the farm and the other 50% is transported back to the origin of the feedstock. The processing of excess digestate is not taken into account. Within this research offsets regarding the replacement of current waste treatment pathways and leaving biomass on the field is taken into account. When looking to maize specially cultivated for AD, no replacement scenario is taken into account. The avoided emissions and environmental impact due to soil erosion and nutrient runoff through the use of catch crops is also not taken into account.

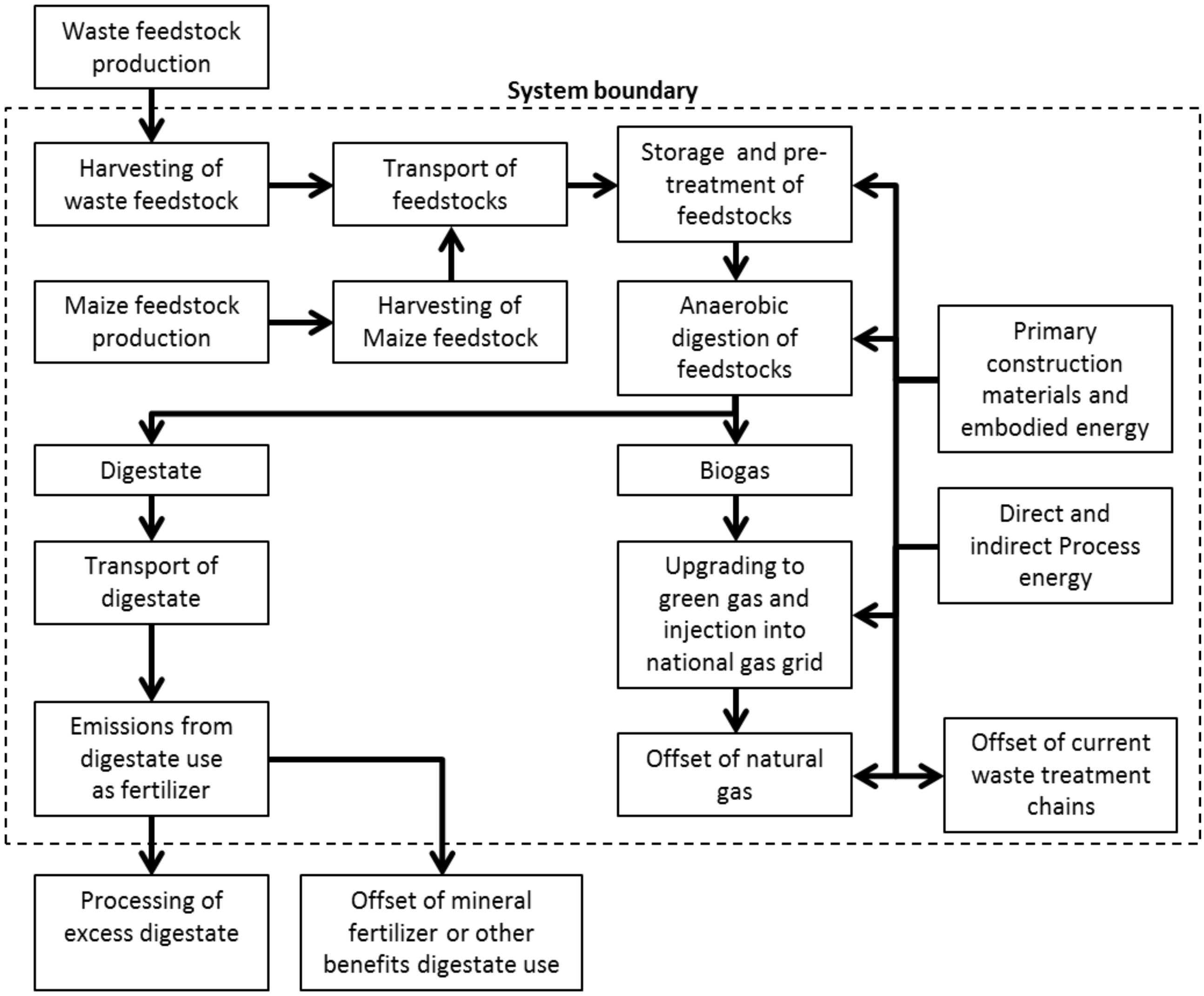

Fig. 5.1. System boundaries of green gas production and end use included in LCA

5.3. Functional unit and expressions

Within this article, the functional unit will be the production and injection of 1GJ green gas into the gas grid. The efficiency, carbon footprint, and environmental impact of green gas production will be expressed in, respectively, (Process) Energy Returned on Energy Invested, Carbon Footprint, and EcoPoints, per GJ of green gas produced and injected in the national grid. The expressions will be discussed in the following section.

1) Efficiency expressed in [P]EROI (GJ/GJ)

To indicate the energy efficiency of a process the (Process) Energy Returned on Invested factor, or [P]EROI, is used. [P]EROI is defined as the ratio between the energy obtained from a resource to the energy expended in the production and processing of a resource. Energy contained within the feedstocks (e.g. maize, roadside grass or catch crops) is not taken into account. The factor is based on the EROI theory [77]. The [P]EROI will be expressed in a single factor. When the [P]EROI of a resource is greater than one it can be classified as a net energy producer, meaning that more energy is obtained from the resource than is expended in the production process. When the

[P]EROI is equal or less than one the resource in question will become a net energy consumer, meaning that less energy is obtained than is expended in the production process [77].

2) Carbon footprint expressed in GWP 100 (kgCO_2eq/GJ)

The carbon footprint is expressed in carbon dioxide equivalents (CO_2eq) using the relevant 100-year global warming potential scale or GWP (100), [79]. Within this article the carbon footprint is quantified as a net increase or decrease of GWP. The biomass itself used in the green gas production pathway is assumed to be carbon neutral. The additional emissions originating from cultivating and processing the biomass feedstock are incorporated in the carbon footprint. There are two main net producers of GWP incorporated in this research: first, carbon dioxide absorbed in biomass may be converted and emitted as a stronger greenhouse gas (e.g. methane), therefore increasing the overall GWP potential; second, use of fossil energy resources in the green gas production pathway will create anthropogenic emissions resulting in a net increase of GWP.

3) Environmental impact expressed EcoPoints (Pt/GJ)

The overall impact on the environment will be expressed with the ReCiPe 2008 Eco indicator, used by the SimaPro model [80, 82]. When following the ISO 14040 and 14044 generic frameworks, an LCA inventory usually results in a very long list of emissions, consumed resources and sometimes other items. The interpretation of this list is often complex and difficult to comprehend. The ReCiPe method is designed to help with the interpretation of the LCA inventory results through the use of the Eco indicator. “An indicator” is an overall expression of total load on the environment (as currently understood in science), based on the damage-oriented approach. The indicator uses weighting factors wherein damage is brought into perspective and is made comparable to other types of damage [82, 94]. Within the Eco indicator multiple impacts are brought together into a single score through the use of damage models and normalization.

5.4. Main parameters and scenarios

Within this article, a green gas production pathway will be discussed which is fed by separate main feedstocks. The feedstocks will each be subjected to four optimization scenarios and the results will be compared with two reference scenarios (Fig. 5.2). The production pathways, feedstocks, and scenarios will be discussed in this section.

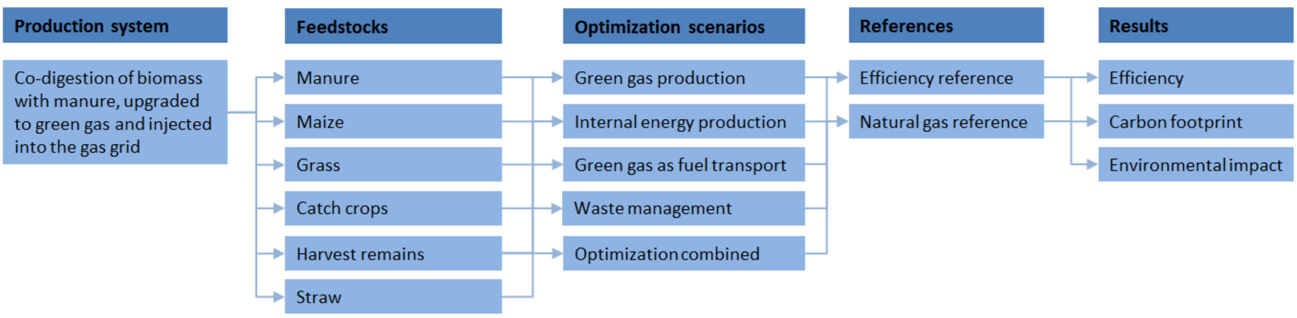

Fig. 5.2. Green gas production pathways and scenarios discussed in article leading to main results

5.4.1. Green gas production pathways

All feedstocks and scenarios will make use of the same digestion plant set up, which will be located on or near a farm with a total biomass input of 20000 Mg of fresh matter (FM) per year. The main product of the plant will be green gas, which is upgraded biogas to gas grid quality, injected into the national gas grid as described in Bekkering et al [105]. The retention time in the digester is 30 days at mesophilic temperature, with a water content in the digester of 80%. Water injection to maintain the preset value and the heating of the injected water will be incorporated. Part of the produced biogas will be used in a small boiler to produce the needed heat in the digestion process. The remaining biogas will be upgraded to green gas with natural gas quality through the use of a high selective membrane upgrader system (Table 5.2). A gas pipe over a distance of one kilometer is incorporated to transport the green gas from the production site to the injection station. The energy use of the green gas upgrading and injection system in the shape of electricity is also incorporated (Table 5.1). Transport of biomass will be conducted by tractor or truck, loading and unloading will be incorporated. Furthermore, the application of digestate back to the field and the emissions during this process are incorporated. The aforementioned primary settings will be similar for all feedstocks and optimization scenarios (Table 5.2). Average values are used in this article based on literature (discussed further in section 5.6).

Table 5.1. Main values used in model

Main components green gas pathway	Value	Unit	Source
Heat use digester	250[a]	MJ/Mg	[27]
Electricity use digester	33[b]	MJ/Mg	[27]
Loss of biogas from digester	1	%	[106]
Electricity use membrane upgrader	0.756[b]	MJ/Nm^3	[84]
Loss of methane in filtrate	0.4	%	[84]
Energy use for green gas injection	0.00023[c]	MJ/Nm^3	[96, 107]
Tractor transport	5.12	MJ/Mg.km	[75, 103]
Truck transport	2.75	MJ/Mg.km	[75, 103]

[a] Regarding the total biomass mix in the digester excluding dilution water
[b] Per upgraded Nm^3 of biogas to green gas
[c] Per injected Nm^3 of green gas at 8 bar into the national gas grid

5.4.2. Feedstocks

Cow manure: The manure source in all pathways will be cow manure. The farm will house one hundred cows which will provide some manure locally and the remainder will be collected from surrounding farms within a radius of five km (table 4.2). The manure will be stored in a closed tank before it is digested, emissions during this period will be incorporated in the results.

Maize feedstock: The maize silage (maize) used as feedstock will be specially cultivated for use in the green gas production pathway. Therefore, agricultural field work and the use of fossil fertilizers and pesticides during cultivation are incorporated (Table 4.2). After harvest the maize will be transported, ensiled and stored; losses during these processes are incorporated.

Roadside grass feedstock: Roadside grass (grass) is naturally growing without any cultivation processes taking place. Mowing, collection and loading of roadside grass is taken into account, including the machinery used for transport of equipment and personnel. After collection the roadside grass will be transported, ensiled and stored; losses during these processes are incorporated. Screening is included for removing non-organic waste (e.g. plastic, metals etc.). Furthermore, grass will also be mechanically pre-treated to improve the digestion and with it the biogas potential, therefore a hammer mill is used (Table 5.2).

Catch crop feedstock: Catch crops will be cultivated directly after a main crop is harvested. During the cultivation process no fossil fertilizers are used. Catch crops are primarily used as soil enhancers and for this to have effect often a mix of plant species is seeded, which will result in a mix of yields and biogas potentials. Within this research average values are selected resulting from several combinations of catch crops [108]. During cultivation, the seed, seeding, mowing, collecting and loading is incorporated. After harvest, the catch crops will be transported, ensiled and stored; losses during these processes are incorporated. Furthermore, mechanical pre-treatment (hammer-mill) will be applied (Table 5.2).

Harvest remains: In some harvests, for instance sugar beets and potatoes, organic material is left on the fields containing parts of the plant and root system. These remains can be harvested and used as feedstock. During the harvesting process the use of machinery and fossil fuel is taken into account, no fossil fertilizers are included as it is seen as a waste product. During harvest, collection and loading are taken into account, mowing the crop will be in service of the main product. After harvest the roots and tops will be transported, ensiled and stored; losses during these processes are incorporated. Furthermore, mechanical pre-treatment (hammer-mill) will be applied (Table 5.2).

Straw from grains: Unused straw can be utilized as a feedstock. During harvest collection, haying, and loading are taken into account, mowing the crop will be in service of the main product (e.g. grain). Furthermore, no fossil fertilizers are included for straw as it is seen as a waste product. After harvest the straw will be transported, and stored; losses during these processes are incorporated. Furthermore, mechanical pre-treatment (hammer-mill) will be applied (Table 5.2).

Table 5.2. Main values regarding the feedstocks used in model

Maize silage substrate	Manure	Maize	Grass	Catch	Tops	Straw	Unit	Sources
Biogas potential	350	606	559.8	640	550	341	Nm^3/Mg.oDM[a]	[43, 109]; [110]; [108]; [27]
Methane potential	180	322	296.5	329	302	174	Nm^3/Mg.oDM[a]	[43, 109]; [110]; [108]; [27]
Organic Dry Matter content (oDM)	6.4%	30	23.5	18	19	82	%	[71]; [111]; [110, 112]; [108]; [27]
Needed energy cultivation/harvest	0	656	276	92	75	172	MJ/Mg.FM[b]	[75, 103]
Emissions cultivation/harvest	0	61	17	7	6	13	$kgCO_2eq$/Mg.FM[b]	[75, 103]
Impact cultivation/harvest	0	11.6	2.0	1.3	0.5	2.5	Pt/Mg.FM[b]	[75, 103]
Average transport distance from source	5	50	50	50	50	50	km	[27]
Production of manure per cow per year	18,120	-	-	-	-	-	Kg/a	[71]
Energy use screening unit	-	-	5.4	-	-	-	MJ/Mg.FM[b]	[113]
Energy use hammer mill	-	-	20	20	20	20	MJ/Mg.FM[b]	[112, 113]

[a] organic Dry Matter
[b] Fresh Matter

5.4.3. Optimization scenarios

There will be several different scenarios influencing the green gas production pathway. The outcomes of the scenarios will be compared to the reference scenario (Fig. 5.2).

1) Green gas production scenario: The green gas production scenario will simulate a normal production pathway, which is focused on the maximum production of green gas injected in the natural gas grid.

2) Internal use scenario: With this scenario the internal energy demand of the green gas production pathway will be supplied by means of a small Combined Heat and Power (CHP) unit (Table 5.3). Fuel is provided by the production pathway itself in the form of biogas. The small CHP unit will produce the same amount of electricity as needed by the production pathway. The resulting heat will be used for heating the process. Additional heat requirements will be produced by the biogas boiler.

Table 5.3. The main values of the micro CHP unit

Micro CHP unit for internal heat and power	Value	Unit	Source
Efficiency CHP unit	38	%	[61]
Heat recovered from engine	80[a]	%	[61]

[a] Of total heat produced from engine in exhaust and cooling water

3) Green gas fuel scenario: Within this scenario all the transport movements of the feedstocks will be performed by trucks running on green gas produced by the production pathway itself. The fuel used during cultivation, mowing, collecting, haying, and loading is not included. Within this scenario the energy requirement when using diesel or green gas is considered the same. Hence, the energy needed for transport by diesel is replaced with the same energy in the shape of green gas.

4) The waste management replacement scenario: Within this scenario the emissions of current waste scenarios, when present, are mitigated with the green gas production pathway. Two types of waste treatment are incorporated: First, the manure offset scenario based on the collection of the manure from the stable, storage within a closed manure tank and the spread of manure as fertilizer on agricultural fields. Second, the composting offset scenario based on mowing the biomass and then leaving it either on the road side, field or ploughing it under as fertilizer [43] (Table 5.4). When utilizing manure, in the green gas production pathway, the emission from storage will be avoided. Also, when utilizing harvest remains (e.g. roadside grass, catch crops, beet tops, and straw) emissions caused by open-air decay will be avoided and, therefore can be mitigated.

Table 5.4. Values used for replacement scenarios per Mg of fresh matter of feedstock processed

	Unit	Manure	Digestate	Composting	Source
Carbon footprint	kgCO_2eq/Mg	98.23	32.65	127.00	[103, 114]; [115]
Environmental impact	Pt/Mg	2.03	0.80	2.48	[103, 114]; [115]

5) The combined scenario: In the combined scenario the aforementioned scenarios, including the waste management replacement scenario, are all implemented together in the green gas production pathway, resulting in the aggregation of effects of the previous scenarios.

5.4.4. Reference scenarios

1) Efficiency reference: Theoretically the [P]EROI reference is set at one. Below one more energy is needed in the process than is obtained. However, determining the exact energy input and output in practice is very difficult mainly due to the accuracy of the data used in the model and the accuracy of the model itself. When the [P]EROI drops below 1.5 GJ/GJ the efficiency of the production pathway becomes questionable, therefore, the reference for the energy requirement is placed at a [P]EROI of 1.5 [78].

2) Emission and environmental footprint reference: This reference is based on the average natural gas mix of the Netherlands 2013 (Table 5.5), which includes production, needed infrastructure (natural gas network), and combustion of the gas when used. The scenario is based on published data, repartition of losses on high and low pressure networks based on calculations with data for other countries. It takes into account the parts of on- (71.6%) and offshore (28.4%) production. For offshore gas, 100 km offshore pipeline are added. Gas losses and emissions during seasonal storage are included [75, 103]. Within the green gas production pathways the natural gas network is taken for granted.

Table 5.5. Values used as reference for average natural gas mix of the Netherlands (2013)

	Natural gas[a]	Unit	Source
Carbon footprint GWP(100)	54.6	($kgCO_2eq/GJ$)	[75, 103]
Environmental impact EcoPoints(Pt)	6.2	(Pt/GJ)	[75, 103]

[a] Natural gas produced from the Groningen gas field and surrounding gas field in the Netherlands

5.5. Results

In the following section the results are discussed per expression (efficiency [P]EROI, carbon footprint GWP(100), and environmental impact (Pt) as described in section 5.3). Within every expression, the focus will be placed on the selected feedstocks, the improvement scenarios used, and the waste management replacement scenario or replacement scenario used. The figures used to express the results will use the naming described in table 5.6.

Table 5.6. Scenario indications in figures: 4, 6, and 8

	Feedstocks				
Scenarios	**Maize**	**Grass**	**Catch crops**	**Tops**	**Straw**
Green gas scenario	maize_1	grass_1	catch crop_1	Tops_1	Straw_1
Internal use scenario	maize_2	grass_2	catch crop_2	Tops_2	Straw_2
Green gas as fuel scenario	maize_3	grass_3	catch crop_3	Tops_3	Straw_3
Replacement scenario (Mitigation)	maize_4	grass_4	catch crop_4	Tops_4	Straw_4
Combined scenario	maize_5	grass_5	catch crop_5	Tops_5	Straw_5

5.5.1. Efficiency of the green gas production pathway

The individual processes in the green gas production pathway require a significant amount of energy (Fig. 5.3). Overall for every two parts of energy produced in the shape of green gas, one part is needed to power the production process (Fig. 5.4). Maize requires substantially more energy during cultivation due to intensive farming, (e.g. field work, chemical fertilizers and pesticides), whereas catch crops, roadside grass and harvest remains require more energy in transport, storage, and digestion due to their lower oDM content or biogas potential. Additionally, energy is required for screening and pre-treatment. Furthermore, biogas upgrading to green gas requires a large input of electricity for compressing the biogas (mostly grey electricity from the grid). Upgrading biogas from maize requires more energy due to the lower methane content in the biogas (Fig. 5.3).

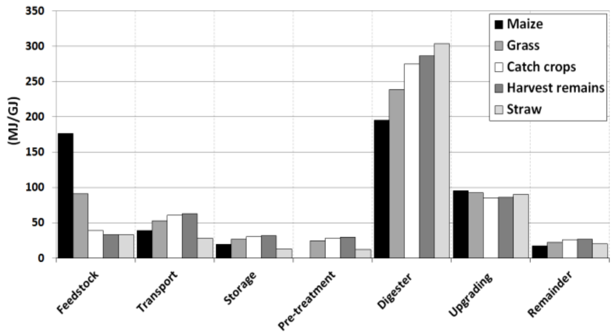

Fig. 5.3. Energy input in the green gas production

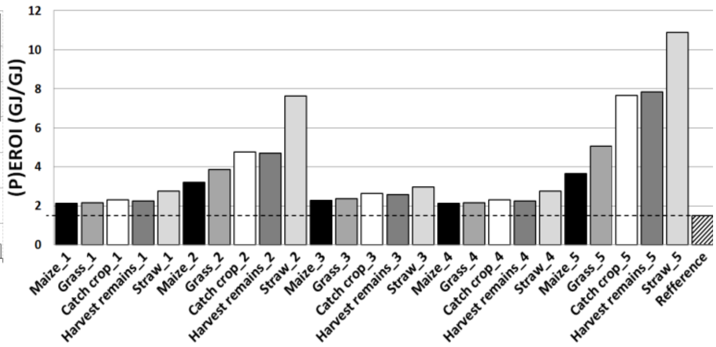

Fig. 5.4. Efficiencies of the feedstocks per scenario

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pathway in MJ per GJ of produced green gas

Implementation of internal energy production significantly increases the efficiency, especially for the feedstock straw as a large share of the energy present in the process is in the shape of grey electricity (Fig. 5.4). Fueling trucks, transporting the feedstocks, with green gas has a slight effect on the efficiency (Fig. 5.4), which indicates that transport distances of 50 km only has a small share in the total energy requirement of the green gas production pathway (Fig. 5.3). The replacement of current waste management pathways has no effect on the efficiency, as the energy replaced is not taken into account. When combining the optimization scenarios, the efficiency of straw, harvest remains and catch crops increases significantly. For maize, however, the replacement effect is less, mostly due to the high energy use during cultivation, which is not offset by the optimizations steps used within this article. Utilizing the optimization scenarios aforementioned, however, will lead to a lower overall injection of green gas in the gas grid (Table 5.7).

Table 5.7. The reduction of green gas injected in the gas grid due to internal consumption compared to green gas scenario

Scenario	Internal use	Green gas as fuel	Replacement	Combined
Maize	6.85%	4.97%	0.00%	11.82%
Grass	8.87%	7.06%	0.00%	15.93%
Catch crops	8.13%	8.30%	0.00%	16.43%
Harvest remains	9.89%	8.81%	0.00%	18.70%
Straw	9.51%	3.95%	0.00%	13.47%

5.5.2. Carbon footprint of the green gas production pathway

The initial emissions of the green gas scenario for all five feedstocks with an average transport distance of 50 km are already lower than the reference scenario of natural gas (Fig. 5.6). Overall, the emissions from the green gas production pathway are closely linked to the consumed energy in the process. However, during the cultivation process of maize, additional emissions originates from soil cultivation (Fig. 5.5), resulting in a relatively higher carbon footprint. Also, the emissions from transport and grey electricity weigh relatively heavier due to additional emissions besides carbon dioxide (e.g. N_2O, CH_4), which have a higher GWP(100). Therefore, transport and biogas upgrading contain a larger share in the overall carbon footprint than within the overall energy use of the green gas pathway (Fig. 5.5).

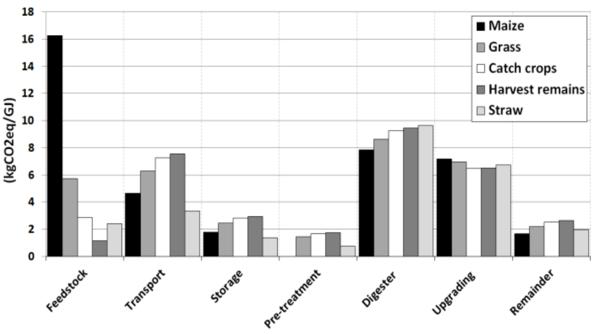

Fig. 5.5. Emissions from the green gas production pathway in kgCO_2eq per GJ of produced green gas

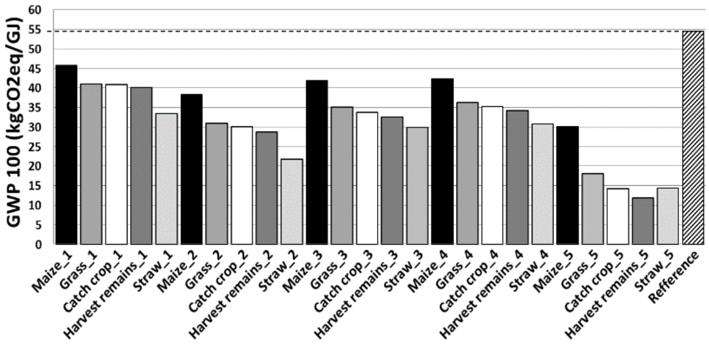

Fig. 5.6. Carbon footprint of the feedstocks per scenarios

The implementation of internal energy production has a positive effect on the overall footprint of all feedstocks, especially when looking at straw (Fig. 5.6); this can be traced back to the offset of grey electricity production. Also, replacing diesel used for the transport of feedstocks with green gas will reduce the footprint. Furthermore, emissions produced in the green gas production pathway can be mitigated by replacing current manure and harvest remains waste management. When combining scenarios, significant reductions can be achieved in greenhouse gas emissions especially when using harvest remains as a feedstock. For maize, optimization has an effect on the overall carbon footprint, however, much less than on grass and catch crops due to the high impact of intensive farming.

5.5.3. Environmental impact of the green gas production pathway

Intensive farming comprises a large selection of impacts ranging from land use, acidification, atmospheric emissions, nutrient use, etc. which when put together result in a high overall impact for maize (Fig. 5.7). Therefore, intensive cultivation of maize, in service of green gas production, has severe implications on the overall environmental impact, even surpassing the environmental impact of fossil natural gas production and combustion (Fig. 5.8). For the remaining feedstocks, other impacts are dominant (Fig. 5.7), which overall do not surpass the reference in the green gas scenario. For all feedstocks, transport by diesel truck has a relatively high impact due to the additional emissions of diesel engines and the production process of diesel fuel. Also, constructions (e.g. storage, digester and upgrader) take a larger share in the overall environmental impact as they have a large selection of impacts (e.g. pollution to soil, water table and air), (Fig. 5.8). However, the lifetime of the installations has a large effect on the environmental impact as the impact is often spread out evenly over the operational lifetime (in this article an average lifetime of 25 years is used).

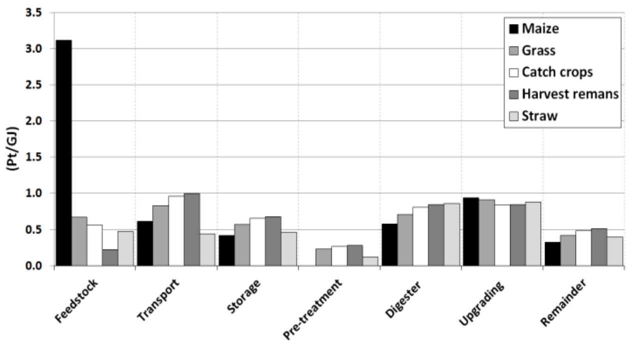

Fig. 5.7. Environmental impact of the green gas production pathway in Pt per GJ of produced green gas

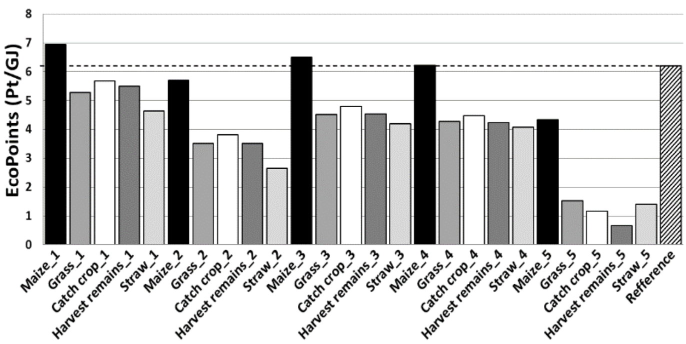

Fig. 5.8. Environmental impact of the feedstocks per scenarios

The use of internal energy production and replacement of transport fuel with green gas will lower the environmental impact as, respectively, grey electricity and transport by diesel truck are replaced (Fig. 5.7). Furthermore, the replacement of current management of manure and harvest remains also lowers the overall impact through mitigation. When the optimization scenarios are combined the environmental impact can be reduced significantly, especially for harvest remains.

For maize, optimization has an effect on the overall environmental impact, however, much less than grass and catch crops due to the high impact of intensive farming.

5.5.4. Influence of transport on the expressions

The average transport distance for the feedstocks was set at 50 km [27], however, in reality this often differs. The Transport distance of feedstocks has a significant effect on the overall sustainability of the green gas production pathway (Fig. 5.9). Transport of harvest remains and catch crops shows a larger increase over distance compared to the other feedstocks; this due to their lower oDM content. On average in can be concluded from Fig. 5.9 that the impact factors of all scenarios surpass the reference scenarios at a transport distance of roughly 150 km (Fig. 5.9, dashed horizontal line), except for straw which performs better due to its high oDM content. When using green gas as a transport fuel the maximum transported distance can be extended to around 300 km (Fig. 5.10) without surpassing the reference scenario. For the environmental impact of maize, however, the reference is already surpassed at a transport distance of 50 km.

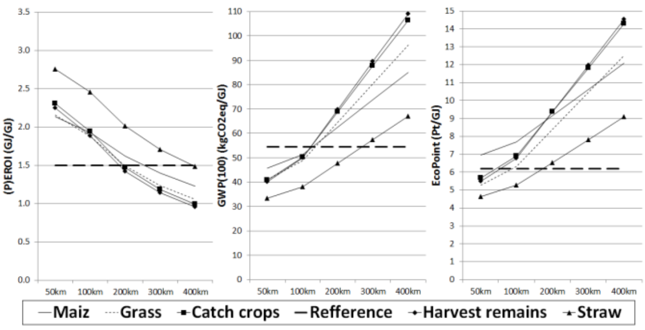

Fig. 5.9. Effect of transport distance on expressions

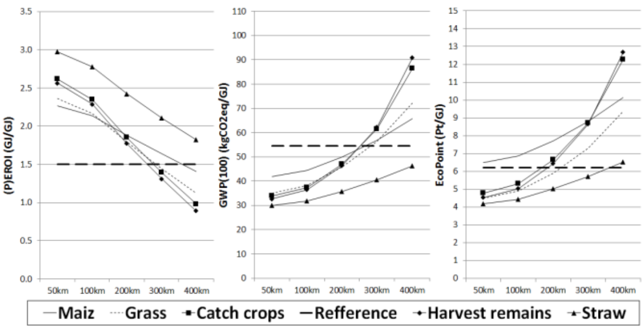

Fig. 5.10. Effect of transport distance on expressions using green gas

In the case of the green gas as fuel scenario, the total amount of green gas injected in the gas grid will decrease as the transportation distance increases (Table 5.8). Transporting, for instance harvest remains over a distance of 400 km, will require more than half of the green gas production to fuel the transport trucks.

Table 5.8. The reduction of green gas injected in the gas grid due to use as fuel in transport compared to 50km

Transport distance	100km	200km	300km	400km
Maize	4.59%	13.76%	22.93%	32.10%
Grass	6.63%	19.89%	33.15%	46.41%
Catch crops	7.98%	23.94%	39.91%	55.87%
Harvest remains	8.44%	25.31%	42.18%	59.05%
Straw	3.59%	10.78%	17.97%	25.15%

5.6. Sensitivity analysis

Using organic material in a biological process inherently creates variations. Within the model several of the values used (e.g. heat use of the digester, transport, Table 5.1) were similar across scenarios. When comparing scenarios, similar settings will cancel out sensitivities in the used values. However, the variables used to define the biomass feedstocks differ (Table 5.5). Therefore,

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the most sensitive values can be found in the feedstock input variables, which include the biogas potential (Nm^3/Mg.oDM), methane potential (Nm^3/Mg.oDM), organic dry matter content (% of FM), and the energy required to produce the biomass and the emissions and environmental impacts of the cultivation process. The sensitivity analysis was performed on the feedstocks maize, grass, and catch crops (Fig. 5.11). Of the variables selected for the sensitivity analysis the methane potential proved to be the most sensitive. The amount of methane produced finally determines the energy output in the shape of green gas injected in the grid. oDM content proves to be a very important variable in transport, storage and processing. The lower the oDM content the more water and other materials not contributing to methane production are transported, stored, heated, and processed. Also important is the required energy, emissions, and environmental impact of the cultivation process. When combined, sensitivity effects range between plus or minus 50% to over 100%, in which case the specific scenario may perform much better or much worse than the reference scenario of natural gas (Fig. 5.11). However, for this to occur, a combination of circumstances working with or against the process is needed (e.g. bad harvest combined with high energy use harvest and low methane yields of the crop). From the selected values from literature the average value are used in the article and the minimum and maximum values are used in the sensitivity analysis.

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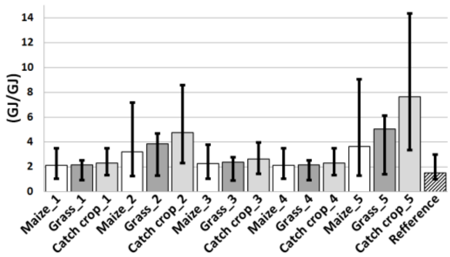

Fig. 5.11a. [P]EROI sensitivity

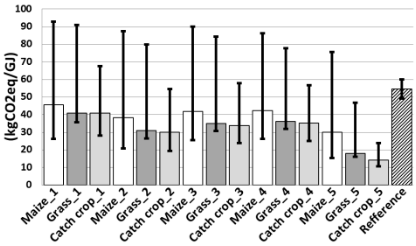

Fig. 5.11b. GWP(100) sensitivity

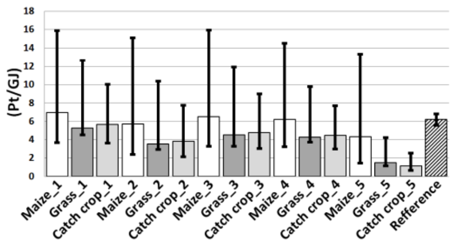

Fig. 5.11c. EcoPoint sensitivity

5.7. Discussion

Green gas production through anaerobic digestion is a promising method for producing a renewable and flexible energy carrier. However, green gas production pathways are complex systems, containing multiple factors and variables which must be taken into account. Accuracy regarding the results presented in this article will depend strongly on the quantity and quality of the data it contains, which comes from both literature and case studies. However, these sources still contain a wide spread of data. Therefore, the model used for calculating the results was extensively validated before being implemented. To express the efficiency and environmental impact, three specific impact factors are chosen in order to give an overview and gain more transparency; however, they cannot give detailed information regarding specific environmental impacts (e.g. acidification). The expression for efficiency, [P]EROI, behaves nonlinearly; due to its dividing element in the equation it will behave exponentially. For instance, a change in the invested energy (e.g. using a micro CHP unit) has an exponential effect on the [P]EROI. Within the "green gas as fuel replacement scenario" the lower efficiency of gas engines compared to diesel engines was not taken into account. Also, emissions from a green gas powered engine will still contain gasses that strongly contribute to the greenhouse effect, which were also not taken into account. Please note that in the case of mitigation the same emissions are still being produced by the green gas pathway, but the emissions from the replaced waste management scenario are subtracted from the total emissions. Furthermore, this part of the research did not go into detail regarding the availability of the selected resources and the economic costs involved. Within a broader perspective the used feedstocks can have other uses, which could include inputs in the production industry or as feed for animals. Also, digestate can be seen as an important product capable of replacing fossil fertilizers, thereby positively affecting environmental impacts. Finally, green gas from anaerobic digestion is often seen as a (fully) sustainable resource, which is not necessarily the case. Currently, economic profitability often results from injecting the highest amount of green gas into the gas grid, which does not necessarily mean it is the most environmentally sustainable or energy efficient scenario. Regulation and subsidization should reflect on emissions and environmental impact just as much as economics in order to promote sustainable energy production. Therefore, understanding of the absolute energy and environmental impact of biogas and green gas production pathways is required to help governments form proper policies which effectively support the European Union in achieving the renewable energy and emission reduction goals, described in the EU energy directive and the EU roadmap 2050 [16, 60].

5.8. Conclusions

The sustainability of the analyzed feedstocks differs substantially, favoring biomass waste flows over the specially cultivated energy crop maize, which starts off with a slightly higher impact on the environment (12% compared to natural gas used as reference). The use of optimization, in the shape of internal energy production, green gas powered trucks, and mitigation can significantly improve the sustainability for all feedstocks, but also favors waste materials. Results indicate a possible improvement from an average [P]EROI for all feedstocks of 2.3 up to an average of 7.0 GJ/GJ. The carbon footprint can potentially be reduced from an average of 40 down to 18 kgCO_2eq/GJ. The environmental impact can potentially be reduced from an average of 5.6 down to 1.8 Pt/GJ. Internal energy production proved to be the most effective optimization. However, the use of optimization aforementioned will result in les green gas injected into the gas grid as it is partially consumed internally. Overall, the feedstock straw was the most energy efficient, where the feedstock harvest remains proved to be the most environmentally sustainable. Furthermore, transport distances of all feedstocks should not exceed 150 kilometers or emissions and environmental impacts will surpass those of natural gas, used as a reference. Using green gas as a fuel can increase the acceptable transportation range to over 300 km. However, when utilizing green gas as a transport fuel it is lost for injection into the gas grid, which can lead up to 59% of the total green gas production when transporting harvest remains over a distance of 400km. Within the context aforementioned and from an energy efficiency and sustainable point of view a more decentralized approach is suggested, wherein the available biomass is harvested, collected and transported close to the location of green gas production and the demand for energy. However, this might affect availability of feedstocks as they are not spread evenly over geographical space. Furthermore, the anaerobic digestion process should be utilized for the treatment of locally available bio-waste streams, e.g. grasses, harvest remains, straw remains or catch crops. Finally, the produced energy should first be used for powering the green gas production process (e.g. by utilizing the use of optimization discussed in this article). When utilized efficiently and responsibly, the anaerobic digestion process can become a more sustainable energy resource capable of processing waste flows and producing renewable energy in the shape of green gas.

Chapter 6
SPACE

Lessons from spatial and environmental assessment of energy potentials for anaerobic digestion production systems applied to the Netherlands

ABSTRACT

Anaerobic digestion (AD) can play an important role in achieving the renewable energy goals set within the European Union. Within this article the focus is placed on reaching the Dutch local renewable production goal set for the year 2020 with locally available biomass waste flows, avoiding intensive farming and long transport distances of biomass and energy carriers. The bio-energy yields, efficiency and environmental sustainability are analyzed for five municipalities in the northern part of the Netherlands, using three utilization pathways: green gas production, combined heat and power, and waste management. Literature has indicated that there is sufficient bio-energy potential in local waste streams to reach the aforementioned goal. However, the average useful energy finally produced by the AD production pathway is significantly lower, often due to poor quality biomass and difficult harvesting conditions. Furthermore, of the potential bio-energy input in the three utilization pathways considered in this article, on average: 73% can be extracted as green gas; 57% as heat and power; and 44% as green gas in the waste management pathway. This demonstrates that the Dutch renewable production goal cannot be reached. The green gas utilization pathway is preferable for reaching production goals as it retains the highest amount of energy from the feedstock. However, environmental sustainability favors the waste management pathway as it has a higher overall efficiency, and lower emissions and environmental impacts. The main lessons drawn from the aforementioned are twofold: there is a substantial gap between bio-energy potential and net energy gain; there is also a gap between top-down regulation and actual emission reduction and sustainability. Therefore, a full life cycle-based understanding of the absolute energy and environmental impact of biogas production and utilization pathways is required to help governments to develop optimal policies serving a broad set of sustainable objectives. Well-founded ideas and decisions are needed on how best to utilize the limited biomass availability most effectively and sustainably in the near and far future, as biogas can play a supportive role for integrating other renewable sources into local decentralized energy systems as a flexible and storable energy source.

Additional information chapter

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Keywords: *Local bio-energy availability, Organic waste, Anaerobic digestion, Biogas, Energy and environmental system analysis, LCA*

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6.1. Introduction

The European Union has set high goals for renewable energy integration in the near future [16, 60]. Within this context, anaerobic digestion (AD) can play an important role as it is capable of processing a multitude of biomass feedstocks, whilst producing both energy in the form of biogas, and fertilizers in the form of digestate. Biogas can be seen as a renewable and flexible energy carrier which is storable and can be transformed into electricity, heat, or upgraded to green gas (biogas upgraded to natural gas quality) [27]. Digestate can be processed to produce quality fertilizers for use in agriculture [116]. AD has been successfully implemented in the treatment of several biomass feedstocks and is already established as a reliable technology in Europe [28]. In the year 2014 around 4% of the total energy supply within Europe was produced through biomass, and this is expected to grow significantly in the future [31]. However, the need for feedstocks will most likely also increase as a result, and the majority of the additional supply is expected will come from agricultural land [31]. Therefore, questions can be raised regarding the achievability, efficiency, and sustainability of the biogas production pathway when utilizing specially cultivated energy feedstocks and transporting them over longer distances. The choice of feedstocks, technologies, and the operational values of AD pathways (e.g. feedstock, transport, process) have a significant influence on the environmental impact [46-50, 52, 101], and the increased biomass use can claim valuable arable land for cultivation [31] and/or effect biodiversity [32].

Within the aforementioned context, focus could be placed on alternative feedstocks which: do not have other applications except as energy sources; do not have an extensive environmental impact; and, are locally available (e.g. manures, organic wastes, natural grasses, harvest remains) [101, 117-121]. Studies have indicated that there is a sufficient amount of local waste feedstocks within the Netherlands to achieve the Dutch decentralized renewable goals of 40 PJ by 2020 [30]. One recent study concluded that locally available biomass waste streams can provide up to 66 PJ annually of energy within the Netherlands [122]. Other studies indicate: natural resources (e.g. roadside grass, natural grass reed) can provide around 12 PJ [123] to 13.5 PJ annually [124]; waste streams from agro-industry potentially hold another 14PJ annually [125]; overall, a range between 53 up to 94 PJ per year will be available by 2020 [126]. However, the aforementioned studies often ignore the energy required in the process of extracting energy from the biomass and the environmental impacts of the process. In order to make more reliable environmental assessments of biogas systems from feedstocks, specific local and regional conditions have to be included [47], which fit a unique geographic location with dispersed availability and quality of biomass. LCA studies on local implementation of AD focusing on single waste flows (e.g. food, vinasse, agro-food waste, municipal solid waste) have indicated environmental benefits over fossil resources [117-120, 127, 128]. However, the LCA studies do not focus on utilizing the multitude of locally available waste products for reaching decentralized renewable production goals. Additionally, the question could be raised, from an environmental perspective, whether to focus on quantity or quality of production: quantity, focusing on producing the largest amount of useful energy; or quality, achieving the highest efficiency or creating the biggest reduction of greenhouse gas emissions and environmental impacts. Currently, regulations in the Netherlands are mostly focused on quantity (e.g. the production of green gas, heat and electricity) [30].

Thus, research is still needed to assess the overall renewability, sustainability, and possible energy yields of biogas production pathways operating on locally available waste feedstocks. Understanding the local availability of biomass, the subsequent, related biogas production pathways, and the best sustainable practices can support decentralized renewable integration as AD can play an important role as a waste treatment system which also produces a flexible energy carrier. One indication can be whether the goal of the Dutch government is achievable and whether the focus should be placed merely on quantity or also on quality of energy production from an environmental sustainability perspective. This article aims to contribute to a proper assessment of the overall renewability, sustainability, and possible energy yields of biogas production pathways operating on locally available biomass waste flows. The goal will be affected by assessing and evaluating the local availability of organic waste materials within five municipalities in the northern part of the Netherlands. For these five locations, the following procedure is followed: first, the available biomass waste flows and bio-energy potentials are determined; second, the net energy yields from three biogas production and utilization pathways are calculated; third, the net average yield of the five municipalities are compared to the required yield to reach the Dutch goal of 40 PJ; and finally, the emissions and environmental impact are determined. Additionally, the effect of an increased percentage of manure in the feedstock for the digester is analyzed in terms of efficiency and environmental impacts. The lessons learned from the case study will be discussed in the conclusion.

6.2. Methods

The assessment of the complete biogas production pathway will be performed through the use of a method for calculating the sustainability of AD production pathways and the sustainability of feedstocks and process optimization (described in [36, 101]) and Life Cycle Analysis (LCA). The LCA analysis is undertaken in accordance with European guidance and DIN EN ISO 14040 to 14044: 2006 [42]. The environmental impacts were obtained through the use of the SimaPro v8.0 (2013) utilizing the Eco Invent database v3.0 (2013) as endpoints.

6.2.1. System boundary

Dutch regulation states that at least 50% of the feedstock fed into the biogas production pathway must be composed of manure sources (e.g. cow, pig, chicken manure), while the remainder can be filled up by other biomass sources (e.g. harvest remains, roadside grass, or maize). Environmental impacts are taken into account when they are in direct service of the biogas production pathway (e.g. production, processing, and transport), which include the direct impact of consumption, the indirect impacts of production and transportation, and the required embodied energy in the shape of installations and infrastructure (Fig. 6.1), [101]. The digestate produced will be returned to the biomass sources as fertilizer and transport of the digestate is included. The processing of excess digestate is not included. Within this research, impact mitigation resulting from the replacement of current waste treatment chains is taken into account (e.g. seasonal storage of manure) including the upgrading process of digestate into a fossil fertilizer replacement [101].

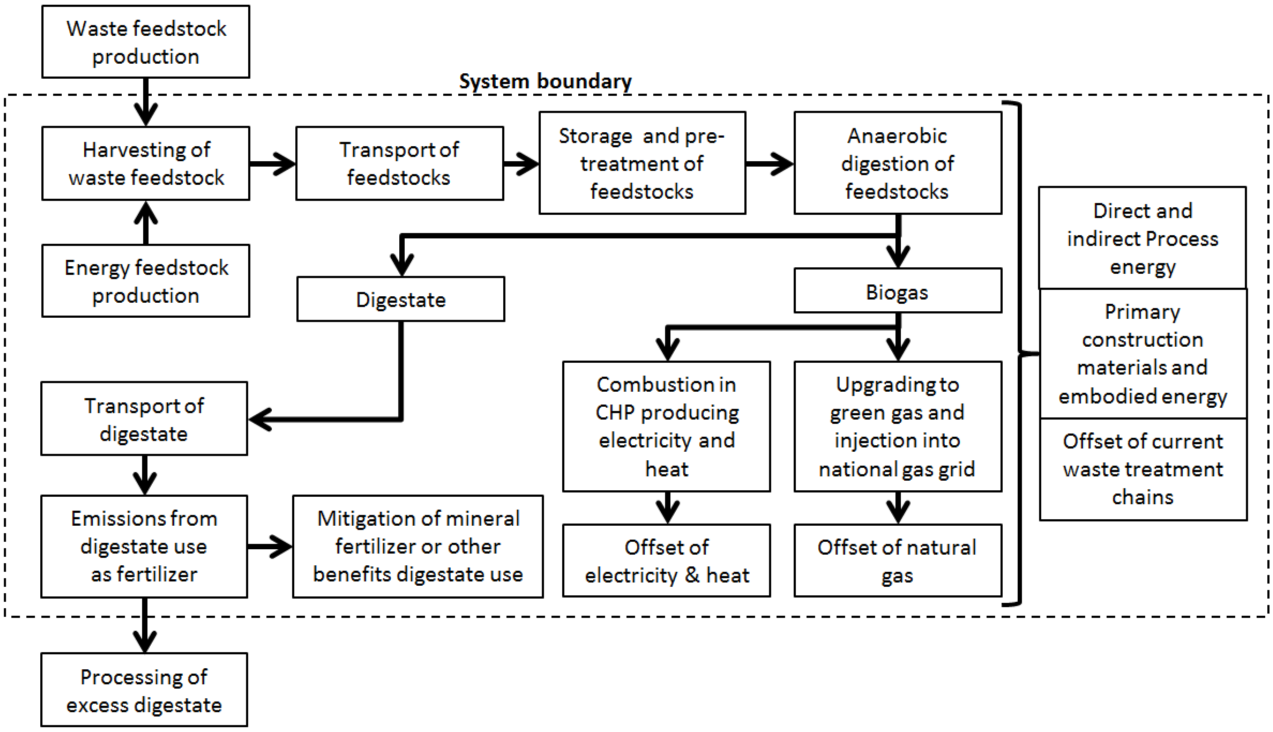


Fig. 6.1. System boundaries of biogas production and utilization pathways, included aLCA

6.2.2. Municipalities

Five municipalities located in the North of the Netherlands are selected where the biomass potential is assessed (Fig. 6.2). These municipalities vary from urban areas with a high population density to rural, agricultural and dairy farming areas, representing the diversity of land usage in the Netherlands (Fig. 6.2). The research is focused on the northern part of the Netherlands as it lays within the scope of the Flexigas project [34] and the project partners responsible for managing and processing biomass flows. However, the calculation method discussed in this article can be used for all areas when sufficient data is available. The data regarding biomass availability in the Netherlands, used in this article, is available per municipality by the Bureau of Statistics of the Netherlands [29].

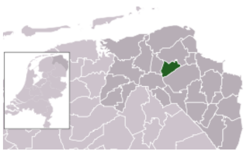
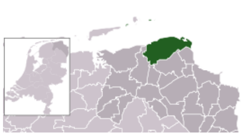
Municipality of Ten Boer	Municipality of Eemsmond	Municipality of Groningen	Municipality of Hoogeveen	Municipality of Noordenveld
				
Rural dairy	Rural mixed	Urban	Semi-urban / rural	Rural agricultural
Population: 7479 Households: 2945 Surface: 45.28 km^2	Population: 15928 Households: 7056 Surface: 189.08 km^2	Population: 198317 Households: 118679 Surface: 78.25 km^2	Population: 54664 Households: 23419 Surface: 127.53 km^2	Population: 31087 Households: 13560 Surface: 200.82 km^2

Fig. 6.2. The municipalities chosen for assessment of local bio-energy potential

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6.2.3. Method for determining the local biomass potential

Due to geographical differences in biomass potential within the selected areas a calculation method is used for determining the average biomass potential. The total biomass potential present within a local municipality is divided by the total land surface of the municipality to obtain an average potential per square kilometer. This method thus averages the distribution of biomass over the surface of one municipality. With the biomass yield per square kilometer known, the land surface required to feed a representative farm-scale digester of 20,000 Mg/a, can be determined (Fig. 6.3). With the surface area known, the average transport distance for the manure and the feedstocks can be determined (discussed in section 6.4).

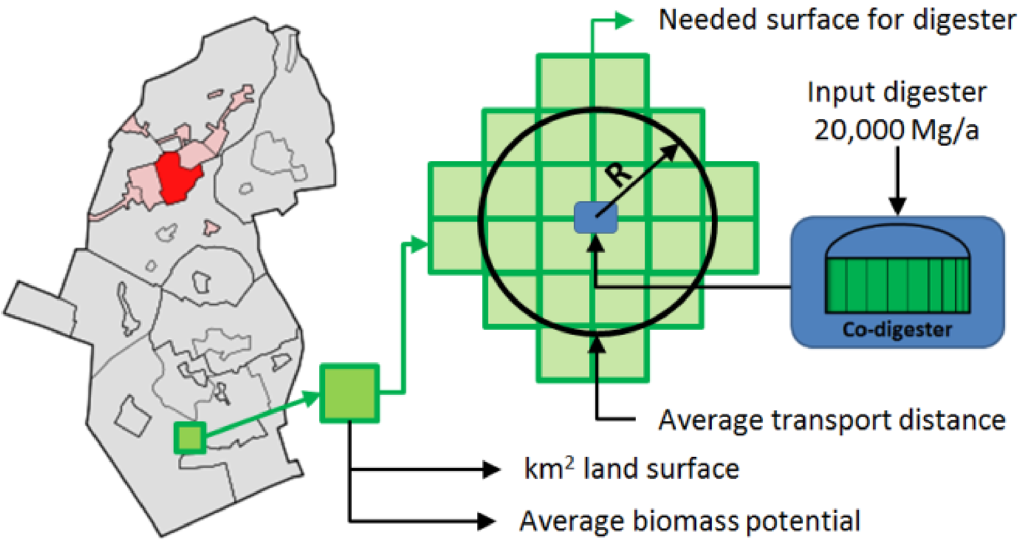

Fig. 6.3. Calculation method used to determine biomass and biogas potential for the municipality of Noordenveld

6.2.4. Expressions of the results

The bio-energy potential per municipality will be expressed in GJ/km^2. The process efficiency, carbon footprint and sustainability of the biogas production pathway, will be expressed by three indicators per GJ of energy produced: (Process) Energy Returned on Energy Invested or [P]EROI, the carbon footprint in GWP 100 year timeframe, and the environmental impact in ReCiPe 2008 Eco indicator. The specific choice for the above-named indicators and a clear description thereof are discussed in Pierie, et al. [36]. The results will be compared with reference scenarios (e.g. intensively cultivated maize, Groningen natural gas, and electricity from the Dutch national grid).

6.3. Biomass inventory

An inventory of biomass waste streams availability has been performed for five local municipalities (Fig. 6.2). The bio-energy potentials of the feedstocks are retrieved from table 5.2 (chapter 5). These represent readily available and easily usable feedstocks for farm-scale digester installations. However, small scale waste flows, other agricultural waste flows, and waste flows from the food industry are not included in this inventory. For the biomass availability in the municipalities (Table 6.1) a lower and upper limit are taken into account in two scenarios:

1) Minimum availability scenario: will focus on the biomass waste flows which are already in use or very easily used as feedstock in the AD process, for instance when infrastructure or management processes are already in place and only need minor modification.
2) Maximum availability scenario: all the available biomass waste flows are utilized as feedstock, including biomass waste flows which need additional energy for collection.

Table 6.1. Biomass waste flows selected as feedstocks for biogas production pathway

1) **Manure:** Dairy manure is readily available in the northern part of the Netherlands. Chicken manure, however, is less available and also has a higher biogas potential due to its higher oDM. The manure availability will be similar for both the current and maximum availability scenario.
2) **Grass feedstock:** Natural grasses can be found spread throughout local municipalities. Natural grasslands and road embankments are already in use and are relatively easy to harvest and therefore make up the current availability. The remainder of grass, for instance in small parks and green spaces, is more difficult to harvest and collect and will be added to the maximum scenario.
3) **Harvest remains:** During harvests of sugar beets and potatoes, organic material is left on the fields containing parts of the plant and root system which can be used as feedstock for the digester. In the minimum scenario around 50% of the remains, consisting of the plant are used, and in the maximum scenario 100% of the available remains from sugar beets and potatoes, consisting of the plant and root system, are used.
4) **Straw from grains:** Straw is a product often used as bedding material for livestock in stables. As other systems (e.g. separated manure, rubber mats) slowly replace part of the market for straw, some degree of overproduction and remaining stocks can result. Unused straw can be utilized as a feedstock. In the minimum scenario around 10% of the total produced straw is available for use as feedstock. In the maximum scenario all produced straw is available as feedstock.
5) **Municipal organic waste:** Municipal waste is collected, on average, every two weeks in the Netherlands through the use of a waste bin system. However, most of the organic municipal waste (83%) finds its way into the normal waste flow. Only a small percentage of organic waste is collected directly (17%), comprising of kitchen and garden waste [129]. The minimum availability scenario will be made up from the currently collected organic municipal waste. The maximum availability will contain all the organic waste including the fraction normally found in the normal waste stream. Within this context a separate collection system is used for collecting the organic waste and to prevent contamination of the biomass. The organic dry matter content (oDM) of waste on average is 18% with a biogas and methane yield of respectively 260 and 156 Nm^3/Mg oDM [130].

6.4. Biogas utilization pathways

All feedstocks and scenarios use the same AD plant setup, located on or near a farm with a total biomass input of 20000 Mg of fresh matter (FM) per year [101]. The produced biogas is utilized in three different pathways: green gas, combined heat and power (CHP), and waste treatment. The manure / feedstock ratio in the digester will be kept at 50% manure and 50% biomass feedstock. The feedstock ratios are determined by the surface area needed to supply the digester, set as a circle around the location (Fig. 6.3). The average transport distance will be based on half the surface area of the biomass circle and a tortuosity factor, which represents inefficiencies in transport e.g. winding roads, multiple pickup locations, etc. (Fig. 6.4), [131]. For the manure and feedstock sources a tortuosity factor of 1.5 is used [132]. For municipal organic waste, which is collected on individual house level through a bin system, a tortuosity factor of 20 is used. For the minimum availability of grass a tortuosity factor of 5 is used, and for the maximum availability a factor of 10 is used, due to the additional transport needed for collecting small patches of natural or roadside grass [131]. The effect of the assumed tortuosity factors will be discussed in the sensitivity analysis section (section 6.6).

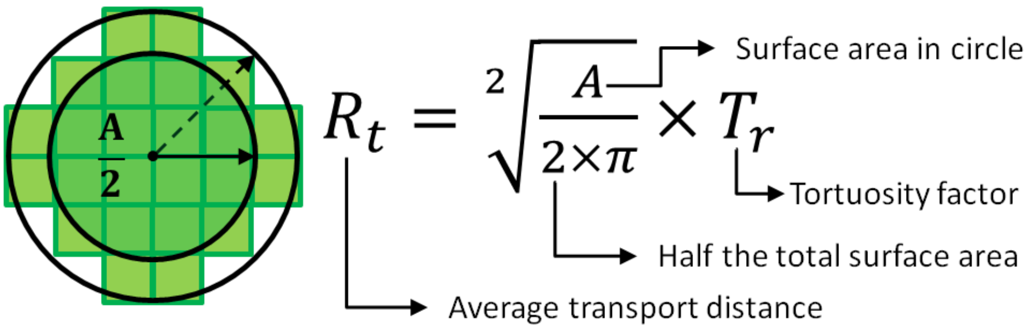

Fig. 6.4. Calculation method used to determine the average transport distance

The solid feedstocks are mechanically pre-treated with a hammer mill in order to improve the digestion and the biogas potential of the feedstock [112]. Grass and municipal organic waste are sieved for foreign debris (e.g. plastics, rocks). Additionally, municipal organic waste will be pasteurized to remove unwanted biological contaminants (Table 6.2).

Table 6.2. Main values used for pretreatment of feedstocks

Feedstocks	**Grass**	**Waste**	**Sugar beet tops**	**Potato tops**	**Straw**	**Unit**	**Sources**
Energy use screening unit[a]	5.4	5.4	-	-	-	MJ/Mg FM	[113]
Energy use hammer mill[a]	20	20	20	20	20	MJ/Mg FM	[112, 113]
Energy use pasteurization[b]	-	162	-	-	-	MJ/Mg FM	[133]

[a] Electricity consumption only

[b] Electricity use 5 MJ/Mg FM and heat use 157 MJ/Mg FM

6.4.1. The green gas production pathway

Within the green gas utilization pathway, the main product is green gas of natural gas quality for injection into the national gas grid. Part of the produced biogas will be used in a small boiler to produce the needed heat for the digestion process. The remaining biogas will be upgraded to green gas through the use of a highly selective membrane upgrader system (see table 5.1 chapter 5). A gas pipe transporting the green gas over a distance of one kilometer to the injection point and the electricity (Average grey electricity mix of the Netherlands, Table 6.5) needed for the process is incorporated.

6.4.2. Combined heat and power

In the combined heat and power (CHP) utilization pathway the main products are electricity and heat (Table 5.3 chapter 5). The produced electricity and heat is firstly used to supply the energy demand of the AD process itself, and the remainder is put on the national electricity grid and on a local heat grid. Within this pathway all the produced heat is considered as useful energy. For both electricity and heat an additional cable and pipeline of one kilometer is incorporated for transportation to the injection locations.

6.4.3. Waste management optimization

The waste management utilization pathway will produce both green gas and CHP. The CHP unit will power and heat the AD process and the digestate upgrading process, which produces fossil-equivalent quality fertilizers. Any remaining heat demand will be supplied by the biogas boiler. The remaining biogas will be upgraded to green gas, which is firstly used as transport fuel for the trucks delivering the feedstocks, thereby replacing diesel use, and the remainder will be injected into the national gas grid. Additionally, a large share of the digestate (90%) is separated into a thin and thick fraction (Table 6.3). The processed thin and thick fractions (the former, after upgrading) will be used to replace fossil fertilizers (Table 6.4), [31, 134]. The remaining 10% of the digestate will be used on-site, replacing manure fertilization on the pasture but not replacing fossil fertilizers.

Table 6.3. Main values for digestate handling, separation of digestate in thin and thick fractions, and thin fraction upgrading

Main components waste management pathway	Value	Unit	Source
Energy requirement separator[a]	4.68	MJ/Mg FM	[135]
Energy requirement evaporator[b]	231	MJ/Mg FM	[136]
Water removed from fraction in evaporator	90%	%	[136]

[a] Based on an electric separator

[b] Based on vacuum evaporator system operating on a heat pump

Table 6.4. Main values for production of fossil fertilizers replaced by upgraded digestate

Fertilizers replaced	Nitrogen as N	Phosphate as P_2O_5	Potassium as K_2O	Units	Source
Required energy for fertilizer production	75.90	27.9	12.9	MJ/kg	[75, 103]
Emission during fertilizer production	12.60	2.22	2.30	kgCO2eq/kg	[75, 103]
Environmental impact during fertilizer production	1.77	0.76	0.24	Pt/kg	[75, 103]

6.4.4. Reference scenarios

The results from the analysis will be compared to two reference scenarios in order to indicate efficiency and sustainability.

1) Fossil reference scenarios: The reference scenarios are based on Groningen natural gas and the grey electricity average mix of the Netherlands (Table 6.5), which includes production, required infrastructure (natural gas and electricity network), and combustion of the gas when used.

Table 6.5. Values used as reference for Groningen natural gas and grey electricity

	Carbon footprint kgCO2eq/GJ	Environmental impact Pt/GJ	Source
Natural gas[a]	54.6	6.2	[75, 103]
Grey electricity[b]	177	28.2	[75, 103]

[a] Natural gas produced from the Groningen gas field and surrounding gas fields in the Netherlands, including infrastructure

[b] Grey electricity, based on the average mix of electricity produced in the Netherlands in 2014, including infrastructure

2) Maize reference scenario: The maize silage used as a feedstock is specially cultivated for use in the biogas production pathway (Table 6.6). Therefore, agricultural field work and the use of fossil fertilizers and pesticides during cultivation are incorporated. Maize will be incorporated in the model as a reference using the same biogas production and utilization pathways as described in section 6.4. The maize will be transported over an average distance of 50 km [27].

Table 6.6. Main properties of energy maize feedstock

Feedstock	Biomass yield Mg/ha	Organic Dry Matter % of FM	Biogas potential $Nm^3/Mg.oDM$	Methane potential $Nm^3/Mg.oDM$	Sources
Energy maize	45	30	606	322	[111]; [43, 109]

6.5. Results

In the following section the results are discussed, starting with the overall bio-energy yields and the efficiencies of the utilization pathways, followed by the [P]EROI and environmental impact of the pathways, and finally, the effect of increasing the percentage of manure in the feedstock is discussed. The figures used to express the results are based on the descriptions in Table 6.7 (scenarios are described in section 6.3).

Table 6.7. Scenario indications in Table 6.8 and Figures: 6.6, 6.7, 6.8

Municipality	Minimum	Maximum
Ten Boer	Ten Boer_min	Ten Boer_max
Eemsmond	Eemsmond_min	Eemsmond_max
Groningen	Groningen_min	Groningen_max
Hoogeveen	Hoogeveen_min	Hoogeveen_max
Noordenveld	Noordenveld_min	Noordenveld_max

6.5.1. Theoretical energy yields

The theoretical bio-energy yield of the municipalities per square kilometer is strongly dependent on the nature of the space available for biomass growth, the types of biomass available, and population density. The average theoretical bio-energy yield of the selected municipalities is around 1614 GJ/km^2, which is comparable to the national average indicated in literature (1400 to 2500 GJ/km^2) as discussed in the introduction (Table 6.8). However, only around 64% (1038 GJ/km^2) of the biomass available is utilized as a feedstock (Table 6.8). The gap can partially be traced back to the high amount of manure available, of which only small amounts are used as feedstock, often due to low biogas yields and difficulty in collection and transport. Therefore, a municipality with a high number of dairy farms can have a high theoretical bio-energy yields with only low utilization realized (e.g. municipality of Ten Boer). Agricultural activity can also lead to higher utilization of bio-energy yield (e.g. municipality of Eemsmond), (Table 6.8). Furthermore, the local theoretical bio-energy yield from waste flows is fairly constant and without the use of agricultural land or intensive farming will most likely not increase significantly in the coming years; therefore, the bio-energy yield can be seen as a set amount.

Table 6.8. Bio-energy yields, energy in feedstocks, and net energy yields of the utilization pathways per municipality

Municipality	Average[a] GJ/km^2.a	Ten Boer GJ/km^2.a		Eemsmond GJ/km^2.a		Groningen GJ/km^2.a		Hoogeveen GJ/km^2.a		Noordenveld GJ/km^2.a	
	Average	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Bio-energy yield	1614	2472	3412	897	2732	436	757	1172	1900	1259	1887
Energy in feedstock[b]	1038	719	1673	659	2563	252	562	277	1018	631	1285
Green gas	757	576	1305	475	1949	161	214	192	672	488	944
CHP	591	460	1039	361	1525	122	187	147	510	384	734
Of which electricity	350	247	573	218	863	85	187	93	342	214	434
Waste management	453	390	900	233	1194	90	44	110	382	306	587
Energy demand[c]	20955	5273		3026		122971		14889		5475	
Of which electricity	2838	714		410		16653		2016		741	
Of which natural gas	18118	4559		2616		106318		12873		4733	

[a] The averages are calculated considering the total bio-energy yield of the municipalities divided by the total land surface of the municipalities and the average between the minimum and maximum scenario.
[b] The bio-energy in the feedstock used as input in the digester installation.
[c] Calculated using the energy consumption for an average household in the Netherlands: Electricity 3050 kWh/a, gas 1200 Nm^3/a [29], excluding shops and industry.

6.5.2. Energy efficiency process

The efficiency of the AD process and utilization pathways determines the amount of energy which can be extracted from the feedstock. The average energy extracted varies: 73% as green gas, 57% as heat and power, and 44% as green gas in the waste management pathway (Fig. 6.5). This lowers the average energy yield of the municipalities to 757 GJ/km^2 as green gas. There will be differences in yields between municipalities, depending on available feedstock, transport distance, etc. (Table 6.8). Within the utilization pathways the green gas pathway is capable of retaining the largest share of energy from the feedstock, due to minimal losses (e.g. leakage, heat), (Fig. 6.5a). However, the energy needed for the production of green gas is substantial: over a quarter of the produced biogas is needed for the production of heat, and over a third of external energy is required for the process itself (e.g. transport, electricity and the embodied energy), (Fig. 6.5a). The CHP pathway retains relatively less energy from the feedstock. This process includes higher losses, primarily in the form of non-recoverable heat. Also, a larger portion of the produced heat and electricity is used internally (than in the green gas pathway), which will result in lower final energy production, but also lower external energy requirements (Fig. 6.5b). Finally, the waste management pathway has the lowest energy yield as green gas. The losses are comparable to the heat and power scenario as the pathway also contains a CHP unit. The internal energy consumption is larger, due to the upgrading of digestate to fertilizer and the replacement of transport fuel with green gas; this, however, also results in the lowest final energy production and external energy demand (Fig. 6.5c). Within the aforementioned context, from a target oriented approach (e.g. 40 PJ in the year 2020 [30]) the green gas utilization pathway would be most capable in achieving the highest energy production.

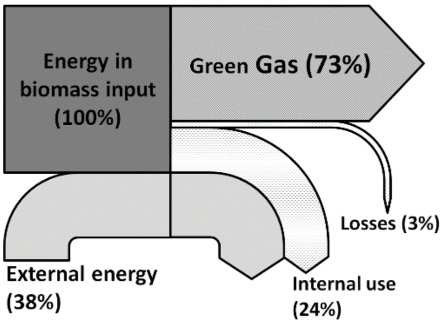

Fig. 6.5a. Average efficiency of the green gas utilization pathway

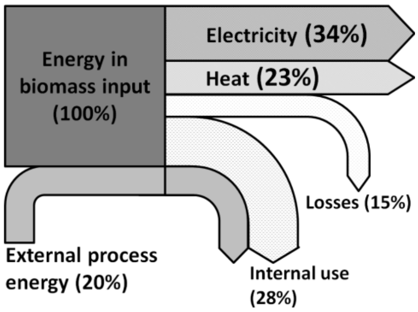

Fig. 6.5b. Average efficiency of the CHP utilization pathway

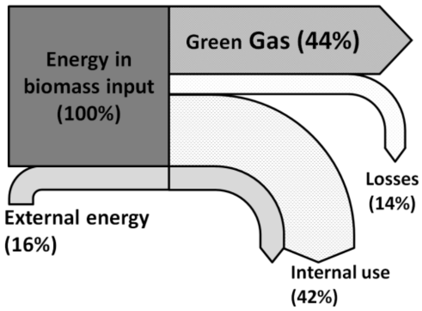

Fig. 6.5c. Average efficiency of the waste management pathway[a]

[a] Replaced energy in fertilizers (0.9%) and green gas used as fuel for transport (0.2%) is included in internal use.

6.5.3. Process Energy Returned on Energy Invested

The efficiency of the process, feedstock availability, and quality, combined with the external energy inputs, strongly influence the process energy return on energy investment or [P]EROI. Feedstocks with low biogas potentials or which need energy-intensive processing will negatively affect the [P]EROI. For instance, the municipality of Groningen has a very low [P]EROI due to the high ratio of organic municipal waste, which requires high energy inputs (e.g. transport, screening, pasteurization). When waste use is maximized in Groningen, more energy is needed in the production process than can be obtained (Fig. 6.6). However, this is not taking into account the energy already required by the waste industry currently in place. For the municipality of Ten Boer the [P]EROI is higher due to a larger share of natural and roadside grass in the feedstock. Therefore, from an efficiency standpoint, one could be selective in the feedstocks used in the production pathway. Furthermore, there are also differences per utilization pathway. The green gas pathway is able to retain the most energy from the available biomass, however, higher use of external process energy has a negative effect on the [P]EROI compared to the CHP and waste treatment scenarios (Fig. 6.6). Heat and power production has a high overall efficiency in most scenarios due to the low external energy requirements. However, when the produced heat from the CHP unit cannot be completely utilized, due to lack of demand in some municipalities, the overall efficiency will go down. Overall, the [P]EROI of the waste treatment pathway is highest due to the low use of external energy in the process and the displacement of fossil fertilizers (Fig. 6.6). Production and utilization pathways with internal energy production and consumption positively influence the [P]EROI, however, they produce lower net energy from the feedstocks.

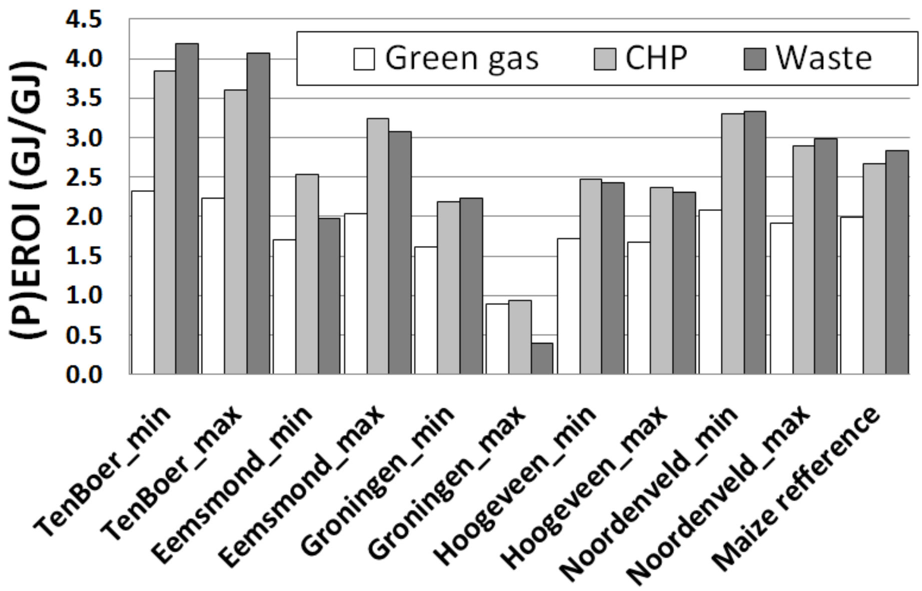

Fig. 6.6. The [P]EROI of the AD utilization pathways per municipality

6.5.4. Environmental assessment

The environmental impacts of the biogas production and utilization pathways are strongly linked to external energy consumption often based on fossil energy, leakages of biogas or green gas, the combustion of biogas, the mitigation of greenhouse gas emissions when feedstocks are left on the field or stored in manure tanks, and the replacement of fossil fertilizers which are often produced from, or with the aid of, fossil fuels. Furthermore, the quality of the feedstock and the corresponding processing also influences the environmental sustainability. In municipalities where larger amounts of municipal organic waste are processed the impacts are higher due to a larger energy requirement. For example, the effect of using large shares of municipal organic waste can be clearly observed in the municipality of Groningen; where, in the maximum scenario, around 18% of the total feedstock is composed of municipal organic waste, which lies on average around 2% per municipality. The large external energy requirements needed for processing the waste has a significant effect on the emissions (Fig. 6.7) and the environmental sustainability (Fig. 6.8) of the process. Environmental impacts and emissions also differ between utilization pathways. On average, the green gas production pathway has the highest impacts, which can be traced back to its higher external energy requirements. In the waste treatment pathway where all emissions saving actions are combined (e.g. internal energy production, green gas fueled transport, mitigation of emissions, replacement of fossil fertilizers) the overall emissions and environmental impacts are significantly lower. In some cases, more impact is avoided in the process than is produced, resulting in negative environmental impact (Fig 6.8). However, when more energy is required in the process than is produced, the impact increases well above the reference of energy maize, natural gas and even grey electricity (Fig. 6.8, municipality of Groningen). Therefore, care should be taken in feedstock selection and/or renewable energy should replace fossil energy inputs. Also, the maximum biomass scenario (section 6.3) on average performs less well in efficiency and environmental impacts, indicating that some biomass feedstocks are not worth collecting (e.g. small patches of biomass). Overall, the environmental footprint is strongly influenced by the feedstocks used, the design of the production, and the utilization pathway.

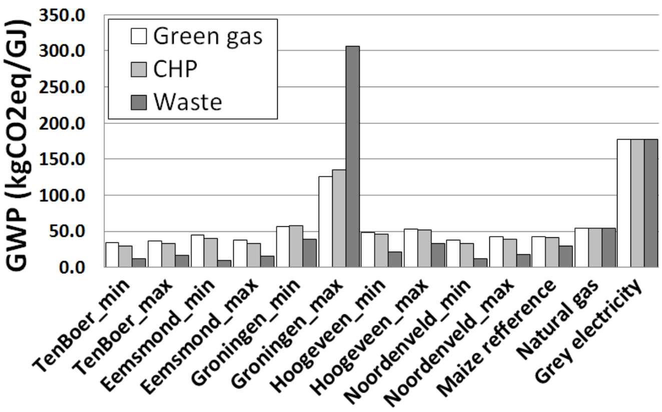

Fig. 6.7. The emissions per municipality

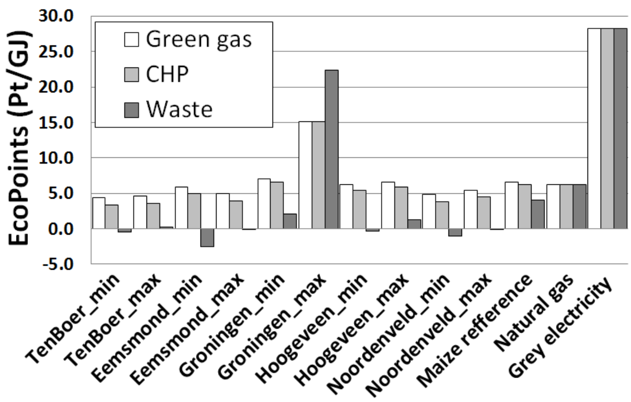

Fig. 6.8. Environmental impact per municipality

6.5.5. Increase of manure as feedstock

As previously indicated in this article, on average only 64% of the bio-energy potential is used as feedstock for the AD process (Section 6.5.1), which can be partly traced back to unused manure waste flows. Feedstocks containing over 50% of manure are often not used, due to the low biogas yields and high process costs of manures. In the municipality of Ten Boer (and to a lesser extent in Hoogeveen and Noordenveld) the availability of cow manure far outweighs the availability of waste feedstocks, and provides an additional source of biomass. However, the lower energy potential of manure can have an effect on the environmental sustainability of the production pathway. Therefore, for the municipality of Ten Boer the manure input in the digester was increased from 50%, by increments of 5%, up to 100% (although the values above 80% are no longer representative and are not presented here) to see the effects of higher percentages of manure in the feedstock (Fig. 6.9).

Results indicate that, for both the green gas and CHP pathway, increasing the manure fraction of the feedstock generally has a negative effect (Fig. 6.9a, b), with only the environmental impact of the CHP pathway being slightly lowered (Fig. 6.9c). Due to the higher percentage of manure, the energy in the feedstock steadily lowers, but the energy input in processing (e.g. transport, heating, stirring) stays the same, resulting in overall negative effects (Fig. 6.9a). For the waste treatment pathway the efficiency drops sharply as a higher percentage of the produced energy is required by the process itself (Fig. 6.9a). However, avoided emissions from manure and the replacement of fossil fertilizers can significantly reduce emissions and environmental impact (Fig. 6.9c). If, for instance, the required external energy input is supplied by renewable resources, then the environmental sustainability would further increase. At this point the waste production pathway ceases to be a net energy producer. However, from an environmental perspective waste management is preferable (Fig 6.9b, c).

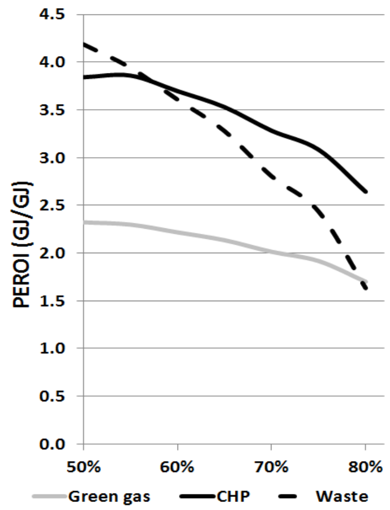

Fig. 6.9a. [P]EROI variable manure input in the municipality of Ten Boer

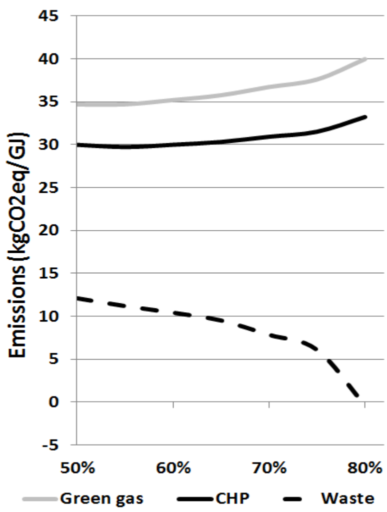

Fig. 6.9b. Emissions variable manure input in the municipality of Ten Boer

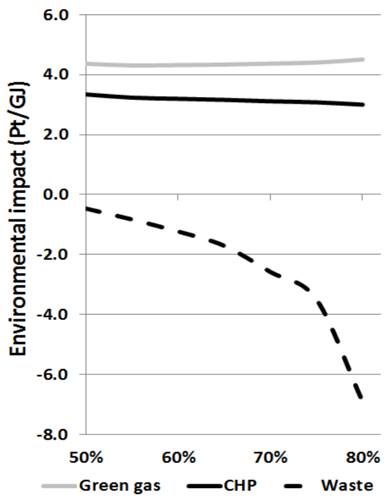

Fig. 6.9c. Environmental impact variable manure input in the municipality of Ten Boer

6.6. Sensitivity analysis

Using organic material in a biological process inherently creates variations. Where possible, values used in the model are similar to each other (e.g. in the biogas production pathway). When comparing scenarios, similar settings will cancel out sensitivities in the used values. However, the variables used to define the biomass feedstocks and the biogas utilization pathways will differ. Within the variables selected for the sensitivity analysis, the methane potential proved to be the most sensitive. The amount of methane produced finally determines the energy output from the AD process. oDM content proves to be a very important variable in transport, storage and processing. The lower the oDM content, the more water (and other materials not contributing to methane production) are transported, heated, and stirred. The complete sensitivity analysis is described in Pierie et al. [101] (Chapter 5). Also, within this article tortuosity factors are used to simulate winding roads used for grass and municipal solid waste collection (section 6.4). The sensitivity regarding the tortuosity factors on grass and municipal organic waste, compared to average transport distances, only accounts for an average difference on the expressions of 5% for green gas, 8% for CHP, and 4.5% for the waste treatment pathway, with a maximum difference of 10%, 14%, and 7% respectively in the municipality of Groningen. The impact of transport is thus substantial, depending on the scenario and location; however, it is not a dominant factor. The municipality of Groningen is most affected due to the high percentage of municipal organic waste within the feedstock. Within the aforementioned context, the energy requirement of pasteurizing the organic waste is also significant. The results of this study are considered to be representative of bio-energy production, on average.

CHAPTER 6: Space

6.7. Discussion

Energy production through AD is a promising method for producing a renewable and flexible energy carrier. However, the production and utilization pathways are complex systems, containing multiple factors and variables which must be taken into account. The accuracy of the results presented in this article depends strongly on the quantity and quality of the data it contains, which comes from both literature and case studies. However, these sources still contain a wide range of data. Therefore, the model used for calculating the results was extensively validated before being implemented. In order to give an overview and gain more transparency, three specific impact factors are chosen to express the efficiency and environmental impact; however, the indicators cannot provide detailed information regarding specific environmental impacts (e.g. acidification). The expression [P]EROI behaves nonlinearly due to its dividing element in the equation which will cause it to behave exponentially. The biomass potential used in this article is based on data from the Dutch bureau of statistics, which represents an average potential. Specific biomass potentials are often difficult to quantify and differ by season and specific location. Furthermore, the biomass potential is spread out evenly over the municipality for determining average transport distances. The effects of multiple feedstocks in combination with digestion are not well documented and can have an effect on the biogas potential of the individual feedstocks. Cutting natural areas and embankments can have an effect on the natural wildlife, which is not considered within this article. In addition, the biomass described in this article could have other uses (e.g. stable flooring, animal feed) which must be considered. The locations chosen for this research lay within the scope of the Flexigas project [34] and the project partners responsible for managing and processing the biomass flows, which does not necessarily make them realistic averages for the whole of the Netherlands. The quantity and quality of the various types of biomass differ per chosen location; however, the calculation method discussed in this article can be used for most areas with sufficiently available data. Municipal organic waste is used as a feedstock within this article; currently the quality is substandard and the digestate therefore cannot be used as fertilizer; however, when separated and collected correctly, quality will be sufficient. Transport distances are difficult to quantify and normalize; therefore, within this article tortuosity factors are used, although transport distances can differ significantly per specific location. Also, in this article all the energy from the CHP unit is utilized; however, heat produced in a CHP unit cannot always be fully utilized as demand must be present and may fluctuate.

6.8. Conclusion

Anaerobic digestion of bio-waste flows can play an important role in achieving renewable goals set within the European Union. Literature indicated that there is sufficient bio-energy potential in local waste streams to reach the Dutch goal for local renewable energy production of around 40 PJ in the year 2020. Within the case study, however, the average useful energy retained is significantly lower. Only around 64% of available biomass is utilized as a feedstock, often due to low quality and difficult harvesting conditions. Utilization of biomass can be increased by using higher amounts of manure in the feedstock. However, increasing the share of manure has a negative impact on the [P]EROI of all utilization pathways. Furthermore, of the potential bio-energy input in the three utilization pathways considered in this article, on average: 73% can be extracted as green gas; 57% as heat and power; and 44% as green gas in the waste management pathway. When utilizing AD biogas production pathways a significant gap arises between bio-energy potential and net energy gain, demonstrating that the Dutch goal cannot be reached using AD and local biomass waste flows alone. The green gas utilization pathway is preferable for reaching production goals as it retains the highest amount of energy from the feedstock. However, environmental sustainability factors favor the waste management pathway. High use of internal energy, green gas for transport, mitigation of emissions, and the replacement of fossil fertilizers with upgraded digestate significantly reduce Green House Gas (GHG) emissions and environmental impact. The main lessons drawn from the aforementioned are twofold: there is a substantial gap between bio-energy potential and net energy gain; and there is also a gap between top down regulation and actual emission reduction and sustainability. Therefore, a full life cycle-based understanding of the absolute energy and environmental impact of biogas production and utilization pathways is required to help governments to develop optimal policies which effectively support the European Union in achieving renewable energy and GHG emission reduction goals within the context of climate policy, as described in the EU energy directive and the EU roadmap 2050 [16, 60]. Decisions will need to be made on how to utilize the limited biomass availability most effectively and sustainably, in the near and far future, as biogas can play a supportive role for integrating other renewable sources into local decentralized energy systems as a flexible and storable energy source.

Appendix 6-I: Biomass yields per type

Feedstocks	Grass	Organic Waste	Beet tops	Potato tops	Straw	Unit	Sources
Yield per hectare	22	-	40	20	4.1	Mg FM[a]/ha	[110, 112, 137]; [138, 139]; [27, 44]
Production per person per year	-	79	-	-	-	kg/person	[29]

[a] Fresh matter

Appendix 6-II: Biomass potential per square kilometer

Municipality	Ten Boer Mg/km2		Eemsmond Mg/km2		Groningen Mg/km2		Hoogeveen Mg/km2		Noordenveld Mg/km2	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Mixed manure dairy / pig	3975.3	4019.4	677.0	756.3	447.3	536.7	2054.4	2132.8	1474.0	1523.8
Solid manure poultry	22.1	22.1	31.7	31.7	0.0	0.0	7.8	7.8	24.9	24.9
Municipal waste	3.7	21.6	2.9	16.8	15.5	91.2	8.5	49.7	4.2	24.5
Natural grasses	228.3	487.8	31.8	338.8	76.9	137.3	58.7	257.5	158.0	318.2
Tops sugar beets	8.8	17.5	136.2	272.4	3.0	6.0	22.2	44.3	27.8	55.5
Tops potato	0.0	0.1	162.2	324.4	2.5	5.1	31.5	63.0	60.5	120.9
Straw	3.6	36.3	11.4	113.9	0.3	3.3	0.7	6.5	0.6	6.5
Total feedstock	244.4	563.3	344.5	1066.3	98.2	242.9	121.5	421.2	251.0	525.6

Appendix 6-III: Biogas potential of the selected feedstocks

Feedstock	Organic Dry Matter % of FM	Biogas potential Nm^3/Mg.oDM	Methane potential Nm^3/Mg.oDM	Sources
Cow manure	6.4	350	180	[71]
Poultry manure	41.6	212	127	[71]
Municipal organic waste	18.3	260	156	[130]
Natural and roadside grass	23.5	560	297	[110, 112]
Sugar beets tops	10.3	420	302	[139]
Potato tops	11.1	420	302	[138, 140]
Straw from grain	82.0	341	174	[27, 44]

Appendix 6-IV: Input in digester per scenario

Municipality	Ten Boer Mg/a		Eemsmond Mg/a		Groningen Mg/a		Hoogeveen Mg/a		Noordenveld Mg/a	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Cow/pig manure stable	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0	1812.0
Cow/pig manure source	7284.5	7795.9	7266.8	7890.4	8188.0	8188.0	7542.4	8001.8	7196.2	7714.3
Poultry manure	903.5	392.1	921.2	297.6	0.0	0.0	645.6	186.2	991.8	473.7
Municipal waste	150.5	384.1	83.1	158.0	1579.1	3756.5	695.9	1180.6	165.6	465.3
Grass meadow	9341.1	8659.3	923.5	3177.4	7825.7	5652.0	4831.1	6115.1	6294.7	6054.6
Sugar beet tops	358.2	310.8	3953.6	2554.3	303.7	245.6	1825.5	1053.0	1105.4	1055.9
Potato tops	1.8	1.6	4709.0	3042.3	257.6	208.4	2593.6	1496.0	2408.4	2300.5
Straw wheat	148.4	644.1	330.6	1068.1	34.0	137.5	53.9	155.3	25.9	123.6
Total feedstock	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000

Appendix 6-V: Transport distances used for feedstocks

Municipality	Ten Boer km		Eemsmond km		Groningen km		Hoogeveen km		Noordenveld km	
Main feedstock	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Manure cow/pig	0.9	0.9	2.3	2.2	2.8	2.6	1.3	1.3	1.6	1.5
Poultry manure	3.8	2.5	3.2	1.8	6.0	3.8	5.4	2.9	3.8	2.6
Municipal waste	36.1	23.8	30.4	17.3	56.9	36.2	51.2	27.5	35.6	24.6
Grass	12.8	16.8	10.8	12.2	20.1	25.6	18.1	19.4	12.6	17.4
Feedstock remainder	3.8	2.5	3.2	1.8	6.0	3.8	5.4	2.9	3.8	2.6

Appendix 6-VI: Percentage of input for digestate management

Municipality	Ten Boer %/a		Eemsmond %/a		Groningen %/a		Hoogeveen %/a		Noordenveld %/a	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Manure cow/pig at farm	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%	9.1%
Manure cow/pig source	36.4%	39.0%	36.3%	39.5%	40.9%	40.9%	37.7%	40.0%	36.0%	38.6%
Manure poultry	4.5%	2.0%	4.6%	1.5%	0.0%	0.0%	3.2%	0.9%	5.0%	2.4%
Waste	0.8%	1.9%	0.4%	0.8%	7.9%	18.8%	3.5%	5.9%	0.8%	2.3%
Grass	46.7%	43.3%	4.6%	15.9%	39.1%	28.3%	24.2%	30.6%	31.5%	30.3%
Feedstocks	2.5%	4.8%	45.0%	33.3%	3.0%	3.0%	22.4%	13.5%	17.7%	17.4%
Total feedstock	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Appendix 6-VII: Land use and biomass availability data local municipalities

Totals per municipality		**Ten Boer**	**Eemsmond**	**Groningen**	**Hoogeveen**	**Noordenveld**
Total population	total	7479	15928	198317	54664	31087
Total households	total	2945	7056	118679	23419	13560
Total land surface	ha	4528	18908	7825	12753	20082

Manure production		**Ten Boer**	**Eemsmond**	**Groningen**	**Hoogeveen**	**Noordenveld**
Mixed manure dairy	Mg/a	179000	124000	34000	212000	262000
Solid manure beef	Mg/a	1000	1000	1000	3000	3000
Thin manure meat calf's	Mg/a	0	1000	0	20000	19000
Solid manure poultry	Mg/a	1000	6000	0	1000	5000
Thin manure pigs	Mg/a	-	1000	0	23000	7000
Thin manure breeding pigs	Mg/a	-	1000	0	4000	5000
Manure animals remainder	Mg/a	2000	15000	7000	10000	10000

Municipal organic waste		**Ten Boer**	**Eemsmond**	**Groningen**	**Hoogeveen**	**Noordenveld**
Municipal organic waste	Mg/a	979.749	3185.6	7139.412	6341.024	4911.746

Municipal areas		**Ten Boer**	**Eemsmond**	**Groningen**	**Hoogeveen**	**Noordenveld**
Train surface	ha	-	37	68	24	-
Road surface	ha	106	431	460	473	347
Airfield surface	ha	-	-	-	28	-
Burial site	ha	6	17	62	25	14
Parks	ha	10	28	434	108	27
Sport parks	ha	22	43	183	160	110
Urban garden	ha	0	-	57	16	5
Recreation area	ha	-	-	39	13	24
Camping grounds	ha	-	7	10	42	205

Natural areas		**Ten Boer**	**Eemsmond**	**Groningen**	**Hoogeveen**	**Noordenveld**
Forrest area	ha	47	1643	282	1326	3631
Grass from road shoulders	ha	14.76	154.38			518.01
Open and dry natural terrain	ha	-	1071	-	97	826
Open and wet natural terrain	ha	1	456	42	58	207

Agriculture		**Ten Boer**	**Eemsmond**	**Groningen**	**Hoogeveen**	**Noordenveld**
Natural grasslands	ha	447.73	351	125.81	80.16	340.04
Temporal grasslands	ha	466.82	776.13	45.28	1075.86	1316.94
Fallow fields	ha	59.58	145.25	12.58	4.15	68.58
Grains	ha	400.71	5252.34	63.75	203.51	318.3
Sugar beets	ha	19.82	1287.51	11.67	141.39	278.64
Potatoes	ha	0.2	3067	19.8	401.76	1214.13

Chapter 7
PROFIT

Improving the sustainability of farming practices through the use of a symbiotic approach for anaerobic digestion and digestate processing

ABSTRACT

The dairy sector in the Netherlands aims for a 30% increase in efficiency, and a 30% carbon dioxide emissions reduction compared to the reference year of 1990, and a 20% share of renewable energy by the year 2020. Anaerobic digestion (AD) can play a significant role in achieving these aims. However, results indicate, that the AD system is not fully optimized in combination with farming prictices, regarding sustainability. Therefore, the Industrial Symbiosis concept, combined with energy and environmental system analysis, Life Cycle Analysis, and modeling is used to optimize a farm-scale AD system on four indicators of sustainability (i.e. energy efficiency, carbon footprint, environmental impacts, and costs). Implemented in a theoretical case, where a cooperation of farms share biomass feedstocks, a symbiotic AD system can significantly lower external energy consumption by 72% to 92%, carbon footprint by 71% to 91%, environmental impacts by 68% to 89%, and yearly expenditures by 56% to 66% compared to the reference cooperation. The largest reductions and economic gains can be achieved when a surplus of manure is available for upgrading into green fertilizer to replace fossil fertilizers. Applying the aforementioned symbiotic concept to the Dutch farming sector can help to achieve the stated goals indicated by the Dutch agricultural sector for the year 2020.

Additional information chapter

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7.1. Introduction

Within the European Union sustainable agriculture could play an important role in achieving the renewable goals set for 2020 [60], and the renewable vision set for 2050 [16]. Research in the domain of agriculture widely recognizes the importance of sustainable agriculture production systems [141]. However, while modern agriculture is very productive, its negative effects on the environment have become increasingly visible [142]. Current practices aim at reducing per unit costs of production, which results in increased intensity, more specialised production, and increased emissions of substances with negative effects on the surrounding ecosystems and the overall climate [142]. Within the context above, and in accordance with the Dutch goals for energy efficiency and renewable energy production [30], the Dutch agricultural sector has formulated goals for sustainable farming. Amongst others, these goals include: less use of fossil resources and with it lowering anthropogenic emissions; lowering the use of fossil fertilizers; increasing renewability and sustainability of agriculture as a whole; and connecting and integrating agriculture into society [143]. Furthermore, an agreement signed between the dairy sector and the Dutch government aims at 30% increase in efficiency, 30% carbon dioxide emission reductions compared to the reference year of 1990, and 20% share of renewable energy in the year 2020 [30, 134].

Amongst others, anaerobic digestion (AD) has been suggested as a potential renewable energy source for use in the farming sector. The AD process has been successfully implemented in the treatment of several biomass feedstocks, AD is already established as a reliable technology in Europe [28], and can extract energy from biomass in the shape of biogas, which is a flexible and storable energy carrier [27]. However, the choice of feedstocks, technologies, and the operational values of AD systems have a significant influence on their environmental impact [46-50, 52, 101]. The use of intensively cultivated energy crops, long transport distances, and the use of energy intensive processes can negatively affect the environmental impact of AD systems [27, 48, 101]. Business cases for farm-scale AD systems within the Netherlands are often negative due to high investment, feedstock, and operational costs [99, 100, 144, 145] and the lack of stable and consistent policies [134]. Also, focus within the agricultural sector is often placed on single issue regulation and or single improvement options (e.g. renewable production, emission reduction, or waste reduction). Within a complex system like agriculture there is a good chance that “single factor” manipulation could result in a cumulative negative overall gain [142].

Within the context aforementioned, implementing the Industrial Symbiosis concept focusing on optimizing the AD system could potentially lower the environmental impact and cost of farm-scale AD systems. Industrial symbiosis, a key concept of industrial ecology, studies the physical flows of materials and energy in local industrial systems using a systems approach [146]. Industrial symbiosis engages separate industries in a collective approach to create a competitive advantage involving the exchange of materials, energy and services [147]. In an ideal symbiotic system, waste material and energy are utilized between/among the actors of the system and the consumption of virgin raw material and energy inputs as well as the generation of wastes and emissions are thereby, reduced [147]. The Industrial symbiosis concept can help avoid the single factor manipulation by making the AD system an integral part of farming activities. In particular, waste resulting from a generic production process can substitute primary inputs in another process [148].

For instance, by creating a circular symbiotic system where bio-waste is used for energy and fertilizer production which can be reused for the production of new biomass [116-121]. Furthermore, the use of local waste products also avoids intensive farming processes [149], long distance transport, and the widespread debate regarding the use of food-quality biomass for energy production [33], whereas green fertilizer use avoids the production, import, and use of fossil fertilizers [101]. To achieve the aforementioned, the AD process will need technical adaption and optimization through the use of several improvement options operating symbiotically. This can give the opportunity to gain collective benefits significantly larger than the sum of the individual benefits [147, 150], making the AD process a more integral part of sustainable agricultural practices, where potential reduction of wastes, emissions, and primary inputs could create environmental and economic benefits.

However, to the authors' knowledge, no literature discusses the integration and optimization of an AD systems within local farming practices using the industrial symbiosis concept; which could indicate, amongst others, that the AD system has not been fully optimized. Therefore within this article a farm-scale AD system, utilizing locally available biomass waste streams, is analyzed and optimized on four indicators of sustainability (i.e. energy efficiency, carbon footprint, environmental impacts, and costs), through the use of the Industrial Symbiosis concept, combined with energy and environmental system analysis, Life Cycle Analysis, and modeling. Optimizing the AD system involves a holistic approach and a selection of improvement options analyzed individually or combined in a circular symbiotic system applied to a theoretical case within current farming practices. Exploring these combinations could lead to environmental and economic improvements on current AD systems and lead to the integration of circular symbiotic AD systems within future farming practices to reduce the overall environmental impact and cost of the farming process.

7.2. Methods

To come to a more sustainable farming concept using the industrial symbiotic concept, first the effect of the individual improvement components on the indicators are analyzed. From this knowledge, and using a holistic approach, circular symbiotic systems can be designed to optimize the sustainable impact indicators (SI-Indicators), (section 7.2.3). Finally, the theoretical lessons learned from the symbiotic systems are applied to a theoretical case study based on a cooperation of dairy and agricultural farms sharing biomass feedstocks and an AD system. Additionally, the effects of national adaptation of the circular symbiotic system will be researched. In the following section the methods used during the formation of the results are described.

7.2.1. The biogas simulator

The assessment is performed by modelling the complete AD system. The excel model used [151, 152] is based on the industrial metabolism concept. To gain insight into the energy use, carbon footprint, environmental impacts, and costs of the AD system, the model combines Material and Energy Flow Analysis [62], Energy and Environmental System Analysis [27], Attributed Life Cycle Analysis, and Net Present Value [153]. The overall sustainability, within this article is defined as "strong sustainability" wherein environmental quality precedes social prosperity and then economic prosperity [21, 76]. The LCA analysis is undertaken in accordance with European guidance and DIN EN ISO 14040 to 14044: 2006 [42]. The environmental impacts were obtained through the use of the SimaPro v8.0 (2013) utilizing the Eco Invent database v3.0 (2013) as endpoints. In the optimization process of the AD system a holistic approach is used to design symbiotic scenarios with maximum impact on the SI-Indicators, calculated with the model aforementioned.

7.2.2. System boundary

Dutch regulation states that at least 50% of the feedstock used in an AD system must consist of manure (e.g. Cow, Pig, Chicken manure), the remainder can be complemented by other biomass (e.g. harvest remains, catch crops, roadside grass, or maize) in order for the digestate to be used as fertilizer. Energy and material flows and their impacts are taken into account when they are in service of the AD system (e.g. production, processing, and transport), (Fig. 7.1) [149]. The embodied energy of the installations is also incorporated. Within this research, mitigation regarding the replacement of current waste treatment chains (e.g. current manure storage and waste crop management) with an AD system and fossil fertilizer with green fertilizers are taken into account. Our analysis only considers the economic aspects of processing excess digestate. Emissions from digestate application to the field are incorporated [101]. Emissions from the soil are not included. Internal energy use is included where external sources of energy can be replaced with the energy gained from the AD system (Fig. 7.1). Additional economic costs or revenues saved or lost through the use of improvement options are taken into account as cash flows within the NPV. The current energy and fertilizer use (e.g. manure, fossil fertilizers) of farms are included in a theoretical case, for determining the effectiveness of a cooperatively owned circular symbiotic AD system. The costs and revenues of the AD system are based on prices and subsidies within the Netherlands [154].

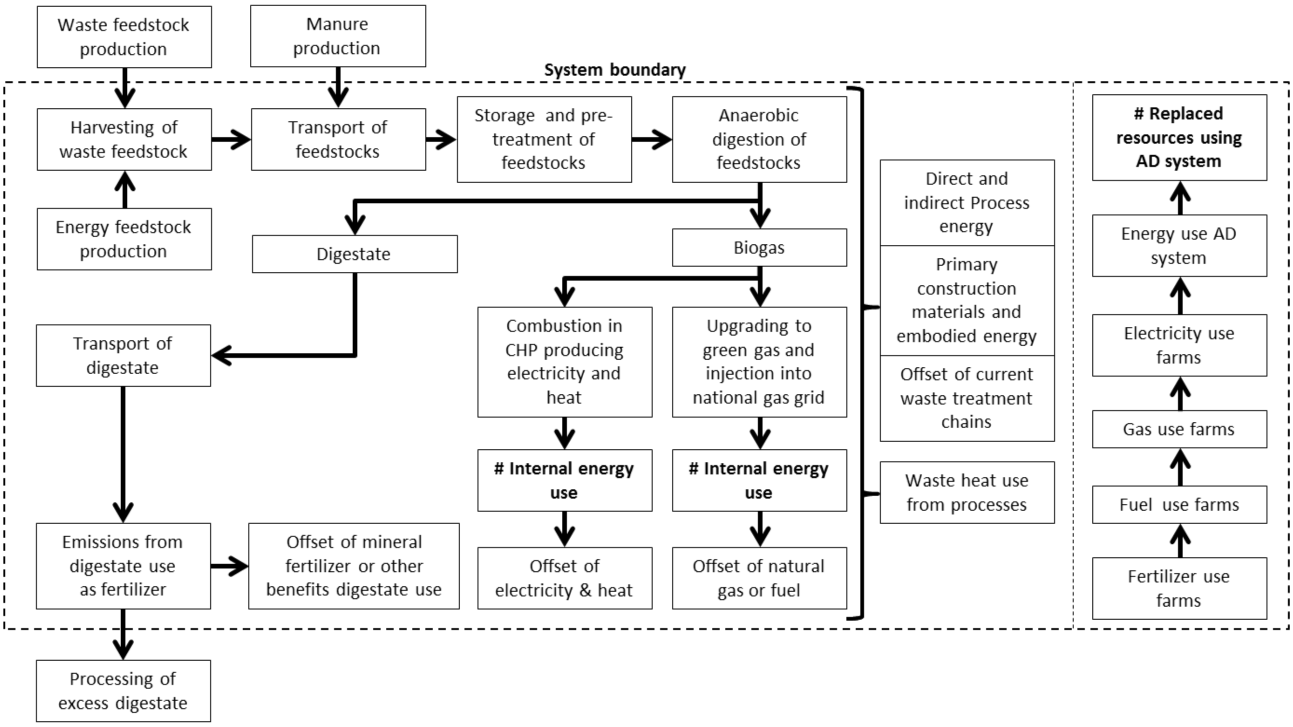

Fig. 7.1. System boundaries of biogas production and utilization, included aLCA

Using the circular symbiotic AD system in the theoretical case will replace current energy and fertilizer flows used on the farm

7.2.3. Sustainable Impact Indicators (SI-Indicators)

The energy efficiency, carbon footprint, and the sustainability of green gas production, are expressed in three indicators: First, (Process) Energy Returned on Energy Invested or [P]EROI, defined as the ratio between the energy obtained from a resource to the energy expended in the production and processing of a resource [77]; Second, the carbon footprint, expressed in carbon dioxide equivalents (CO2eq) using the relevant 100-year global warming potential scale or GWP (100), [79]; And finally, the overall impact on the environment, expressed in the ReCiPe 2008 Eco indicator, used by the SimaPro model [80, 82]. The specific choice for the above-named indicators and a clear description thereof are discussed in Pierie, et al., [36]. The financial feasibility is expressed in Net Present Value (NPV) over 25 years [153]. The NPV method was selected as it is a commonly used indicator for economic feasibility and indicates the overall returns of the investment [153]. The general rule of thumb is if the NPV is positive "invest" and if it is negative "don't invest". The NPV rule recognizes that the value of money today is worth more than the value of money tomorrow, because the money can be invested today to start earning interest immediately. NPV depends solely on the forecasted cash flows of the project and the opportunity cost of capital. Since the present values are all measured in today's value, they can be added [153]. The aforementioned SI-Indicators will be the measure of sustainability within this article.

7.3. The location and biomass feedstocks

The AD system is located on a dairy farm in the middle of the biomass collection area, represented as a circle (biomass circle). The distribution of biomass, dairy farms, and agricultural farms, averaged for the Netherlands, are retrieved from Pierie, et al., [36]. In addition, catch crops (e.g.

flower rich margins or buffer strips) are also used as feedstock for the AD system. During the cultivation of catch crops the use of machinery and fossil fuel is taken into account for seeding and harvesting, no fossil fertilizers are used. Average biogas and methane yield values are selected resulting from several combinations of catch crops [108]. The radius of the biomass circle is determined by the feedstock needs of the AD system; therefore, the mix of feedstocks is determined from the availability of biomass in the biomass circle (Table 6.1). With the average radius of the biomass circle known the average transport distances can be determined [149]. Additionally, a tortuosity factor is included, which represents inefficiencies in transport (e.g. winding roads, multiple pickup locations), [131, 149], (Table 7.1). A clear description of the aforementioned can be found in in Pierie, et al., [36]. For biomass waste flows only transport cost are included (Table 7.1), except for manure from external sources where negative prices are used within the Netherlands, due to its over-abundance [71], and for roadside grass where harvesting costs from road embankments are included [155].

Table 7.1. Feedstocks used including costs and transport retrieved from Pierie et al. [101, 149]

	Feedstock Mg/a	Costs €/Mg	Tortuosity factor	Transport km	Biogas potential Nm3/Mg.oDM[a]	Methane potential Nm3/Mg.oDM[a]
Manure farm/cooperation	1820	0	1	0.1[d]	350	180
Manure source	8000	-10[b]	1.5	1.5	350	180
Chicken manure	475	0	1.5	3	416	212
Natural grasses	6000	10[c]	5	15	560	297
Tops sugar beets	1100	0	1.5	3	550	302
Tops potatoes	2300	0	1.5	3	550	302
Straw from grains	500	0	1.5	3	341	174
Catch crops	1100	0	1.5	3	640	329
Digestate	-	-	-	-	47[f]	19[f]
Energy Maize (Reference)	10000	35[e]	1	50	606	322

[a] Biogas and methane potential in production per Mg of organic Dry Matter
[b] Price of manure from external sources derived from and Kwin, 2013 [71]
[c] Price of grass from road embankments and natural areas [155]
[d] Transport by pipeline
[e] Costs of maize feedstocks derived from Kwin, 2013 [71]
[f] Biogas and methane potential of the digestate retrieved from [156]

All scenarios will use the same AD plant setup as a starting point (Normal scenario), (Fig. 7.2). The AD system, with a feedstock throughput of 20000 Mg/a (Table 7.1), is stirred and heated to maintain mesophilic temperature. When required, feedstocks are mechanically pre-treated, screened for foreign debris (e.g. plastics, stones), and/or pasteurized. Transport of biomass is conducted by truck, loading and unloading is incorporated (Table 7.1). Part of the produced biogas is used in a small boiler to produce the needed heat for the digestion process. The remaining biogas is upgraded to green gas through the use of a highly selective membrane upgrader system [84]. The green gas is injected in the national gas grid (Fig. 7.2). A gas pipe over a distance of one kilometer is used to transport the green gas from the production site to the injection station. The electricity use for the AD system is imported from the national electricity grid. The digestate is used on site as fertilizer on the pastures (Fig. 7.2). The NPV of the business case, over a technical lifetime of 25 years and an economic write off period of 15 years, is based on economic factors within the Netherlands (e.g. energy prices, CAPEX, OPEX) [71, 144, 157]. Subsidies for green gas or electricity production are given per kWh of energy injected into the grid [154], (Appendix II).

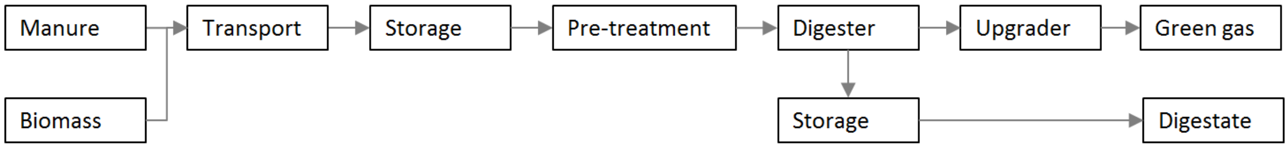

Fig. 7.2. Main green gas production pathway of the Normal scenario

7.4. Scenarios

To come to a more sustainable farming concept, first, the effect of the individual improvement components on the SI-Indicators, applied to the AD system, is analyzed (Appendix 7-I). Second, multiple individual improvements are combined in a symbiotic design with maximum positive impact on all the SI-Indicators (Fig. 7.3). Finally, the theoretical lessons learned from the symbiotic systems are applied in a theoretical case based on a cooperation of dairy and agricultural farms including average consumption of farming practices, which include energy, fuel and fertilizer use (Fig. 7.3).

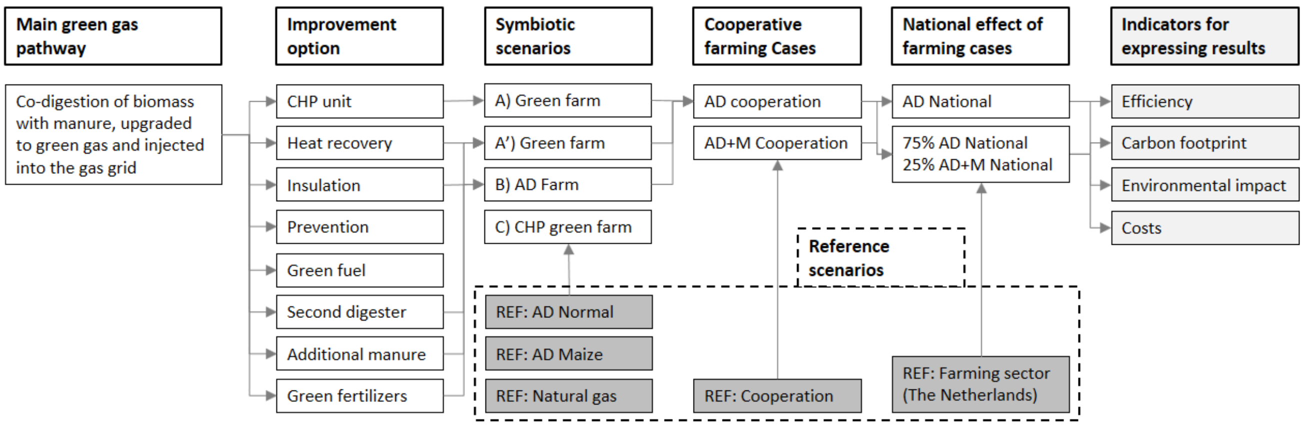

Fig. 7.3. The scenarios and cases used in this article

7.4.1. Circular symbiotic scenarios

Within the circular symbiotic scenarios the main biogas production and green gas utilization pathway (Fig. 7.2) is expanded with several improvement options (Appendix 7-I) to research possible improvements on the main SI-Indicators (section 7.2.3). The optimum sub-scenarios (Table 7.2) are determined through empirical modelling of several combinations of individual improvement scenarios using a holistic system approach. Additional installation properties, investment, and operational costs of improvement options are included (Appendix 7-II).

Table 7.2. The symbiotic scenarios

affiliation	Description of symbiotic scenario
Scenario A	Scenario A, describes the symbiotic system which combines; a Combined Heat and Power unit (CHP) for internal energy production, a 2nd digester with additional manure input, green fuel production from green gas, prevention of leakages and emission, heat recovery, and green fertilizer production which is used in the surrounding farms to replace fossil fertilizers (Appendix 7-I). Additional insulation of the AD system is not used as the required heat is already produced internally.
Scenario A'	Within this scenario one adaption is made to scenario A, namely; the produced green fertilizers are sold on the market for lower prices and not used within the surrounding farms to replace fossil fertilizers. This only has an economic effect and, therefore, will only be indicated in the NPV results.
Scenario B	Within scenario B, regulations prevent the use of green fertilizers for replacing fossil fertilizers in the Netherlands by decree of the European Union [158], (Although the Dutch government has made some exceptions [159]). Therefore, green fertilizer production is not included. The scenario combines; a CHP unit for internal energy production, a 2nd digester with additional manure input, green fuel production from green gas, heat recovery from the digestate, prevention of leakages and emissions, and insulation of the digester (20%) for additional heat savings (Appendix 7-I).
Scenario C:	Currently, many farm-scale AD systems within the Netherlands utilize CHP instead of green gas production; therefore, scenario C describes the possibilities of a circular symbiotic AD system combined with CHP. The scenario includes; internal energy production based on CHP, a 2nd digester with additional manure input, prevention of leakages and emission, heat recovery, insulating the digester, and green fertilizer production which is used in the surrounding farms to replace fossil fertilizers (Appendix 7-I). Within the scenario the full utilization of the waste heat is assumed.

7.4.1.1. Reference scenarios

The results from the symbiotic scenarios are compared to four reference scenarios (Table 7.3).

Table 7.3. Reference scenarios used for comparison

affiliation	Description of the symbiotic reference scenario
Normal	The basic AD green gas production pathway without any modifications as described in section 6.3.
# CHP # Fertilizer #2nd Digester	The best individual improvement options per SI-Indicator are indicated as a reference scenario for comparison with the circular symbiotic scenarios. The best options are; for [P]EROI the CHP unit; for carbon footprint and Environmental impact the green fertilizer production option; and for NPV the 2nd digester with added manure option. Full description of individual improvement scenarios can be found in Appendix 7-I.
Ref gas	This fossil reference scenario is based on Groningen natural gas and includes; the production, needed infrastructure for transport and distribution, and combustion of the gas when used [149].
Ref maize	Within the maize reference scenario 50% maize and 50% manure is used as feedstock for green gas production using the same AD system as explained in section 6.3, (Table 7.1). The maize (silage) used as feedstock is specially cultivated for use in the AD system. Therefore, agricultural field work and the use of fossil fertilizers and pesticides during cultivation are incorporated [101]. The maize is transported over a distance of 50km [27]. Within this scenario, the carbon footprint and environmental impact from normal manure management is also mitigated.

7.4.2. Cooperative farming theoretical case

The theoretical lessons learned from the individual improvement options and the symbiotic scenarios (section 7.1.) are applied to a theoretical case based on a cooperation of five dairy and seven agricultural farms, which are treated in this article as a single entity called the cooperation. The required amount of farms within the cooperation is determined by the feedstock needs of the AD system (Table 7.1). The feedstocks acquired within the cooperation (including manure) only include transport costs. Within the theoretical case all manure is retrieved within the cooperation. The cooperation will use biomass from the local government and water board responsible for managing the biomass growth alongside roads, canals, natural areas, and/or parks (Table 7.4); however, this will include harvesting costs (Table 7.1). The fields used for roadside grass and natural grasslands do not require fertilization, due to natural inflow of nutrients. Regulation regarding green gas production within the Netherlands is stable with a guaranteed subsidy for a maximum of 22 years, however, the taxes and subsidy schemes for the symbiotic systems aforementioned are currently undefined; therefore, the effect on the yearly costs is difficult to indicate. For instance, policies and subsidies for green electricity, green gas and green fuel produced and used within the cooperation are currently nonexistent. Within the NPV cost calculation the Dutch low tax rate of 6% is included for the internal energy products produced within the cooperation (e.g. electricity, green gas, green fuel, and green fertilizers), which is comparable to the current form of subsidy.

Table 7.4. Energy and fertilizer requirements cooperation of farms

	Unit	Dairy farms	Agricultural farms	Natural areas	Total	Source
Average farms needed	farms	5.4	6.9		12.3	
Agricultural land size	ha	270[a]	276[b]	275[c]	821	[71], [101]
Diesel use	l/a	35100	65688		100788	[71]
Electricity use	kWh/a	253800	151524		405324	[71]
Natural gas use	Nm3/a	8640	2898		11538	[71]
Nitrate cap[d]	Kg/a	71550	46920		118470	[71]
Phosphate cap[d]	Kg/a	25650	17940		43590	[71]
Potassium cap[d]	Kg/a	60750	62100		122850	[71]

[a] Based on average dairy farm with 100 cows and two cows per hectare of land [71]

[b] Based on production of beat tops, Potato tops, Straw, and Catch crops respectively 40, 20, 41, and 18.5 Mg/ha.a [101]

[c] Based on the production of roadside and natural grass of 21.8 Mg/ha.a [101]

[d] Cap means the maximum yearly allowed use of nutrients on a farm

All three theoretical cases (Table 7.5) are based on the same energy and fertilizer needs of the cooperation (Table 7.4). Within the cases the SI-Indicators are calculated over a period of 25 years and are expressed per year. The SI-Indicators are expressed in absolute numbers, not including mitigation, and return on investment for NPV, as used in the previous section. The cases (Table 7.5) are based on the average land occupation and feedstock availability described in section 7.3 and the basic AD system described in section 7.4.

Table 7.5. Main cooperative farming cases

affiliation	Description of the sustainable farming cooperation cases
REF (Case)	The reference cooperation (REF): In this case, based on current average farming activities in the Netherlands, the cooperation will import all of their energy and most of their fossil fertilizers. The dairy farms within the cooperation will use their own manure as fertilizer on their fields, whereas agricultural farms will use fossil fertilizer for all their nutrient demands. Additionally, fuel for the machinery, electricity, and natural gas are imported to supply the energy needs of the cooperation (Table 7.4). The environmental impacts of fertilizer, fuel, electricity, and natural gas production are included. Inflation and increase of prices for energy and fertilizers are taken into account for the upcoming 25 years (Appendix 7-II).
AD (Case)	The AD cooperation (AD): Within this case, the cooperation will operate a circular symbiotic AD system, producing renewable energy and fertilizer from local bio-waste. Dairy farmers within the cooperation use the digestate from the AD system as fertilizer on their fields. Excess digestate is processed into green fertilizers and used by agricultural farms in the cooperation. Additionally, the fuel for the machinery, electricity, and natural gas is supplied by the AD system (Table 7.4). The remaining energy or fertilizer requirements are imported. The overall cost of the AD system is based on the NPV calculation (section 7.3.3). Within this case 23% of the total digestate output is upgraded into green fertilizer to replace fossil fertilizer. The income from selling the remaining green gas is incorporated in the NPV; however, mitigation of carbon footprint and environmental impact by replacing green gas with natural gas is not included, as it does not lower the impacts of farming practices itself.
AD+M (Case)	The AD cooperation using surplus manure (AD+M): The AD+M case is similar to the AD case, except, within this case a surplus of manure from surrounding dairy, pig, or chicken farms of 10,000 Mg is available for the production of additional energy and green fertilizer. In some parts of the Netherlands there is a surplus of manure available, often linked to farms with no agricultural land (e.g. pig, chicken farms). For the additional manure feedstock mixture the properties of cow manure are assumed (Table 7.1). Within this scenario around 50% of the total digestate output is available for upgrading to green fertilizer, which can be used to replace fossil fertilizer. Excess fertilizer is sold on the market for market prices (Appendix 7-II).

7.4.2.1. National implementation case

To indicate the possible effect of the theoretical case aforementioned on a national level, results are extrapolated towards full implementation in the Netherlands. Within this case the assumption is made that all farms will participate in cooperatives and that all the local biomass availability is utilized. Also, the available feedstock in the biomass circle described in section 6.3 is assumed to be similar for all cooperations (Table 7.1). Please note however, that in practice biomass circles can differ, therefore, when actually implemented at national scale the results can vary. The amount of cooperations is determined by dividing the total land availability for farming in the Netherlands by the land required by the farms within the cooperation (Table 7.6).

Within the national scope case, the total amount of surplus manure available nationally determines how many AD+M cooperations can be set up. According to the Bureau of Statistics of the Netherlands in the year 2015 there was a nutrient surplus for both nitrogen and Phosphate of around 25% (Appendix 7-III) [29]. Therefore, within the AD+M national case, 25% of the cooperations are based on an AD+M and the rest are based on AD cooperations (Table 7.6). The results are compared with the total national carbon footprint and the carbon footprint from the farming sector in the Netherlands, for the year 2015 and the reference year of 1990.

Table 7.6. Possible amount of farming cooperations within the Netherlands

	Total land (ha)	Average farm (ha)	Amount of farms	Farm per cooperation	Amount of cooperations	AD cooperations	AD+M cooperations	Source
Dairy farming	956000	50	19120	5.4	3541			[29]
Agri farming	995756	40	24894	6.9	3608			[29]
Average					3574	2680	894	

7.5. Results

Within this section first the results of the symbiotic AD system are discussed, followed by the theoretical case and the national case.

7.5.1. Symbiotic circular systems

When implementing the single improvement options individually, improvement on the SI-Indicators can already be observed (Appendix 7-I). For instance, a substantial gain in [P]EROI, can be achieved through the use of a CHP unit (Fig. 7.4a CHP), by avoiding external electricity and heat requirements. Replacing fossil fertilizer with green fertilizer has a significant effect on the carbon footprint and environmental impact as fossil fertilizers require high energy investment during production (Fig. 7.4b, c Fertilizer). Installation of a second digester and additional input of manure directly into the second digester can improve the NPV (Fig. 7.4d Manure). The second digester system requires little additional energy and maintenance but still produces additional biogas. However, the reduction achieved by individual improvement options is often significant for only one or two of the four SI-Indicators (Appendix 7-I). For instance, green fertilizers production positively affects carbon footprint and environmental impact but negatively affects the [P]EROI and NPV; caused by high energy use in the process, substantial initial investment costs, and additional operational costs for energy and maintenance. Within this context, and given the systemic nature of agricultural systems, focusing on single factors does not necessarily lead to optimal results.

Whereas the impacts of individual improvement options are relatively minor, results from the symbiotic scenarios indicate that a symbiosis of improvement options can significantly improve all SI-Indicators compared to the reference scenarios, (Fig. 7.4). Internal energy production significantly improve the [P]EROI in all scenarios, with additional improvement in scenario A and C due to the high energy needs of green fertilizer production (Fig. 7.4a). For both scenarios A and C, the effect of fertilizer replacement is larger than the produced impacts in the biogas pathway, resulting in negative carbon footprint and environmental impacts (Fig. 7.4b, c). In contrast, the actions taken in scenario B reduce the carbon footprint by 69% and environmental impact by 89% (Fig. 7.4b, c), indicating the effect of fossil fertilizer replacement. Furthermore, scenario C indicates that only operating a CHP unit combined with fertilizer production is sustainable and profitable, suggesting the option for modification of current CHP operated AD systems (Fig. 7.4d). Finally, the NPV for all scenarios are positive, with scenario A being most profitable due to the combination of internal energy production and the production and selling of green fertilizers (Fig. 7.4d). However, economic success is strongly dependent on possible utilization and added value of digestate. If for instance, in scenario A, the green fertilizers cannot be used for replacing fossil fertilizer or sold, the

NPV will become negative. Also, if in scenario B more than 65% of the digestate has to be discarded at 10 €/Mg (Average rate in the Netherlands 2010-2016 [99]) the NPV will turn negative.

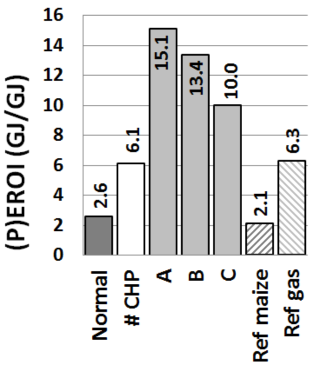

Fig. 7.4a. Efficiency of the symbiotic system

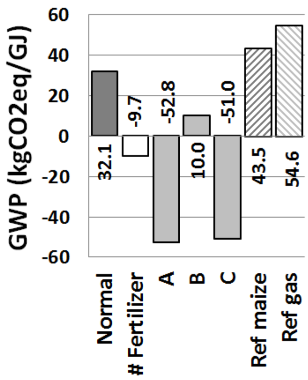

Fig. 7.4b. GHG emission of the symbiotic system

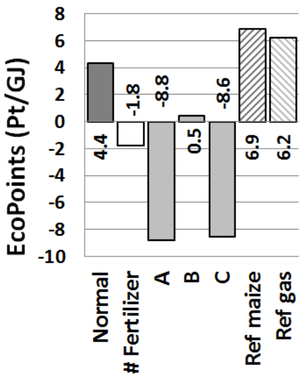

Fig. 7.4c. The environmental impact of the symbiotic system

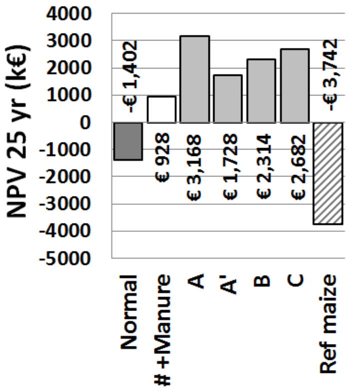

Fig. 7.4d. Efficiency Net Present Value of the symbiotic system

7.5.2. The theoretical cooperative farming cases

Within the theoretical case focus is placed on combining the circular symbiotic AD system with current farming practices in a cooperative setting. Current farming practices, incorporated in the reference case (REF), include; fossil energy use (e.g. electricity, natural gas) for powering machinery and heating, fossil fuel use (e.g. diesel) for powering machinery, and fossil fertilizer use for nutrient replacement (Fig 7.5). Results indicate that internal production of energy, transport fuel, and green fertilizers within a cooperation of farms operating a circular symbiotic AD system can significantly lower energy consumption, environmental impact, and yearly costs (Fig. 7.7).

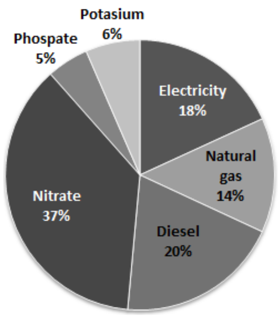

Fig. 7.5a. Shares within total energy use REF case

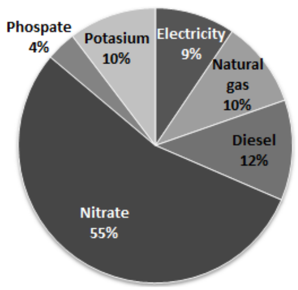

Fig. 7.5b. Shares within total GHG emission REF case

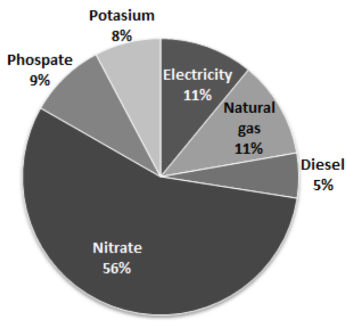

Fig. 7.5c. Shares within total environmental impact REF case

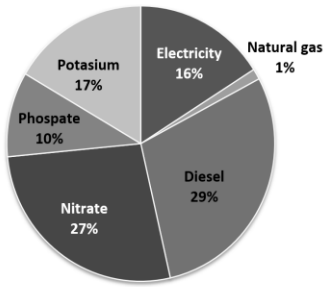

Fig. 7.5d. Shares within total costs REF case

Energy use in the shape of electricity, diesel, gas and the production of fertilizers can be reduced by 72% in the AD case up to 92% in the AD+M case compared to the REF case (Fig. 7.7a). The biggest reduction in energy use can be achieved through the replacement of fossil energy sources (e.g. electricity, natural gas, diesel), closely followed by fossil fertilizers which require significant amounts of energy during production (Fig 7.5a). However, to substitute the fossil energy sources and produce green fertilizer, around 52% of the produced biogas is used internally within the AD case and around 49% in the AD+M (Fig. 7.6). The AD+M case produces more biogas due to the added manure in the second digester and, therefore, uses relatively less biogas internally (Fig. 7b). Due to internal energy production and fossil energy replacement, external energy demand within both cases is minimal; mostly in the shape of embodied energy (e.g. installations and infrastructure, steel, concrete, etc.), (Fig. 7.6). However, due to insufficient manure availability in the AD case, fossil fertilizers have to be imported (Fig. 7.6a).

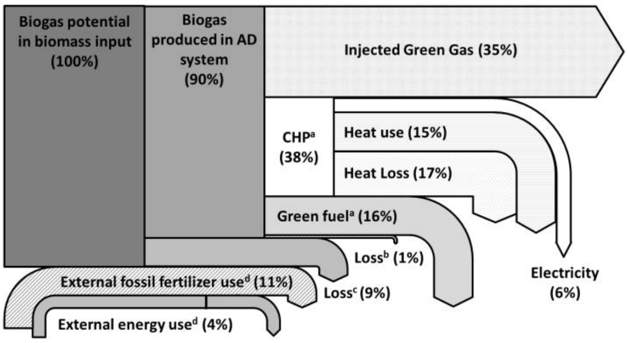

Fig. 7.6a. Sankey diagram of energy flows for AD scenario

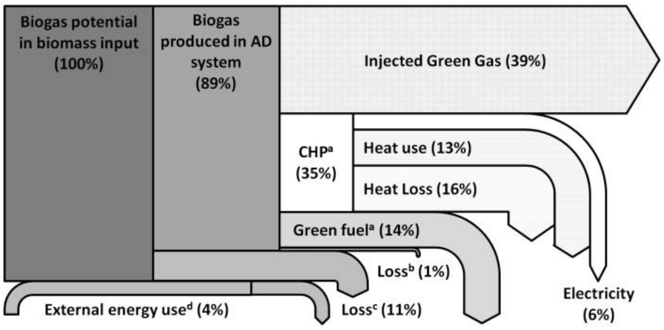

Fig. 7.6b. Sankey diagram of energy flows for AD+M scenario

[a] All energy produced by the CHP and green fuel systems is used within the cooperation
[b] The leakage loss still occurring from the biogas production and CHP and green gas utilization pathway
[c] Losses during feedstock transport, handling, storage, and leakages of feedstocks
[d] Energy requirement from outside of the system (e.g. energy, materials)

The carbon footprint can be reduced by 71% in the AD case up to 91% in the AD+M case and the environmental impacts reductions can be reduced with 68% up to 89% respectively compared to the REF case, (Fig. 7.7b, c). The biggest emission sources in the REF case are the production of fossil fertilizers (Fig. 7.5b, c), therefore replacing them with green fertilizers has a significant effect on the carbon footprint. Within this context, the availability of excess manure feedstock for processing and upgrading into green fertilizer used for fossil fertilizer replacement has a significant effect on energy use, carbon footprint, and environmental impact (Fig. 7.7a – 7.7c). Therefore, when looking to reduce energy and impact of farming practices a spatial distribution of dairy, agricultural, and pig and chicken farms in close proximity working closely together within a cooperation could be suggested. Unfortunately, currently the use of green fertilizers replacing fossil fertilizers is not allowed by the European Union [158]. There are, however, exceptions made within the Netherlands for some companies [159]. Without the replacement of fossil fertilizers the carbon footprint and environmental impact can only be reduced by a maximum of 31% in the AD case and 27% in the ADM case, compared to the REF case (Fig. 7.5b, c). Additionally, the remaining green gas is injected into the national grid (Fig. 7.6) replacing natural gas and further reducing carbon footprint and environmental impacts indirectly. This effect is not included within the AD or AD+M case as it does not lower the carbon footprint and environmental impact of farming practices, however, the avoided impacts are still significant and can be included on a national scope (Table 7.7).

Table 7.7. Possible mitigation of energy, carbon footprint, and environmental impacts per year through replacement of natural gas with green gas

	AD	AD+M	Unit	Source
Energy	13.6	17.5	TJ/a	[75, 103]
Carbon footprint	642	826	MgCO2eq/a	[75, 103]
Impact	73	94	kPt/a	[75, 103]

Based on Groningen natural gas including production with 40.6 MJ/Nm3, 1.92 kgCO2eq/Nm3, and 0.22 Pt/Nm3 [75, 103]

Yearly costs can be reduced by 56% in the AD case and 66% in the AD+M case compared to the REF scenario (Fig. 7.7d). The biggest reductions and economic gains can be achieved when a surplus of manure feedstock is available for processing and upgrading into green fertilizer used for fossil fertilizer replacement (Fig 7.7d). However, the effect of additional manure input is smaller on costs reductions than when looking to the other SI-Indicators, which can be traced back to the higher initial investment needed in the AD+M case and the higher operational and maintenance costs compared to the AD case. Initial investment costs are substantial ranging from 3.1 million € for the AD case up to 3.9 million € for the AD+M case. Another important cost reduction is the selling of green gas. After internal consumption the remaining green gas (around 35% in the AD case and 39% in the AD+M case) is sold and injected into the gas grid lowering the yearly costs (Fig. 7.7).

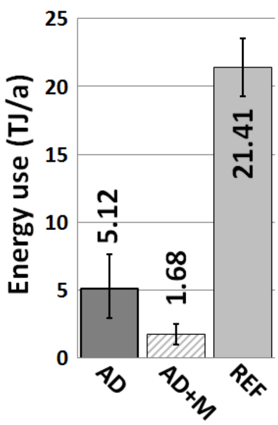

Fig. 7.7a. Energy use cooperation

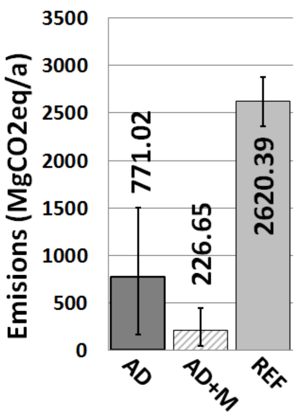

Fig. 7.7b. Carbon footprint cooperation

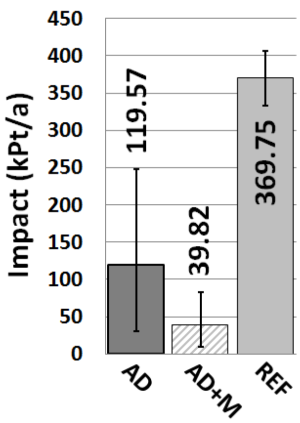

Fig. 7.7c. Environmental impact cooperation

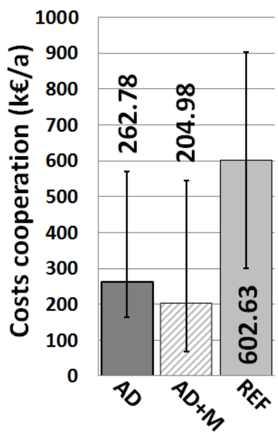

Fig. 7.7d. Yearly costs NPV cooperation

Additionally, within the local setting of this article, the cooperation can become a local handler of organic waste streams and also a supplier of green fuel, green energy (e.g. electricity, gas, heat), and green fertilizer. For instance, green gas and/or excess heat could be used locally to balance the electricity grid, heat buildings, and help integrate intermittent energy sources (e.g. solar PV, wind). Within this context, heat losses from the CHP unit (Fig. 7.6) could be used in heating surrounding buildings with district heating. When selling heat to external consumers, energy saving options (e.g. insulation, heat recovery) becomes viable options, where now in the AD and AD+M cases there is excess heat. Unfortunately, regulations on green fuel and fertilizer use and subsidies for circular symbiotic systems are currently unclear. Unstable policies combined with a significant investment and operational costs place substantial risks on the business case. Therefore,

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to support a stable business case over the economic and technical lifetime of the circular symbiotic AD system, focused and stable policies, improved regulation, and strong cooperation must be initiated to achieve the above results.

7.5.2.1. National scope

When applying the concept described in the theoretical case to the agricultural sector in the Netherlands the targets set by the Dutch agricultural sector (of 30% increase in efficiency, 30% Carbon dioxide emission reductions compared to the reference year of 1990 and 20% share of renewable energy in the year 2020 [30]) can be achieved for the 25% AD+M case (Table 7.8). Also, the additional production of green gas could supply the whole agricultural sector with electricity and heat. However, part of the energy and emissions saved within the cases are outside of the agricultural sector, for instance, the production of fertilizers and the mitigation of green gas. Also, within the theoretical case the energy use and carbon footprint from electricity and fuel production are taken into account, where the carbon footprint from the agricultural sector is often linked to direct use and emission. Furthermore, within the total carbon footprint of the agricultural sector, the service sector and other agricultural activities are included (e.g. offices, greenhouses) which are not incorporated in the cooperative case. Overall, by fully utilizing the manure and other biomass waste streams, in an circular symbiotic AD system producing energy, green fuel, and green fertilizer, the energy efficiency, carbon footprint, and environmental impact can be improved upon. Within this context, the circular symbiotic approach can optimize the AD system and help the agricultural sector to become more sustainable and profitable.

Table 7.8. National possible saved emission and mitigated fossil energy compared to reference years 2015 and 1990

		Reference year 2015[a]		Reference year 1990[b]	
		AD	**25% AD+M[c]**	**AD**	**25% AD+M[c]**
Total emission savings		33.4%	37.5%	27.1%	30.4%
	AD cooperative	24.8%	26.6%	20.1%	21.6%
	Sold green gas	8.6%	10.9%	7.0%	8.8%
Total fossil fuel saved		79.8%	98.6%	87.3%	104.9%
	AD cooperative	43.5%	52.7%	47.0%	55.6%
	Sold green gas	36.3%	45.9%	40.3%	49.3%

[a] Carbon footprint and energy use Dutch farming sector 2015, respectively 26.7 Tg and 133.9 PJ [29]

[b] Carbon footprint and energy use Dutch farming sector 1990, respectively 32.9 Tg and 142.9 PJ [29]

[c] MAX national scope case exists of 75% AD case and 25% AD+M case, taking into account manure surplus in the Netherlands

7.6. Sensitivity analysis

Using organic material in a biological process and uncertainties surrounding business cases inherently creates variations and sensitivities. When comparing scenarios similar settings will cancel out sensitivities in the used values. This approach has been applied to the symbiosis scenarios (section 7.4.1 and 7.5.1). Sensitivities connected to biomass use within the aforementioned scenarios are described in Pierie et al 2015 [101]. However, in the cooperative scenarios (section 7.4.2 and 7.5.2) the results will be more prone to sensitivities as they are compared with a reference farm in more absolute terms; therefore, focus is placed on these results. The most sensitive values regarding the feedstocks, (e.g. biogas potential, methane potential, organic dry matter content, and environmental impacts of the collection and/or cultivation process) are retrieved from Pierie et al 2015 [101] (Appendix 7-II). The results indicate that within the range of the indicators, even the worst case improvement scenario has less impact than the reference scenario (Fig. 7.7a – 7.7c). Within the economic variables, biogas production, maintenance, and interest are most dominant. When combined the sensitivity of all SI-Indicators vary significantly (Appendix 7-II) in which case it can perform better or worse than the reference scenario (Fig. 7.7d). For instance, in the worst case, projected costs for the cooperation exceed the best case of the reference farms, indicating some risks in the business case. However, for this to happen a combination of circumstances working with or against the process is needed (e.g. bad harvest, high energy use harvest, low methane yields of crop, low market prices, and weak regulations).

7.7. Discussion

Energy production through AD is a promising method for producing a renewable and flexible energy carrier. However, the production and utilization pathways are complex systems, containing multiple factors and variables which must be taken into account. The accuracy of the results presented in this article depends strongly on the quantity and quality of the data it contains, which comes from both literature and case studies. However, these sources still contain a wide range of data. Therefore, the model used for calculating the results was extensively validated before being implemented [151, 152]. Specific biomass potentials are often difficult to quantify and differ by season and specific location. Furthermore, the biomass potential is spread out evenly over the municipality for determining average transport distances. Transport distances are difficult to quantify and normalize; therefore, within this article tortuosity factors are used, although transport distances can differ significantly per specific location. The biomass described in this article could have other uses (e.g. stable flooring, animal feed) which must be considered. New AD system technologies are not included in this study; they can, however, improve the process by producing more biogas from the feedstocks, preventing leakages, and being more efficient in heat and energy use. Within this research, soil emissions from farming activities are not included. The use of green fertilizers replacing fossil fertilizers is currently not allowed by the European Union, there are however exceptions made within the Netherlands for some companies. Subsidy schemes for a cooperative AD system are currently not present within the Netherlands, therefore, the green gas subsidy scheme is chosen.

7.8. Conclusions

The reference scenario used in this article only indicates a minor reduction in carbon footprint and environmental impacts and a low efficiency with a negative NPV for farm-scale AD installations within the Netherlands. This indicates that, amongst others, the AD system has not been fully optimized. Implementation of the single improvement options individually already has a positive impact on the SI-Indicators (i.e. energy use, carbon footprint, environmental impacts, and costs). However, the reduction achieved by individual improvement options is often significant for only one or two of the four SI-Indicators. For instance, green fertilizers production positively affects the carbon footprint and environmental impact but negatively affects the [P]EROI and NPV; caused by high energy use in the process, substantial initial investment costs, and additional operational costs in the shape of energy and maintenance. Given the systemic nature of agricultural systems, focusing on single factors does not necessarily lead to optimal solutions. Using a circular symbiotic system of improvement options, however, can significantly improve all SI-Indicators including costs, making the system profitable over a lifetime of 25 years. When the circular symbiotic AD system is applied to the theoretical case, results are also positive for all SI-Indicators. Internal production of energy, transport fuel, and green fertilizers can significantly lower external energy consumption by 72% to 92%, carbon footprint by 71% to 91%, environmental impacts by 68% to 89%, and yearly expenditures by 56% to 66% compared to the reference cooperation. The biggest reductions and economic gains can be achieved when a surplus of manure is available for processing and upgrading for fossil fertilizer replacement. Within this context, economic success and also the reduction of emissions and environmental impacts is strongly dependent on the use and added value of the digestate. Therefore, when looking for reducing energy and impact of farming practices a spatial distribution of dairy, agricultural, and pig and chicken farms in close proximity working closely together within a cooperation could be suggested. Unfortunately, existing laws prevent the use of green fertilizers to replace fossil fertilizers in the Netherlands. However, without fertilizer replacement a circular symbiotic system can still be created which produces positive results for all SI-Indicators. Within the cooperative cases approximately half of the produced energy is used internally, the remaining green gas, electricity, and/or heat can be sold and used locally to replace fossil energy sources and help integrate other intermittent energy sources in the local energy grids. Applying the aforementioned circular symbiotic AD systems can lower environmental impact of farming by decreasing dependency on fossil based energy and fertilizers and lowering the carbon footprint from farming, helping the Dutch agricultural sector in achieving their stated environmental goals. However, to achieve the aforementioned, focused and stable policies, improved regulation, and strong cooperation must be initiated, as regulations on green fuel and fertilizer use and subsidies for circular symbiotic systems are currently unclear within the Netherlands and European Union.

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Author contribution: Main research and body of article is written by lead author (Frank Pierie) and reviewed by second authors on focus and quality.

Conflicts of interest: To the authors knowledge there in no conflict of interest steering the results in any way shape or form towards benefits of stakeholder.

Appendix 7-I: Individual improvement options

The individual improvement options and their location within the AD system, indicated in Figure. A1 using corresponding numbers in Table A1.

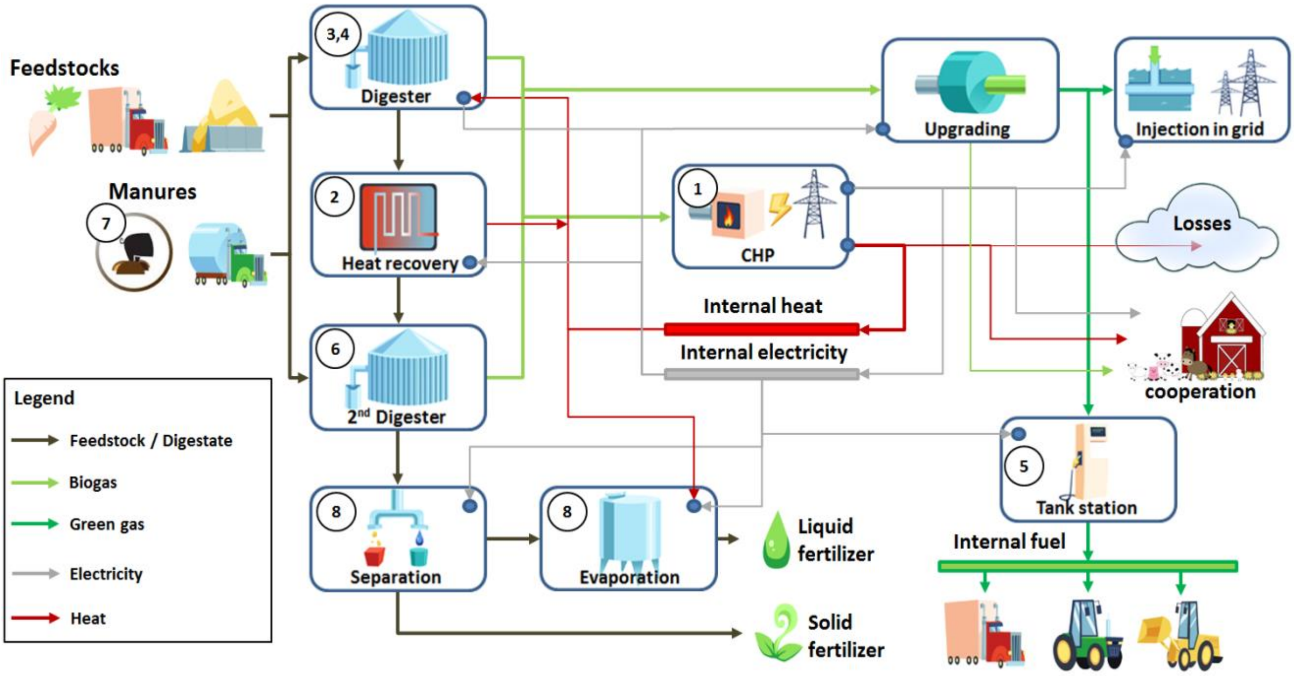


Fig. A1. The optimized AD system for use in the sustainable farming concept

Table A1
Main improvement options

Nr.	affiliation	Description of improvement option
1)	CHP	A Combined Heat and Power unit (CHP) is used to produce electricity and heat [101] to fulfil the energy demand of the complete AD system (e.g. digester, green gas production, digestate upgrading). Cables and pipelines are incorporated for transportation to the AD production processes [101]. Additional heat requirement not supplied by the CHP is produced by the biogas boiler. In the case of overproduction electricity is put on the local electricity grid and heat is discarded.
2)	Recovery	The main digester operates at a mesophilic temperature of around 35 to 48 degrees Celsius; outgoing digestate will be at the same temperature. Therefore, heat energy in the outgoing digestate can be utilized through a heat exchanger to heat up the ingoing feedstocks at ambient temperature fed into the digester. Infrastructure and energy use for heat recovery is taken into account (Appendix Table 3).
2)	Heat pump	Additionally a heat pump can be added to the Heat recovery system aforementioned
3)	Insulation	Insulation of the main digester will lower the heat loss from the main digestion tank, which operates at mesophilic temperatures. Therefore, biogas can be saved resulting in more green gas finally produced. Insulation will bring with it additional capital expenditure and embodied energy but will also reduce the heat demand of the process. Heat requirement of the main digester is lowered with 20% to simulate the effect of insulation on the SI-Indicators.
4)	Prevention	Gas leakages can be prevented through the use of repair and higher greenhouse gas emissions (e.g. methane) can be reduced using catalytic conversion lowering the carbon footprint. Repair focusses on actual leaks in biogas equipment such as the main and second digester, piping, upgrading installations. Catalytic conversion focusses on outputs from upgrading or combustion, which often contain methane or Nitrogen oxides, which are brought back to CO2 level using catalytic conversion. Within this improvement option, losses and emissions from the main digester and second digester are eliminated and higher greenhouse gas emissions from the green gas utilization pathway and CHP unit are reduced to carbon dioxide level.
5)	Green fuel	Green gas produced by the AD plant is used as fuel for agricultural machinery ranging from tractors, front loaders, and trucks transporting the biomass, replacing the use of fossil fuels (e.g. diesel). To achieve the aforementioned, infrastructure in the shape of a filling station is needed [160] which compresses the green gas and stores it in large enough quantities to fill several tanks (Appendix Table 3).
6)	2nd digester	Processed digestate still contains some biogas potential [156]. However, it is often not efficient and economical to retain this using the main digester, as it is kept at mesophilic temperature and is stirred continuously. Within this context, a second digester (not heated and often stirred) can be used to store the digestate and collect the residual biogas production. The longer retention time in the second digester (up to 5 to 6 months) gives the AD process additional time to break down the last remaining digestible organic material into biogas. Infrastructure and energy use is taken into account (Appendix Table 4), also including the biogas potential of digestate which is based on an average number, as digestate composition is dependent on the feedstocks use in the digester (Appendix Table 4).
7)	+Manure	Due to overabundance and low quality, the available manure is often not fully utilized. Manure can be directly pumped in the second digester to retain the produced biogas to replacing seasonal manure storage during winter or mix it with the digestate for utilization in fertilizer production. This technology can also produce additional environmental benefits, which can be mitigated. A maximum of 10000 Mg of additional manure is added directly to the second digester. Infrastructure and energy

		use is taken into account (Appendix Table 4). For determining the biogas production of the additional manure the biogas potential of manure is used (Table 1).
8)	Green fertilizers	Within this improvement option, a large share of the digestate (80%) is separated into a thick and a thin fraction using a manure separator [161]. The thin fraction is rich in nitrogen and contains most of the water, whereas the thick fraction contains most of the phosphates, potassium and organic materials. The thin fraction is processed using reversed osmosis to decrease the water fraction [159, 162]. The processed and upgraded thin and thick fractions are used as green fertilizers on the farm replacing fossil fertilizers (table 5). The remaining 20% of the digestate is used for replacing manure fertilization on the pasture; however, this will not replace fossil fertilizers. The needed infrastructure and energy use of the installations is taken into account.
8)	Selling fertilizers	Green fertilizers can also be sold on the market when own demand is fulfilled, unfortunately for lower prices. Within this improvement option all the green fertilizer produced is sold on the market (Appendix Table 3).

In the following figures the impact of the individual improvement options on the SI-Indicators are indicated, the affiliations used to express the results in the figures will use the description in Appendix 7-I Table A1. The Normal scenario in the graphs describes the basic AD green gas production pathway without any modifications as described in section 7.1.1.

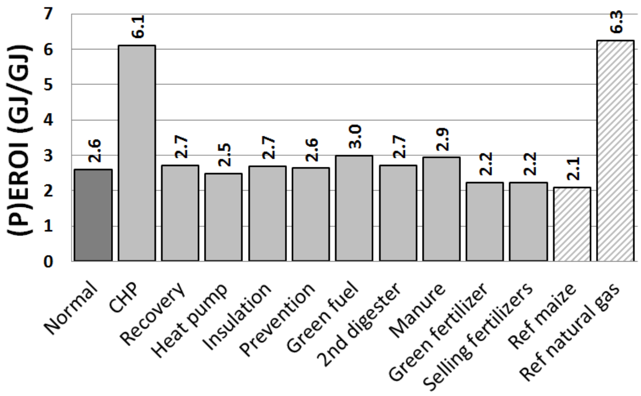


Fig. A2a. The (P)ROI of the improvement scenarios

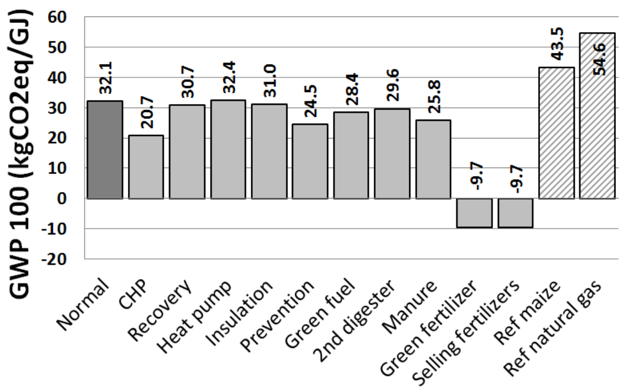


Fig. A2b. The carbon footprint of the improvement scenarios

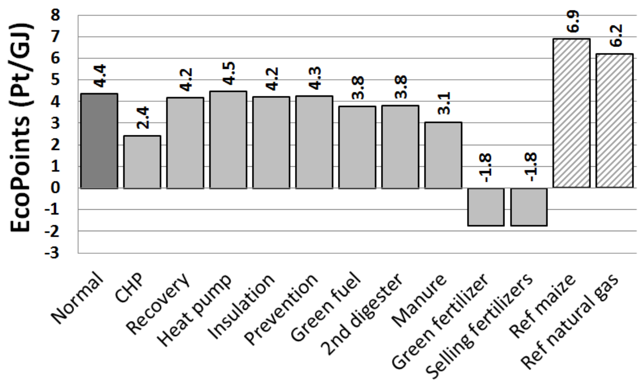


Fig. A2c. The environmental impact of the improvement scenarios

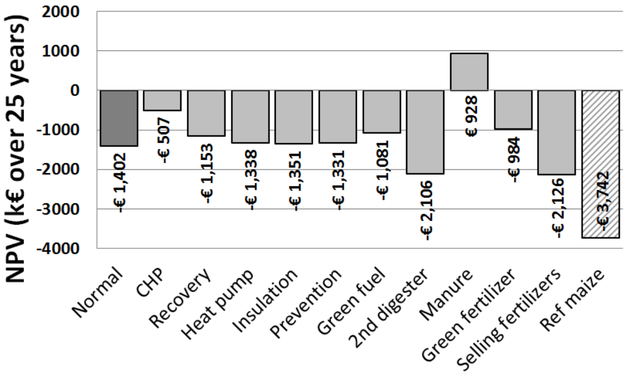


Fig. A2d. The NPV of the improvement scenarios

Appendix 7-II: Additional data used in article

Table B1
The main economic values used in the calculation of the NPV

Main economic values	Value	Unit	Source
Interest on loan and Required rate of return	5	%	[157]
Inflation	1.8	%	[163]
Increase of electricity and gas price per year[a]	2	%	[164]
Economic write off period	15	Years	
CAPEX Main installation	**Value**	**Unit**	**Source**
AD system	53.64	€/(Mg/a capacity)	[100]
Feedstock pre-treatments systems	3.00	€/(Mg/a capacity)	[112]
Upgrading system	4024.88	€/(Nm^3/hr capacity)	[100]
Green gas injection system	550.00	€/(Nm^3/hr capacity)	[100]
Scrap value installation after 25 years	5%	%/CAPEX	[165]

OPEX	Value	Unit	Source
Operation and maintenance	5	% Investment/a	[100]
Tax on products	6	%/costs resource	[166]
Income tax	25	%/costs resource	[167]
Transport by truck	0.05	€/ton.km	[100]
Electricity from grid	0.19	€/kWh	[29]
Natural gas from grid[c]	0.53	€/Nm^3	[29]
Diesel fuel	1.40	€/l	[71]
INCOME GREEN GAS[b]	**Value**	**Unit**	**Source**
Green gas market price[c]	0.020	€/kWh	[154]
SDE Subsidization (12 years)	0.076	€/kWh	[154]
SDE extended (additional 12 years)	0.067	€/kWh	[154]
Correction fee SDE Subsidization (12 years)	0.022	€/kWh	[154]
Correction fee SDE extended(12 years)	0.022	€/kWh	[154]
INCOME GREEN ELECTRICITY[b]	**Value**	**Unit**	**Source**
Green electricity market price	0.025	€/kWh	[154]
SDE Subsidization (12 years)	0.114	€/kWh	[154]
SDE extended (additional 12 years)	0.101	€/kWh	[154]
Correction fee SDE Subsidization (12 years)	0.032	€/kWh	[154]
Correction fee SDE extended(12 years)	0.033	€/kWh	[154]
CAPEX improvements	**Value**	**Unit**	**Source**
Heat recovery digestate	25	€/kWth	
Heat recovery with heat pump system	200	€/kWth	
Insulation of the AD system	4000	€/% improvement	
Second digester / manure storage	90	€/m3 (storage capacity)	[71]
CHP unit	946.16	€/kWe	[168]
Digestate separation unit	1.45	€/(m3 digestate/a)	[161]
Digestate upgrading system (reversed osmosis)	30	€/(Mg/a capacity)	[159]
Fueling station (approx. 4-8 trucks, tractors per day)	75000	€/(20-40 GGE/day)[d]	[169]

[a] The Increase of electricity and gas price per year is assumed based on [164] as the marked is very volatile and the price dependents on many factors
[b] The subsidy is determined by the SDE subsidies minus the correction fee
[c] Based market price gas of 12.5 €/MWh. Groningen natural gas and green gas have an higher energy content of 35 MJ/Nm^3 or 9.7 kWh/Nm^3
[d] GGE/day = Gallons of Gasoline Equivalent per day

Table B2
The main values of the added technologies

Added technologies	Value	Unit	Source
Efficiency heat exchanger	90	%	
COP value heat pump	5		[170]
Energy requirement second digester	5	MJ/Mg(FM)	
Energy requirement separator[a]	4.68	MJ/Mg FM	[135]
Energy use reversed osmosis	35	MJ/Mg FM	[159]
Energy use filling station[b]	4.68	MJ/Nm^3	[160]

[a] Based on an electric separator [135]
[b] INTERMECH BBR/FBR/VIP CNG compressors 55-450 kW / 75-600 HP [160]

Table B3
Main values for production of fossil fertilizers replaced by upgraded digestate

Fertilizers replaced	Nitrogen as N	Phosphate as P_2O_5	Potassium as K_2O	Units	Source
Market price fossil fertilizer	1.10	1.05	0.65	€/kg	[71]
Market price Green fertilizer	0.60	0.51	0.26	€/kg	[171]
Required energy for production	75.90	27.9	12.9	MJ/kg	[75, 103]
Emission during production	12.60	2.22	2.30	kgCO2eq/kg	[75, 103]
Environmental impact during production	1.77	0.76	0.24	Pt/kg	[75, 103]

Table B4
Scenarios used within the sensitivity analysis of the more sustainable farming cooperation cases

Variable or SI-Indicators	Worst %	Ave %	Best %	Source
[P]EROI	57.18%	100.00%	149.02%	[101]
Emission	194.16%	100.00%	21.74%	[101]
Impact	207.00%	100.00%	25.51%	[101]
Total investment	120.00%	100.00%	80.00%	
Salvage value	0.00%	5.00%	10.00%	[71, 165]

Biogas production	57.18%	100.00%	149.02%	[101]
Interest	6.00%	5.00%	2.00%	
Taxation on internal use	21%	6%	0%	[166]
Discarding digestate	50.00%	0.00%	0.00%	
Fertilizer price	150.00%	100.00%	50.00%	
Maintenances	7.00%	5.00%	3.00%	

Table B5
Energy and fertilizer use average Dutch dairy and agricultural farm

	Dairy farm	Agricultural farm	Natural areas	Unit	Source
Total land use the Netherlands	956000	995756	?	ha	
Diesel use	130	238	-	l/ha.a	[71]
Electricity use	940[a]	549	-	kWh/ha.a	[71]
Natural gas use	32[a]	10	-	Nm3/ha.a	
Water use	80[a]	10	-	m^3/ha.a	[71]
Nitrate cap	265	170	?	kg/ha.a	[71]
Phosphate cap	95	65	?	kg/ha.a	[71]
Potassium cap	225	225	?	kg/ha.a	[105]

[a] Based on two cows per hectare of land producing 8500 kg of milk per year [71]
[b] Based on average agricultural farm of 40 ha [29] KWIN table page. 57

Appendix 7-III: Main calculation output national case

Table C1
Carbon footprint and energy reduction of cooperative cases compared to Dutch carbon footprint and energy use in 2015

	Total NL[a]	Farming[a]	AD+M	AD	Unit
Carbon footprint	193.7	26.7	18.1	20.1	Tg
Carbon footprint green gas			23.8	24.4	Tg
Energy	2206.0	133.9	63.4	75.7	PJ
Energy green gas			72.4	85.3	PJ

[a] Carbon footprint and energy use retrieved from Dutch Central Bureau of Statistics [29]

Table C2. Carbon footprint and energy reduction of cooperative cases compared to Dutch carbon footprint and energy use in 1990

	Total NL[a]	Farming[a]	AD+M	AD	Unit
Carbon footprint	193.7	26.7	19.6	20.1	TgCO2eq
Mitigation green gas			23.8	24.4	TgCO2eq
Energy	2206.0	133.9	63.4	75.7	PJ
Mitigation green gas			72.4	85.3	PJ

[a] Carbon footprint and energy use retrieved from Dutch Central Bureau of Statistics [29]

Table C3. Carbon footprint and energy reduction of cooperative cases compared to Dutch carbon footprint and energy use in 2015

	Nitrogen	Phosphate	Source
Total nutrient production	497500	180100	[29]
Possible placement of nutrients[a]	377000	134300	[29]
Nutrient	120500	45800	
Percentage deposit	24.22%	25.43%	

[a] The possible placement of nutrients within the Netherlands is determined by the available land surface [29]

Chapter 8
CONCLUSION AND DISCUSSION

A new approach for designing, measuring, and optimizing the overall sustainability of renewable energy production pathway expressed in a clear label

8.1. Conclusion

Within the line of research presented in this dissertation, a gap in literature is indicated regarding the need for a transparent and structured approach for measuring and indicating the sustainability of a REPP. In this context, the following main question was raised: how to measure and optimize the sustainability of complex REPPs; focused on farm-scale AD biogas production pathways? To answer this question, a new approach is developed in this dissertation for measuring and optimizing the sustainability of REPPs. This approach is presented in full in Chapter 1. Within the new approach, the structure of a REPP is determined through the use of the modular approach; the environmental sustainability (Planet) is determined through the use of the MEFA method, in combination with an aLCA; the space requirement (Space) is determined through the use of a local energy potential analysis; and the NPV and payback period (Profit) are determined through cost optimization modeling. However, further research is required to complete the overall assessment of (renewable) EPPs. To include temporal dynamics (Balance), the load demand curve and net load signal (NLS) are suggested, and a practical solution is proposed for starting and guiding the discussion on REPP integration into local communities (People) through the use of the WE-Energy Game. Also, more research is required in the direction of biomass and biogas specification and/or the integration of AD biogas production pathways into the agricultural process. In this section, the new approach will be explained in a step-by-step plan for measuring the sustainability of a REPP, and in section two, a reflection on the new approach and the results from this new approach will be presented.

8.1.1. New approach for measuring the sustainability of a REPP

The new approach is constructed from a synthesis of literature and practical information, which integrates the physical, economic, and social indicators of sustainability into one set of comprehensive and comparable expressions (or a label). The label of individual REPPs, which indicates the expressions used within the new approach in a comprehensive overview, can be compared to other analyses (of the same or other REPPS) that have already been performed. Furthermore, the label, together with the modular design, can aid in optimizing REPPs based on the indicators. The use of the new approach also requires a logical and research-oriented approach, as every local energy system is often different in design and location. Also, the order in which the steps are applied can vary depending on the REPP analyzed. Therefore, the main rules described in this method are similar between pathways; however, the details for specific REPPs can and most likely will differ. In this section, the main steps for performing an analysis of a REPP will be discussed using AD biogas production as an example (Fig. 8.1).

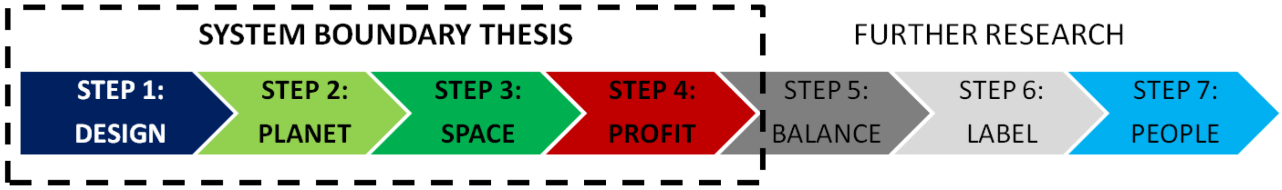


Fig. 8.1. Process flow measuring the sustainability of a REPP

STEP 1 (DESIGN): Design of the EPP

The analysis will start with a determination of the main components (fig. 8.2) and main flows of the REPP using the modular approach, where a specific structure is followed. Within the modular approach, the REPP is defined as a collection of physical processes working together to achieve a common goal (e.g. biogas or green gas production). These individual, physical processes are called sub-modules, and they are assigned to groups, called modules, which perform the same physical process (Fig. 8.2). The REPP will be built from a succession of sub-modules in logical order, forming a chain that, for instance, could result in the AD green gas production pathway depicted in Fig. 8.2. The aforementioned approach will allow several arrangements of sub-modules to form different production pathways, including multiple energy sources (e.g. wind, solar PV, and geothermal). In a later stage (optimization), the modular approach can be used to design the optimum production pathway to fit particular cases by changing, adding, or removing individual sub-modules during the modeling (or planning) process. For a more elaborate explanation, see Chapter 2.

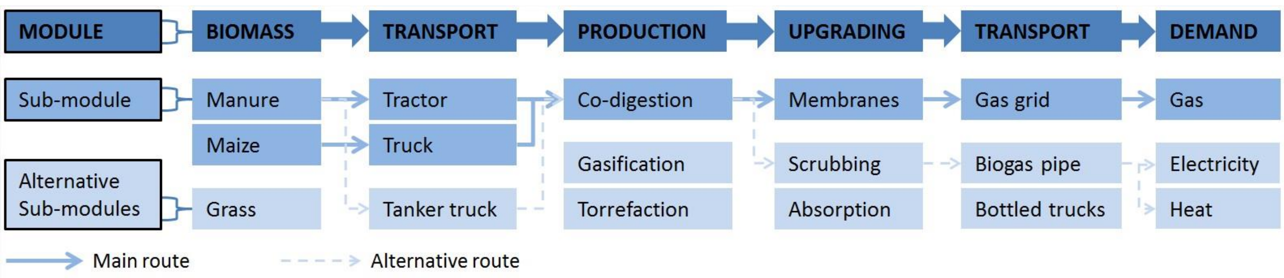


Fig. 8.2. The main modules and sub-modules used in an example green gas production pathway

STEP 2 (PLANET): Determining the environmental impact

The impact on the PLANET or environmental sustainability is determined per sub-module. Within each sub-module (e.g. co-digestion in Fig. 8.2), one main physical process of the energy production system is described (Fig. 8.3). Every sub-module will be capable of determining three environmental impact indicators. The following indicators are used: the (process) energy returned on invested ([P]EROI), which indicates the efficiency of the chosen scenario; the carbon footprint (GWP100), which indicates global warming potential; and the Eco Indicator ReCiPe 2008, which indicates the overall environmental impact on the ecology, nature, and human health. Taken together, these indicators can provide a clear overall impression of the efficiency and environmental sustainability of a REPP. To determine the aforementioned factors, each sub-module is separated into four levels (Fig. 8.3): level one, the primary (mass) flow level; level two, the direct energy and material level; level three, the indirect energy and material level; and level four, the embodied energy level. When looking at an AD installation, primary mass flows are defined as raw materials (e.g. biomass, biogas, digestate, and/or losses of the previous flows), which run through the system; direct energy flows are used during the handling and conversion process of raw materials towards a finished product (e.g. diesel, electricity, heat, and fertilizer); indirect energy and material flows are required for the production of the direct energy and material flows (e.g. production of diesel); and embodied energy and material flows are required for the construction, maintenance, and deconstruction of the installations used for processing the primary flows (e.g. digester). Each level will be described through the use of an existing method, and each one will require its own calculations (Fig. 8.3). For a more elaborate explanation, see Chapter 2. Within this dissertation, the new approach is integrated into a mathematical (what if) model called the BioGas Simulator (Chapters 3 and 4), specified for calculating the sustainability of farm-scale biogas production pathways.

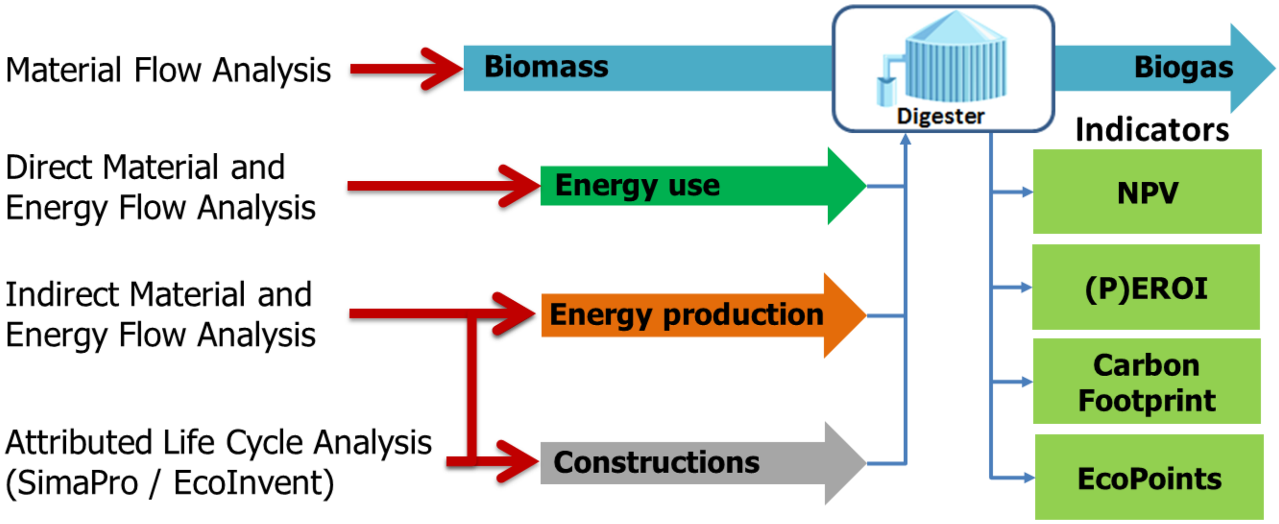


Fig. 8.3. Structure of a single sub-module based on dynamic MFA/MEFA/LCA

STEP 3 (SPACE): Determining local energy availability and space use

A REPP interacts with its surroundings, and it has an impact on space. This impact determines the amount of renewable energy that can be produced or placed within a certain area. The space required per renewable energy source or energy system is determined by the energy density of the fuel source. For instance, the biogas yield of an AD system using local biomass depends on the biomass potential within the selected area (Chapter 6). To collect solar and wind energy, space is also an important requirement for determining yield (Fig 8.4), together with local solar irradiance and wind speeds. The needed space of the REPP must be in line with the available space in the selected area, and it must align with other uses of this space (e.g. agriculture or residential). In the Netherlands, the space that is utilized for a REPP often had a previous function; therefore, space can be seen as a valuable resource, and it must be allocated with care. There is the option to import energy from other locations; however, this only shifts the land use allocation to another region.

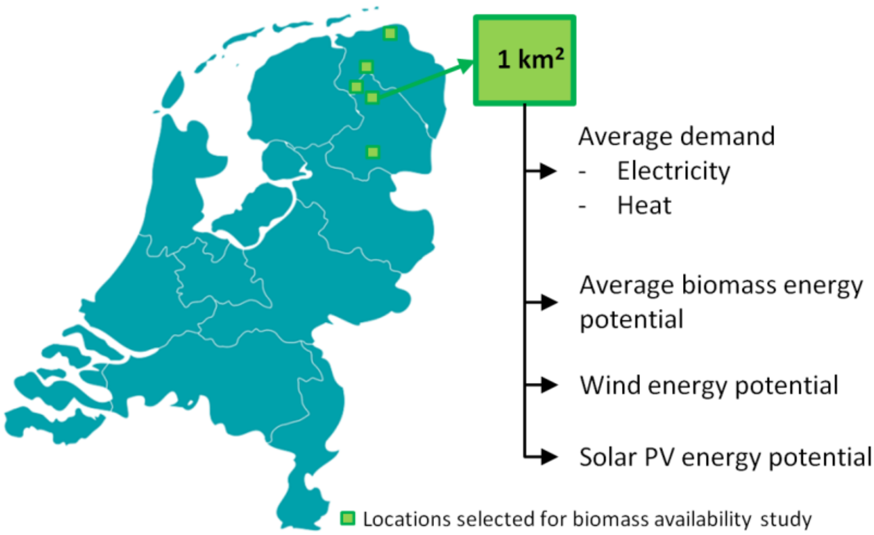


Fig. 8.4. Determination of average biomass availability (Chapter 5)

STEP 4 PROFIT: Economic cost calculations

Profitability is an important element in every business case, amongst other things. The indicators of profitability include payback period, net present value (NPV), and/or internal rate of return. Within this research, the NPV method was selected, as it is a commonly used indicator for economic feasibility, and it indicates the overall profitability of an investment over its economic lifetime. To determine the NPV within the new approach, CAPEX, OPEX, and revenues are first included in the MEFA element of the new approach (Fig. 8.3.). The CAPEX represents capital investments in the REPP (e.g. digester installation, upgrader, and CHP), while OPEX refers to the operational expenditures (e.g. cultivating or purchasing biomass, electricity, or diesel), and revenues are the sales of products (e.g. green gas and green fertilizers). In addition, there are other important factors that make up the cost of capital (e.g. interest, inflation, and taxation). Combined, the aforementioned factors represent the cash flows in the system, and they will be used in the NPV analysis to come to the final NPV indicator. Net present value depends solely on the forecasted cash flows of the project and the opportunity cost of capital. The general rule of thumb is if the NPV is positive, then "invest," whereas if it is negative, then "do not invest." For a full explanation of the approach, see Chapter 6. However, further research is required in this field, as Profit is more than the NPV. Setting up a business model of a REPP requires insight into, inter alia, economics, stakeholders, regulation, and the services provided (Dissertation D'Souza, 2018 [172]).

STEP 5: Optimization (modeling)

The optimization of the REPP can be achieved through the use of both optimization modeling and the symbiotic approach (Chapters 3 and 7). Optimizing a REPP involves a holistic approach and a selection of improvement options, which are analyzed individually or combined in a circular symbiotic system, applied to a theoretical case through the use of modeling. In an ideal symbiotic system, waste material and energy are utilized between/among the individual sub-modules of the system, and the consumption of virgin raw material and energy inputs as well as the generation of wastes and emissions are thereby reduced. Within this context, exploring multiple combinations (scenarios) of sub-modules could lead to environmental and economic improvements on current REPP systems. For example, in a (theoretical) case where a cooperation of farms share a symbiotic AD system, external energy consumption, emissions, and costs of farming can be substantially reduced. In this context, farm-scale AD biogas production is used to optimize the farming process as a whole. For a full explanation of the approach, see Chapter 7.

8.1.2. Results from the analysis of AD biogas production pathways

The results from applying the new approach (described in Section 8.1.1.) to the AD biogas production pathway indicated that from an energy efficiency and sustainability point of view (i.e. energy efficiency, carbon footprint, environmental impacts, and costs), the AD process should be utilized to process locally available waste feedstocks with the added advantage of producing energy, which should first be used internally to power the AD biogas production pathways, thereby optimizing the AD biogas production pathway itself. Furthermore, the transport distances of feedstocks not including manure (e.g. maize, grass, straw, harvest remains, and catch crops) should not exceed 150 kilometers, otherwise emissions and environmental impacts will surpass those of natural gas, used as a reference. Therefore, a more decentralized approach is suggested wherein the available biomass is harvested, collected, and transported close to the location of the AD biogas production pathways. Finally, the AD production pathway should be used to optimize the sustainability of the farming process as a whole, looking to individuals and farmers, but preferably to cooperation between dairy and agricultural farmers, to increase the renewability and sustainability of the farming sector as a whole.

Optimization of the AD biogas production pathway

The optimization of the biogas production pathway involves the use of different feedstocks and individual improvement options (e.g. internal use of the energy production, green gas powered trucks, green fertilizer production, and the mitigation of current waste treatment systems) first applied per technology to observe possible improvements. When utilized, they can already significantly improve the sustainability for all used feedstocks analyzed; however, the use of waste materials is favored. While positive effects on the indicators can already be observed when implementing individual improvement options, the reduction achieved is often significant for only one or two of the four indicators used in the new approach (i.e. energy efficiency, carbon footprint, environmental impacts, and costs). Therefore, focusing on individual factors does not necessarily lead to optimal solutions. In contrast, a symbiotic system, which combines multiple improvement options, significantly improves all indicators. When a symbiotic system is implemented in a theoretical case, where a cooperation of farms shares biomass feedstocks and a symbiotic AD system, a substantial reduction in energy consumption, carbon footprint, environmental impacts, and yearly expenditures can be achieved, compared to the same reference cooperation of farms without a symbiotic AD system. The internal production of energy, transport fuel, and green fertilizers can significantly lower external energy consumption between 72% to 92%, carbon footprint by 71% to 91%, environmental impacts by 68% to 89%, and yearly expenditures by 56% to 66%, compared to the reference cooperation. The largest reductions and economic gains can be achieved when a surplus of manure is available for upgrading into green fertilizer to replace fossil fertilizers. Additionally, the cooperation uses approximately half of the produced energy internally to replace energy and fuel needs and to produce green fertilizer; the remaining green gas, electricity, and/or heat can be sold and used to replace energy from fossil sources. When utilized efficiently and responsibly, the AD process can become a more sustainable energy resource that is capable of processing waste flows and producing renewable energy in the form of green gas.

Local and national biomass availability

The average theoretical bio-energy yield of local waste materials, within the selected municipalities (i.e., Ten Boer, Eemsmond, Groningen, Hoogeveen, and Noordenveld) is around 1,614 GJ/km2 (61 PJ), which is comparable to the national average indicated in literature of 1,400 to 2,500 GJ/km2 (53 PJ up to 94 PJ) [2]. The same literature indicated that there is sufficient bio-energy potential in local waste streams to reach the Dutch goal for local renewable energy production of approximately 40 PJ in the year 2020 [3]. However, only around 64% of the biomass available in the municipalities can be utilized as a feedstock, resulting in 39 PJ. The gap can partially be traced back to the high amount of manure available, of which only small amounts are used as feedstock, often due to low biogas yields and difficulty in collection and transport. Furthermore, of the potential bio-energy input, on average, 73% (29 PJ) can be extracted as green gas, 57% (22 PJ) as heat and power, and 44% (17 PJ) as green gas in the optimized pathway. Therefore, to reach production goals, the green gas utilization pathway is preferable, as it retains the highest amount of energy from the feedstock. However, environmental sustainability favors the waste management pathway, since it has a substantially higher overall efficiency and lower emissions and environmental impacts. In the best case, around 29 PJ can be produced, which is only 73% of the amount of biogas needed to reach the goal of 40 PJ in the year 2020. However, reductions in GHG emissions are then limited, and in the worst case, 42% can be filled in with maximized reductions in GHG emissions.

The AD biogas production pathway integrated into the Dutch farming sector

When applying the concept of a cooperation of farmers operating a symbiotic circular AD system to the agricultural sector in the Netherlands, the targets set by the Dutch agricultural sector (of a 30% increase in efficiency; 30% carbon-dioxide emission reductions, compared to the reference year of 1990; and a 20% share of renewable energy in the year 2020 [3]) can be achieved when additional manure is used in the AD biogas production pathway (around 25% additional manure). Also, the additional production of green gas could supply the whole agricultural sector with electricity and heat. However, part of the energy and emissions saved within the cases are outside of the agricultural sector—for instance, the production of fertilizers and the mitigation of green gas. Also, within the theoretical case, the energy use and carbon footprint from electricity and fuel production are taken into account, where the carbon footprint from the agricultural sector is often linked to direct use and emission. Furthermore, within the total carbon footprint of the agricultural sector, the service sector and other agricultural activities are included (e.g. offices and greenhouses) that are not incorporated in the cooperative case. Overall, by fully utilizing the manure and other biomass waste streams—in a circular symbiotic AD system producing energy, green fuel, and green fertilizer—the energy efficiency, carbon footprint, and environmental impact can be improved. In this context, the circular symbiotic approach can optimize the AD system and help the agricultural sector to become more sustainable and profitable. Applying the symbiotic AD systems can lower the environmental impact of farming by decreasing dependency on fossil-based energy and fertilizers and by lowering the carbon footprint from farming, thereby helping the Dutch agricultural sector to achieve its stated environmental goals.

8.1.3. Further research

Not all elements regarding the new approach for designing, measuring, and optimizing the overall sustainability of renewable energy production could be fully examined within the scope and timeframe of the research. However, based on research already performed, a suggestion for Balance, People, and a Label of sustainability can be made.

STEP 6 (BALANCE): Strain on the energy system

Renewable energy production pathways will also integrate into the local landscape; therefore, local energy infrastructure must be able to absorb or even balance the produced energy from REPPs. Within this context, it is important to measure the impact or (im)balance of REPPs on the local energy system. The expression of (im)balance is based on the load duration curve, which indicates the amplitude of the demand per hour, ranging from the highest amplitude to the lowest as a function of time, distributed over a year; it is also called the net load signal (NLS), and it will be used as an indicator for balance. By plotting all the amplitudes per hour, starting with the highest positive (e.g. overproduction) down to the highest negative (e.g. demand), a load duration curve will appear with a demand and production side (Fig. 8.5). When this net load duration curve (NLDC) is zero, local energy production is equal to energy demand (Fig 8.5). Additionally, within the NLDC, the maximum grid strain will be indicated based on the average grid situation in the Netherlands. The thickness of the cable transmitting electricity to individual houses and the capacity of the transformers serving the houses determine the maximum possible grid load. Not all grids are similar; older grids have lower capacity than newer grids, hence, the range in the max grid load (Fig. 8.5). The aforementioned indicator can inform the grid-responsible parties on balance and grid stability.

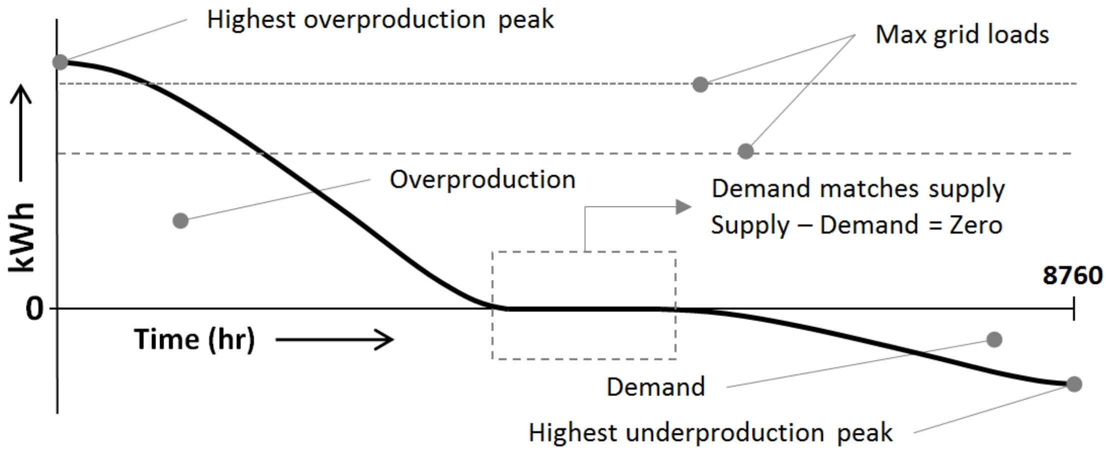


Fig. 8.5. Example of load/demand duration curve and load/average demand duration curve

STEP7 (LABEL): Indicating the sustainability of a REPP

A summation of the expressions in a clear overview will result in a label representing the sustainability of the measured REPP, (Fig. 8.6). The results are indicated in the main terms: Production, representing the produced amount of energy by the REPP; Planet, representing the environmental impact; Profit; indicating the NPV and payback period; SPACE, indicating the REPPs required space; Balance, indicating the strain on the local energy system; and People, indicating advantages for the location of the REPP (Fig. 8.6). This overview of the overall sustainability of a REPP can help in the planning and decision-making process of REPPs, and it can be used to compare or optimize individual REPPs or combined systems. Additionally, by using the developed We-Energy game, impacts on space can be made more apparent through the use of a scaled map, where the REPP can be planned in (Fig. 8.7a).

Fig. 8.6. Example of the sustainability label of a REPP (for this example, a solar park of approximately 9 ha, within the Netherlands)

STEP 8 (PEOPLE): Defining social impacts

Defining the social impacts regarding the integration of REPPs was originally omitted from the main research, as these impacts are difficult to quantify using physical modeling. Social impacts are based on a culmination of environmental, economic, spatial, and social impressions that make up the local opinion on a specific matter. Opinion is often based on a discussion of the matter, and within that perspective, a link can be drawn with the other indicators for sustainability. Therefore, the factual and quantifiable properties of REPPs can be used in a social activity to either measure or even influence local opinion on a specific matter. The aforementioned link was further explored through the development of a serious game (based on the indicators of sustainability discussed in this section) called the We-Energy Game. This game (Fig. 8.7a) is a representation of how energy transition affects different stakeholders or sectors within a local community (People, Planet, Profit, Balance, Space, Production, and Permits). The players of the game will assume the roles of one of these important stakeholders, and from the perspective of this stakeholder, they will try to make their village or city energy neutral regarding domestic electricity demand. The players will need to reach their individual score for the chosen role and the production score of the village or city. To be able to achieve their goals, the players must place renewable energy technology cards on the map (Fig. 8.7a), representing specific renewable production and space use on the map. Additionally, the technology card also has a score for each individual role, and the scores differ depending on the various roles, which indicate the dilemmas facing different renewable options (Fig. 8.7b). The score of each card is based on the realistic impacts of each energy source. The game opens the minds of the players and teaches them that the sustainability of a system depends on multiple factors, for instance the height of a wind turbine (People), the land requirements of solar panels (Space), the imbalance caused by solar panels on the electricity grid (Balance), the environmental impact of using maize in an AD system (Planet), and the high costs of battery systems for storage (Profit). This knowledge is helpful in future discussions. Within this context, the players in the game must devise a solution together through discussion, where every stakeholder is satisfied with his score. Through this discussion, the participants become aware of the dilemmas facing renewable energy technologies and the importance of collaboration between stakeholders. Social optimization will require active stakeholder sessions where People, Planet, Profit, Balance, Space, and Permits are intensively discussed. The We-Energy Game can be a useful tool in this context. The game has been successfully used multiple times in education for companies, governments, and local communities. In one specific project, in collaboration with the province of Groningen, the game was used to discuss and shape future policies together with local inhabitants; this was necessary for achieving the goals stated by the province of Groningen of 60% renewable energy in the year 2035. To date, these discussions have been deemed successful [173, 174]. Further research can help to determine the effectiveness of serious gaming in optimizing REPPs for local specifications.

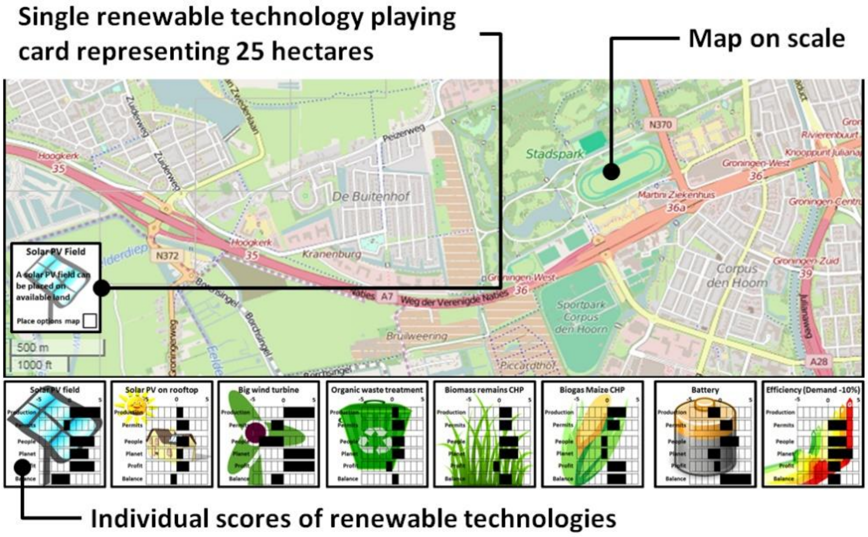


Fig. 8.7a. Example of the We-Energy Game map with placed cards representing a specific space use.

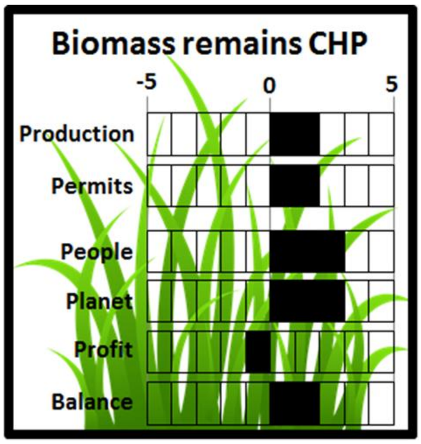


Fig. 8.7b. Example of a single renewable technology card

8.2. Discussion and reflection on the new approach

If sustainability cannot be clearly defined as an end goal or measured uniformly and transparently, then the direction and progress towards this goal can only be roughly followed. Therefore, a clear understanding of and a transparent, uniform measuring technique for sustainability are required for a fully sustainable and circular (renewable) energy production pathways (introduction to this dissertation).

8.2.1. Researching biogas production pathways using the new approach

When focus was placed on determining the sustainability of biogas production through the use of farm-scale AD, it became clear from the literature that the subject was already well documented and researched. However, there is wide variability in both scope and approach, which makes the interpretation of the various results difficult. A literature study brought to light substantial differences in results between multiple attributional LCA (aLCA) and consequential LCA (cLCA) analyses of biogas production pathways. Amongst others, these differences could be traced back to different approaches in the definition of the system boundaries, the life cycle inventory (LCI) phase of the LCA, and the different choices of indicators for sustainability. Additionally, focus was often specific regarding technology and location, thereby making the results also specific. In this regard, focus is required to achieve precision in the indicators of sustainability; however, on the other hand, a holistic overview of the complete system must be maintained to avoid “single factor manipulation,” as it does not necessarily result in an overall sustainability gain. The new approach was able to include both elements, with a specific focus achieved through the detailed calculations in the sub-modules and a holistic overview achieved through the use of the modular approach and clear indicators for sustainability. Furthermore, the flexibility of the modular approach allowed for easy adaptation of new research elements, including more indicators of sustainability, added complexity of the biogas production pathway in the BioGas Simulator model, and optimization optionality towards industrial symbolism and circular economy within the larger farming system, thereby also focusing on “multi factors” of sustainability. Through the use of the new approach (combined with numerical modeling), including a multi-factor indication and quantification of sustainability, the focus of this research shifted from producing the maximum amount of renewable energy to using farm-scale AD for optimizing the overall farming process on multiple elements of sustainability (Planet, Space, and Profit) and on closing open-ended systems toward a more circular economy through the use of the symbiotic approach. Traditional energy systems, including farm-scale AD biogas production pathways, are often designed in an open-ended manner with a low tendency to close loops, whereas within a circular system, emphasis is placed on energy and material reuse, cascading and upgrading, and industrial symbiosis. However, the circular economy is often seen as (fully) sustainable, which is not always the case. Furthermore, subsidies for renewable energy production within the Netherlands are currently received per unit of energy placed on the grid. This does not always guarantee a reduction in either emissions or environmental impacts, and it indicates a mostly economic incentive. Therefore, focused and stable policies, improved regulation, and strong cooperation must also be initiated, as regulations on green fuel and fertilizer use and subsidies for circular symbiotic systems are currently unclear within the Netherlands and the EU. From a meso-level perspective, the national government and the EU create the rules and financial framework in which farm-scale AD biogas production pathways operate; therefore, they will strongly influence the overall business case. On the other hand, from a micro-level perspective, local governments will need to apply the technologies within the set of rules, within the economic framework, and most importantly, within the local community. In the aforementioned context, social aspects became evident when municipalities requested a clear and understandable overview of the sustainability of AD biogas production pathways. The aim was to increase factual knowledge in the decision-making process for handling and extending permits for AD biogas production pathways in those municipalities. The use of a clear and transparent structure, based on the use of scientific rigor combined with clear expressions toward the societal debate, are highly important for the fact-supported component in this decision-making process. There is consequently a need for a clear understanding of and a transparent, uniform measuring technique for sustainability in terms of fully sustainable and circular REPPs, as society is asking for an integrated and understandable overview of the decision-making and planning process for a future sustainable energy system.

8.2.2. Future perspective on farm-scale AD biogas production pathways

Small-scale biogas production pathways in the Netherlands currently only produce a minor reduction in carbon footprint and environmental impacts and a low efficiency with a negative NPV, based on the reference scenario used in this research. This indicates that, amongst other things, the AD system has not been fully optimized. However, when utilized efficiently and responsibly, that process can become a more sustainable energy resource that is capable of processing waste flows and producing renewable energy in the form of electricity, heat, green gas, green fuel, and green fertilizers. Within the aforementioned context and from an energy efficiency and sustainability point of view, a more decentralized approach is suggested, wherein the available biomass and manure are harvested, collected, and transported close to the location of the processing, production, and demand for energy. Furthermore, the produced energy should first be used for powering the biogas production process; further upgrading the biogas to electricity and heat, green gas, or green fuel; and further upgrading the digestate to green fertilizers, which would replace fossil fertilizers. Applying the aforementioned "symbiotic circular" concept to the Dutch farming sector can help to achieve the following stated goals indicated by the Dutch agricultural sector for the year 2020: a 30% increase in efficiency; 30% carbon-dioxide emission reductions, compared to the reference year of 1990; and a 20% share of renewable energy. Within this research, focus is placed on the AD biogas production pathway and energy use within the farming process, thereby excluding the focus on the sustainability of agriculture as a whole. However, the focus must be on achieving the most sustainable farming system as a whole, including soil quality and productivity, which could be an important focus for future research. Overall, symbiotic circular biogas systems in the farming sector can supply green electricity, gas, fuel, and fertilizer for use in the farming process, thereby avoiding external import and increasing independence. Additionally, biogas can play a supportive role in integrating other renewable sources into local, decentralized energy systems as a flexible and storable energy source. However, decisions will need to be made on how to most effectively and sustainably utilize the limited biomass availability both in the near and far future, as biomass has a limited availability and many possible uses. To this end, focused and stable policies, improved regulation, and strong cooperation must be initiated, since regulations on green fuel and fertilizer use and subsidies for circular symbiotic systems are currently unclear within the Netherlands and the EU.

8.2.3. A new approach for measuring the sustainability of REPPs

Through the use of AD as a case, a gap in the literature is indicated and addressed regarding the need for a transparent and structured approach to measuring and indicating the overall sustainability of a REPP. In this context, farm-scale AD biogas production contained all general elements that influence the sustainability of a REPP, making it well suited for testing the new approach for measuring and optimizing sustainability and for validating the approach for use on other REPPs. This research concluded, amongst other things, that there is a substantial difference between renewable and sustainable energy production (as discussed in Chapter 1), where renewability focuses more on the resource, and sustainability places more emphasis on the process of extracting energy from a renewable resource and on the interaction with the energy system and surroundings into which the process is integrated (as discussed in Section 8.1). The elements of sustainability used within the new approach (see Section 8.1) are already indicated within the triple bottom line and the PESTEL analysis. The triple-bottom line describes a hierarchal order wherein environmental quality (Planet) precedes social prosperity (People) and then economic prosperity (Profit) [22]. Without a functioning life support system, societies cannot thrive, and without social structures and institutions, economies cannot flourish [21]. "The PESTEL framework primarily concerns six factors: political, economic, social, technical, environmental, and legal. As a structured way to organize environmental factors, PESTEL is used to analyze and map how the external environment influences an industry [23]. Both frameworks indicate the presence of multiple main elements (or stakeholders) within sustainability; however, they do not quantify them for comparison, nor do they demand a clear method and structure for defining sustainability. The new approach is a combination of the existing approaches and methods (PESTEL and MEFA/aLCA), brought together for the specific function of measuring the sustainability of REPPs. The combination of the aforementioned independent methods enables the new approach to perform a multi-perspective approach that also quantifies each specific element. Within this context, complexity is required, as sustainability cannot be simplified to single elements or "single-factor manipulation" without maintaining a holistic overview that should result in an overall gain regarding sustainability. Therefore, a successful transition to a complete renewable and sustainable energy system, often indicated as a circular economy, should be sought in a symbiosis of the elements of sustainability discussed in the triple bottom line and PESTEL. The new approach can provide a clear understanding of and a transparent, uniform measuring technique for the elements of sustainability to be able to clearly indicate and communicate the goal and progress towards a sustainable circular economy.

8.2.4. Using focused expressions to create a clear indication of sustainability

To calculate the main expression [P]EROI, GWP100, and EcoPoint end points, the LCA methodology is used. The LCA approach utilizes physical properties such as the mass, heating, or economic value ratios of products to determine the impact (e.g. the share of resource demand and the emissions of pollutants) of the functional unit chosen to characterize a production system [9]. A distinction is made between two types of LCAs: attributed and consequential. Attributed LCA (aLCA) is applicable for understanding the environmental impacts directly associated with the life cycle of a product using average data for each unit process [9]. A consequential LCA (cLCA) approach seeks to describe the consequences of decision making [9], and it is applied to obtain information about the changes in pollution and resource flows caused by a change in either the demand or the output of the functional unit [9], thereby creating many scenarios and/or possible answers. However, many LCA studies have difficulties differentiating between aLCA and cLCA [9]. Furthermore, a potential weakness of LCA is the tremendous amount of data involved, the availability of those data, and the resource and time intensities of LCA [9]. The primary limitation is the high degree of uncertainty that arises from the Life Cycle Inventory (LCI) that causes the results to exhibit high variability [10, 11]. A further limitation is the lack of a systematic method for generating and identifying sustainable solutions [12, 13].

To overcome the aforementioned challenges, this research uses the modular approach and MEFA to structure the LCI with the goal to make it more transparent when used for an LCA. Based on the focus of structuring the LCI phase and creating a clear and transparent assessment and indication of the sustainability of REPPs, and to include average (not marginal) technologies and a single impact analysis, the aLCA was included in the new approach. Additionally, to create a more transparent indication of sustainability, three main elements are described: the [P]EROI, GWP100, and EcoPoint end points. The three elements are chosen as the most simplistic and the most representative indications of the sustainability of a REPP. However, the choice for a clear and transparent indicator focused on aiding decision makers; also, the three specific impact categories chosen cannot provide detailed information regarding specific environmental impacts (e.g. acidification). The financial feasibility is expressed in NPV over 25 years [36]. The NPV method was selected, as it is a commonly used indicator of economic feasibility, and it indicates the overall returns of the investment [36]. The NPV rule recognizes that the value of money today is worth more than the value of money tomorrow because the money can be invested today to start earning interest immediately. The NPV depends solely on the forecasted cash flows of the project and the opportunity cost of capital. Since the present values are all measured in today's value, they can be added [36].

Overall, the approach is a new and untested method for determining the overall environmental sustainability of REPPs. Although the separate methods used in the approach are proven in literature, this new approach itself will need validation when used. In future research, the new approach would need to be used in multiple cases including a multitude of REPPs as single producers or combined symbiotic systems. Also, decisions would need to be made on the use of clear indicators for sustainability, as there is no overall consensus on the main indicators of sustainability.

8.2.5. Practical application and added value of the new approach

It has long been accepted in the scientific community that climate change is affecting the planet and that human activity is strongly effecting climate change [6, 7]. Every unit of fossil fuel consumed creates a net GHG increase that potentially adds to global warming, destabilizes natural processes, and endangers the Earth's carrying capacity for advanced forms of life [8-10]. Therefore, in the face of climate change, the mitigation and reduction of GHG emissions can be considered to be the most important factor. Within this context, REPPs can be implemented for replacing fossils to lower resource depletion; however, the main goal of reducing environmental impact (e.g. pollution and GHG emission reduction) might not be achieved (see Chapter 2). By definition, renewable refers to the energy resource and not the process of extracting and refining the energy from this resource. Often, the overall process of extracting energy from a renewable resource still requires fossil input, which will have an impact on the environment and therefore on the sustainability of the process. Also, other factors (as mentioned in Section 8.1) can and will influence the overall sustainability of a renewable resource. Hence, assuming that sources such as biomass, solar, or wind—being renewable—are also sustainable, which equals zero GHG emissions or environmental impact, can and will indicate a wrong incentive towards a sustainable circular economy. Therefore, the regulation and subsidization for REPPs should reflect on energy efficiency, emissions, and environmental impact as much as on economics in order to promote realistic sustainable energy production. This should also be done to ensure a sustainable future instead of only a renewable one. Regulation could indicate or even obligate the routes and methods used to define sustainability and not make predetermined decisions on which sources are sustainable, since every REPP will have a different environmental impact based the factors of sustainability discussed in this dissertation (Section 8.1). Therefore, for a future sustainable circular economy, a multi-perspective and multi-stakeholder approach must be initialized to avoid a single-perspective approach from individual stakeholders. A clear and transparent multi-perspective measuring technique is thus required to indicate the overall sustainability of REPPs on which correct decisions for adoption can be based. Within this context, the new approach combined with the suggestions made for expressing balance and people, as explained in Section 8.1.3, can be a valuable tool for evaluating the overall sustainability of REPPs and communicating the results to important stakeholders in the decision-making process, as indicated in the case of AD biogas production.

8.2.6. Measuring sustainability—the final word

Renewable integration within the Netherlands has been and currently still is unfortunately a slow process, as we occupy the second-last position in the EU regarding renewable production (Fig. 8.8). Renewable production in the Netherlands is currently 6.2% (year 2018), and the stated goal is 14% renewable energy in the year 2020 (it was initially 20% in the year 2020 but was later revised). The aforementioned information can be seen as an indicator that the availability of affordable technologies capable of producing renewable and even sustainable energy is not sufficient for the energy transition (Fig. 8.8). This is contradicted by the example of Denmark, which has similar geographical properties to the Netherlands and has already reached over 30% renewable energy production, surpassing its goal for the year 2020 (Fig. 8.8). Moreover, the acceleration of renewable energy integration and the transition to a sustainable circular economy is also largely a social process, where stakeholders need to be made aware of, correctly and transparently informed of, and involved in the process. Stakeholders need to understand the urgency and, more importantly, participate in the design and implementation process of renewable technologies, as many REPPS will have a significant impact on their surroundings in many aspects. For a successful renewable integration, all stakeholders (e.g. People, Planet, Profit, Balance, Space, and Politics) need to converge and collaborate closely. Furthermore, it is important to make the discussion regarding the energy transition sustainable in order to integrate sustainability as a part of the norms, values, and consumption behavior of everyday life. This is important because the lifestyle lived today and the decisions made tomorrow will echo for many years to come and will therefore also affect the next generations. Acknowledging the importance of the individual stakeholders within the concept of sustainability and providing them with transparent and clear information can help in forming proper discussions, decisions, and policies. In this regard, the correct information, offered at the correct time in the discussion, regarding not only the overall sustainability but also geographical placement, can help with the integration of REPPs, and it can accelerate the transition towards a sustainable circular society.

Finally, within the aforementioned context, Let us make well-informed decisions regarding the sustainability of our common home to safeguard our future and that of many generations to come on this beautiful planet.

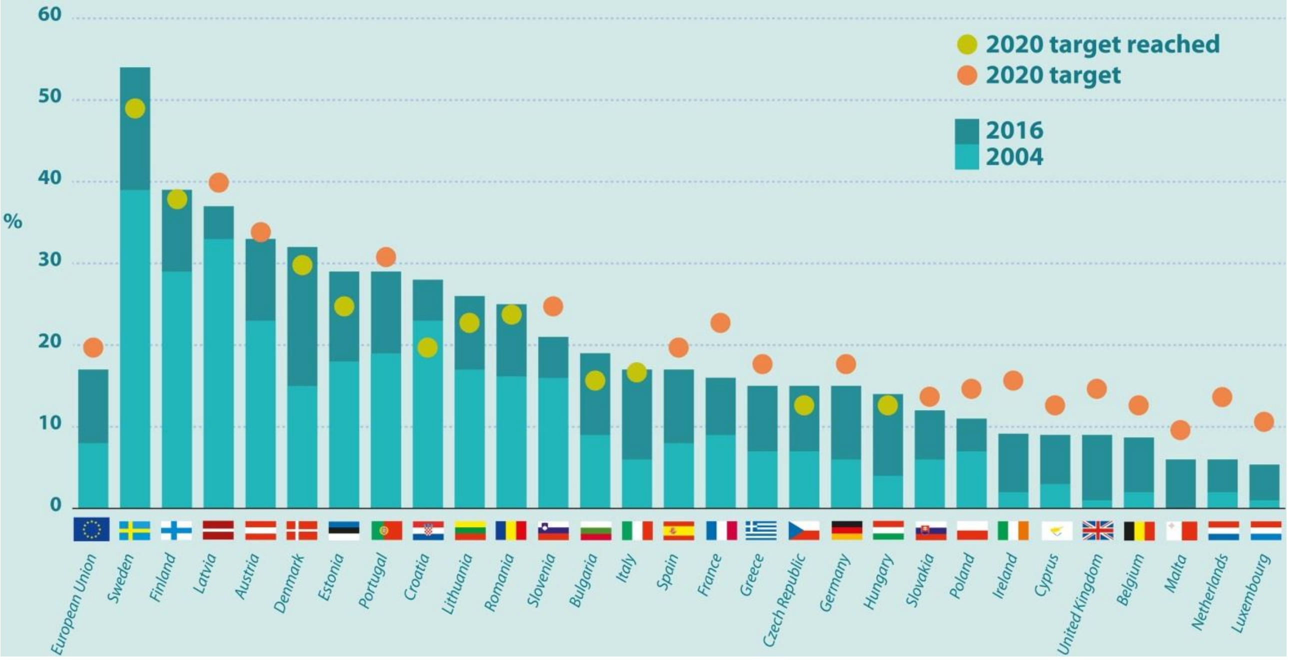


Fig. 8.8. Share of energy from renewable sources in the EU member states, in percentage of gross final energy consumption [175]

8.2.7. Using the new approach to measure the sustainability of a REPP

When utilizing the new approach to analyze the overall sustainability of a REPP, it is important to remember that the process of defining the system boundaries, the data used in the analysis, and the expressions used for indicating sustainability have a substantial effect on the environmental sustainability of the selected REPP. Therefore, this process must be selected with care and transparency. In theory, the overall sustainability of every energy system—either fossil or renewable—can be analyzed on a micro, meso, or macro level through the use of the new approach. This approach focuses on the material and energy flows (through an MEFA) in the system, their environmental impact (through an LCA), and the way in which to express them in clear and understandable indicators of sustainability; therefore, the size, complexity, or position of the REPP within the energy system is not of importance. Furthermore, accuracy regarding the results will depend strongly on the quantity and quality of the data and model used. Therefore, the model used for calculating the results should be extensively validated before being implemented. The strength of the analysis of a REPP can be increased through the use of a transparent model and changeable data and/or functions, thereby making it accessible to other experts who can help to improve the quality of the analysis. Finally, the new approach that has been worked out in this dissertation has much room for interpretation; therefore, it must be used by an expert in the field of energy, modeling, and LCA.

8.3. Future research needs on AD

- Within the follow-up project, namely, Agro-Cycle, the theoretical exercise in Chapter 7 is applied to a practical case study together with farmers and advisory companies in the field. The goal of the project is to determine whether the theoretical improvements possible in Chapter 7 are also possible in practice using real-time data and commercially available technology. Within this context, AD can fulfill a role other than a renewable source of energy, namely, that of increasing the sustainability of the farming process as a whole by supplying energy, fuel, and fertilizer and by processing waste materials. Additionally, insight into nutrients cycles and crop quality is required when using digestate and green fertilizers as replacements for manure and fossil fertilizers.
- Specific biomass, biogas, and methane potential in the biogas are often difficult to quantify and can differ by season, location, and even per AD installation. There is a substantial spread regarding biomass and biogas potentials in the current literature. Additional research is required in this context to more specifically determine the biogas production of several biomass types, including combinations of biomass used as feedstock and several AD technologies used to process them. More insight into the real energy use, biogas production, and biomass production in multiple biogas installations is required by a more accurate measuring of inputs and outputs of biomass, digestate, biogas, and leakages.
- Biomass is a precious resource, with only a limited amount available per year. Within this context, biomass can also have other uses (e.g. stable flooring, animal feed, or bio-based products), which must be considered. Also, further research is required regarding how to optimally use the finite amount of biomass most efficiently.
- In farming practices, emphasis and focus is currently placed on nutrient cycles, including carbon, nitrogen, phosphates, and organic matter. However, the correct balance between extracting organic matter and nutrients for product and energy production versus environmental conditions (e.g. of the field) is still unclear.

Summary

FINDING A BALANCE

How to measure and optimize the sustainability of complex (renewable) energy production pathways: applied to farm-scale biogas production pathways

Introduction: A new approach for measuring the sustainability of renewable energy pathways

To avoid energy scarcity as well as climate change, a transition towards a sustainable society must be initiated. Within this context, governmental bodies and/or companies often view sustainability as an end goal, for instance as a green circular economy. However, if sustainability cannot be clearly defined as an end goal or measured uniformly and transparently, then the direction and progress towards this goal can only be roughly followed. Therefore, a clear understanding of and a transparent, uniform measuring technique for sustainability are required for fully sustainable and circular (renewable) energy production pathways (REPPs), as society is asking for an integrated and understandable overview of the decision-making and planning process in terms of a future sustainable energy system. Based on this reasoning, a new design method has been developed in this dissertation that allows the sustainability of REPPs to be measured, compared, and optimized on the elements of sustainability that have been identified both by Elkington and in the PESTEL framework (political, economic, social, technical, environmental, and legal). These elements are People, Profit, Planet, Space, Balance, and Politics. Within this thesis, the emphasis is placed on three of the aforementioned elements, namely, Planet, Space, and Profit, which will be discussed step by step in this section (Fig. S.1).

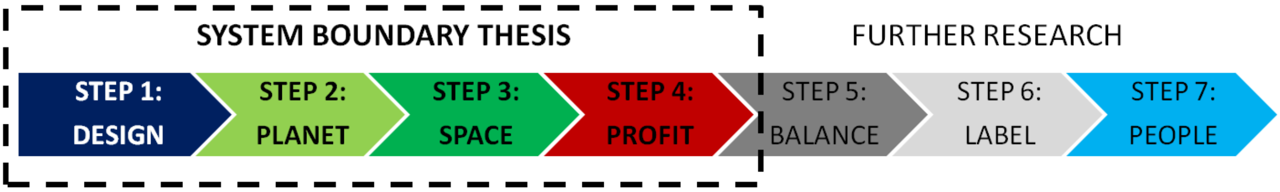


Fig. S.1. Steps in measuring the sustainability of a REPP

Step 1: The new approach for measuring the sustainability of a REPP

In this dissertation, a new approach is developed for measuring the sustainability of REPPs, and it is useful for the analysis, comparison, and optimization of REPP systems regarding all elements of sustainability. The new approach is applied to the analysis of farm-scale anaerobic digestion (AD) biogas production pathways (see Chapter 1). It is a combination of existing approaches and methods brought together for the specific purpose of measuring the sustainability of REPPs. The main layout is based on the industrial metabolism concept, a material and energy flow analysis (MEFA), and an attributed life cycle analysis (aLCA). The expressions of sustainability are based on the triple bottom line, which currently includes indicators for Planet, Space, and Profit. The new approach demands a clear and structured MEFA of the REPP, expressed with clear indicators for energy efficiency and environmental sustainability, thereby making the analysis more transparent and easier to interpret and compare. Additionally, the modular structure of the new approach enables the option to optimize REPPs.

The (Excel) BioGas Simulator (EBS)

The new approach is used to construct the (Excel) BioGas Simulator or EBS model (see Chapter 2), which is capable of calculating the economic cost, efficiency, carbon footprint, and sustainability of farm-scale AD biogas production pathways. The EBS model offers insight into the sustainability of specific biogas production pathways, and it helps to indicate options for improvement and optimization. The results from the model are expressed in four main indicators: the economic cost in a net present value (NPV) and payback period analysis, the efficiency in process energy returned on invested ([P]EROI), the carbon footprint in the Global Warming potential 100-year scale (GWP100), and the environmental impact in EcoPoints (Pt). The modular approach separates the biogas production pathway into individual physical processes, which makes the model more transparent, flexible in use, and programmable for different settings. All of this allows for the research of several aspects of the biogas production pathway. To validate the EBS model (see Chapter 3), a validation and verification (V&V) method is researched, selected, and applied specifically for the validation of the EBS model. Through the use of this method, mistakes in the model are resolved, the strengths and weaknesses of the model are found, and the concept of the model is tested and strengthened. The validation process not only improves the model, but it also helps the modelers to widen their focus and scope. The main result from the V&V process indicates that the EBS model is valid; however, it should be considered as an expert model and hence only used by expert users.

STEP 2: Measuring the sustainability of an AD biogas production pathway

Through the use of the new approach integrated into the EBS model, the energy efficiency and sustainability of a farm-scale AD biogas production pathway is evaluated (see Chapter 4), taking into account the use of five biomass feedstocks, the optimization of the green gas production pathway, the replacement of current waste management pathways by mitigation, and the transport of the feedstocks. The use of optimization through the internal use of the energy production, through green gas powered trucks, and through mitigation can significantly improve the sustainability for all feedstocks; however, the use of waste materials is favored. Moreover, optimization will result in less green gas injected into the gas grid, as it is partially consumed internally. Overall, the feedstock "straw" was the most energy efficient, where the feedstock "harvest remains" proved to be the most environmentally sustainable. Furthermore, the transport distances of all feedstocks should not exceed 150 kilometers, otherwise emissions and environmental impacts will surpass those of natural gas, used as a reference. Using green gas as a fuel can increase the acceptable transportation range to over 300 km. Within the aforementioned context, and from an energy efficiency and sustainability point of view, the AD process should be utilized to process locally available waste feedstocks with the added advantage of producing energy, which should first be used internally to power the green gas production process.

STEP 3: Availability of biomass waste flows for producing biogas

For the next step in the optimization of the AD biogas production pathways, the focus is placed on renewable biogas production with locally available biomass waste flows, thereby avoiding intensive farming and long transport distances of biomass and energy carriers (see Chapter 5). To determine local biomass waste flow availability, the bio-energy yields, efficiency, and environmental sustainability are analyzed for five municipalities in the northern part of the Netherlands, using three utilization pathways: green gas production, combined heat and power (CHP), and waste management. However, the average useful energy finally produced by the AD production pathway is significantly lower than the local theoretical bio-energy potential, often due to the poor quality of biomass and the difficult harvesting conditions. Furthermore, of the potential bio-energy input in the three utilization pathways considered in this article, on average, 73% can be extracted as green gas, 57% as heat and power, and 44% as green gas in the waste management pathway. The green gas utilization pathway is preferable for reaching production goals, as it retains the highest amount of energy from the feedstock. However, environmental sustainability favors the waste management pathway, since it has a higher overall efficiency as well as lower emissions and environmental impacts. The main lessons drawn from the above-mentioned information are twofold: there is a substantial gap between bio-energy potential and net energy gain, and there is also a gap between top-down regulation and actual emission reduction and sustainability. In this context, well-founded ideas and decisions are needed regarding how best to utilize the limited biomass availability most effectively and sustainably both in the near and far future, as biogas can play a supportive role in integrating other renewable sources into local, decentralized energy systems as a flexible and storable energy source and as the treatment of locally available bio-waste streams.

STEP 4: Optimizing the energy system of a farm through the use of a biogas production pathway

Finally, the focus is placed on the further optimization of AD biogas production pathways in combination with the farming process, using the industrial symbiosis concept combined with the new approach and the EBS model, (see Chapter 6). Optimizing the AD system involves the use of locally available biomass waste flows and a selection of improvement options that are either applied individually or combined in a symbiotic system. When implementing individual improvement options, positive effects on the indicators can already be observed; however, the reduction achieved is often significant for only one or two of the four indicators used in the new approach (i.e. energy efficiency, carbon footprint, environmental impacts, and costs). Therefore, focusing on individual factors does not necessarily lead to optimal solutions. In contrast, a symbiotic system, which combines multiple improvement options, significantly improves all indicators. When that symbiotic system is implemented in a theoretical case, where a cooperation of farms shares biomass feedstocks and a symbiotic AD system, a substantial reduction in energy consumption, carbon footprint, environmental impacts, and yearly expenditures can be achieved, compared to the reference cooperation of farms. The largest reductions and economic gains can be achieved when a surplus of manure is available for upgrading to green fertilizer to replace fossil fertilizers. Additionally, the cooperation uses approximately half of the produced energy internally to replace energy and fuel needs and to produce green fertilizer; the remaining green gas, electricity, and/or heat can be sold and used to replace energy from fossil sources. Applying the aforementioned symbiotic concept to the Dutch farming sector can help to achieve the Dutch agricultural sector's stated renewable energy and greenhouse gas reduction goals for the year 2020.

3. Reflection on the new approach

In retrospect, the elements of sustainability used in the new approach are already revealed in the triple bottom line and the PESTEL analysis. Both frameworks indicate the presence of multiple main elements (or stakeholders) within sustainability. The new approach is a combination of the existing approaches and methods (PESTEL and MEFA/aLCA), brought together for the specific function of measuring the sustainability of REPPs. The combination of the above-mentioned independent methods enables the new approach to operate with a multi-perspective approach that also quantifies each particular element. The new approach is able to include specific focus, achieved through the detailed calculations in the sub-modules, and a holistic overview, achieved through the use of the modular approach and clear indicators for sustainability. Within the present context, REPPs are being implemented to replace fossils in order to lower resource depletion; however, the main goal of creating a sustainable resource might not be achieved (e.g. pollution and greenhouse gas emission reduction). The present assumption that sources such as biomass, solar, or wind—being renewable—are also sustainable, which equals zero greenhouse gas (GHG) emissions or environmental impact, can and will indicate the wrong incentive for a sustainable circular economy. To achieve full sustainability, regulation and subsidization for REPPs should reflect on energy efficiency, emissions, and environmental impact as much as economics in order to promote overall sustainable energy production. This would also ensure a sustainable future instead of only a renewable one. Regulation should indicate or even obligate the routes and methods used to define sustainability and not make predetermined decisions on which sources are sustainable, since every REPP will have a different environmental impact based the factors of sustainability discussed in this dissertation (see conclusion Chapter).

The acceleration of renewable energy integration and the transition towards a sustainable circular economy is also largely a social process, where stakeholders need to be made aware of, correctly and transparently informed of, and involved in the process. Stakeholders need to understand the urgency and, more importantly, participate in the design and implementation process of renewable technologies, as many REPPS will have a significant impact on their surroundings in many aspects. Therefore, for a future sustainable circular economy, a multi-perspective and multi-stakeholder approach must be initialized to avoid a single-perspective approach from individual stakeholders. Furthermore, it is important to also make the discussion regarding the energy transition sustainable in order to integrate sustainability as a part of the norms, values, and consumption behavior of everyday life, since the lifestyle lived today and the decisions made tomorrow will echo for many years to come and will thus also affect the next generations. Acknowledging the importance of the individual stakeholders within the concept of sustainability and providing these stakeholders with transparent and clear information can help in forming proper discussions, decisions, and policies. The correct information, offered at the correct time within the discussion, regarding both the overall sustainability and geographical placement, can thus help the integration of REPPs and accelerate the transition towards a sustainable circular society. The approach developed in this thesis, combined with the suggestions made for expressing balance and people (conclusion chapter), delivers a valuable and firm base for evaluating the overall sustainability of REPPs and communicating the results to important stakeholders in the decision-making process. Finally, in the aforementioned context, Let us make well-informed decisions regarding the sustainability of our common home to safeguard our future and that of many generations to come on this beautiful planet.

Of course, further research is required to complete the overall assessment of REPPs. To include temporal dynamics (BALANCE), the load demand curve and net load signal (NLS) are suggested, and a practical solution is proposed for starting and guiding the discussion on REPP integration into local communities (PEOPLE) through the use of the WE-Energy Game. Also, more research is required regarding biomass and biogas specification and/or the integration of AD biogas production pathways into the agricultural process.

Samenvatting

HET VINDEN VAN EEN BALANS

Hoe de duurzaamheid van complexe (hernieuwbare) energieproductiesystemen te meten en te optimaliseren: toegepast op boerderijschaal biogasproductiesystemen

Inleiding: Een nieuwe aanpak voor het meten van duurzaamheid van hernieuwbare energie-productiesystemen

Om zowel energieschaarste als klimaatverandering te voorkomen, zal een transitie naar een duurzame samenleving zo spoedig mogelijk ingezet en doorgezet moeten worden. Het woord duurzaam wordt in die discussie omtrent de energietransitie vaak genoemd als een einddoel door overheidsinstanties en/of bedrijven, voorbeelden hiervan kunnen zijn; energieneutraal, klimaatneutraal, een duurzame samenleving en een groene circulaire economie. Maar wat betekent “duurzaam” nu echt? Kun je het ook meten? Als we niet precies weten wat duurzaamheid is, of niet kunnen meten hoe duurzaam we zijn, hoe kunnen we de richting en de voortgang richting dit doel dan volgen en/of bepalen? De zoektocht naar wat duurzaamheid kun je vergelijken met het voorbereiden van een reis. Als je op het punt staat een reis te beginnen, maar je weet niet waar je heen gaat en welke route je gaat volgen, hoe zorg je er dan voor dat je in ieder geval de goede richting opgaat? Als je in ieders geval weet waar je ongeveer heen wilt wordt het al een stuk gemakkelijker. Hetzelfde geld voor de transitie naar duurzame energie. En om in ieders geval de goede richting te kiezen is inzicht nodig. Dit inzicht kan komen in de vorm van een transparante uniforme meettechniek voor het meten van de duurzaamheid van (hernieuwbare) energie-productiesystemen. In dit onderzoek wordt dat ook wel renewable energy production pathways (REPP) genoemd. De huidige samenleving vraagt om een geïntegreerd en begrijpelijk overzicht in het besluitvormings- en planningsproces naar een toekomstig duurzaam energiesysteem. Vanuit de zoektocht naar een bestemming en route naar duurzame energieproductie (zoals hierboven benoemd) is in dit proefschrift een nieuwe designmethode ontwikkeld waarmee de duurzaamheid van REPPs gemeten, vergeleken en geoptimaliseerd kunnen worden op de elementen van duurzaamheid benoemd door Elkington en in het PESTEL-raamwerk. Deze elementen zijn: mensen, winst, planeet, ruimte, balans en politiek. Binnen dit proefschrift ligt de nadruk op drie van deze elementen, namelijk: planeet, ruimte en winst.

Aanvullend worden er suggesties gedaan voor drie extra elementen van duurzaamheid, namelijk: balans, mensen (Fig. N.1) en een duidelijk label waar de voorgenoemde elementen aangeduid worden. In deze samenvatting worden de stappen in Figuur 1 doorlopen.

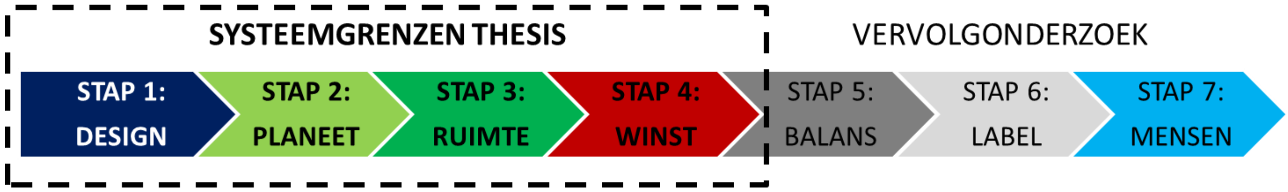


Fig. N.1. Stappen in het meten van de duurzaamheid van een REPP

Stap 1: Een nieuwe designmethode voor het meten van de duurzaamheid van bio-vergisters

De nieuwe designmethode (zie hoofdstuk 2) is toegepast en getest op een bio-vergistingsketen gebaseerd op Anaerobe Vergisting (AD) op boerderijniveau. Het gaat om een luchtdichte tank waar biomassa (mest en co-substraten zoals mais, gras of oogstresten) door bacteriën wordt omgezet in biogas. Dit biogas bestaat voor het grootste gedeelte uit methaan. Dit brandbare gas kan gebruikt worden om elektriciteit, warmte en/of groen gas (biogas op aardgas kwaliteit) op te wekken. De nieuwe methode is een combinatie van bestaande benaderingen en methoden die zijn samengebracht voor het meten van de duurzaamheid van hernieuwbare energieketens (REPPs). De hoofdlijn van de methode is gebaseerd op het concept van industrieel metabolisme, aangevuld met een methode gebaseerd op Materiaal en Energiestroomanalyse (MEFA-methode), de modulaire aanpak en de toegerekende (attributed) levenscyclusanalyse (aLCA). De nieuwe methode vereist een duidelijke en gestructureerde materiaal- en energiestroomanalyse van de REPP, uitgedrukt in duidelijke indicatoren voor energie-efficiëntie en milieuduurzaamheid, waardoor de analyse transparanter en gemakkelijker te interpreteren en te vergelijken is. Bovendien biedt de modulaire structuur van de nieuwe methode de mogelijkheid om REPPs te optimaliseren. De indicatoren van duurzaamheid zijn gebaseerd op de tripple-bottom-line-theorie die de elementen planeet, ruimte en winst omschrijft en de PESTEL-analyse (politiek, economisch, sociaal, technisch, milieu en juridisch). Beide kaders geven de aanwezigheid aan van meerdere hoofdelementen (of stakeholders) binnen duurzaamheid. De combinatie van de bovengenoemde onafhankelijke methoden stelt de nieuwe methode in staat om te werken met een multi-perspectiefbenadering, die vervolgens elk specifiek element kwantificeert. Dat kan zowel een beeld geven op detailniveau per specifieke techniek, bijvoorbeeld het transport van biomassa, en een holistisch beeld van een hele installatie of keten waar meerdere technieken worden gecombineerd. Denk hierbij bijvoorbeeld aan de productie van biogas of een combinatie van wind, zon, biogas en opslag.

De (Excel) BioGas simulator

De eerdergenoemde nieuwe methode is geïntegreerd in de (Excel) BioGas-simulator (EBS-model) (zie hoofdstuk 3), waarmee de economische kosten, efficiëntie, broeikasgasemissies en duurzaamheid van een bio-vergister op boerderijniveau kan worden berekend. Het EBS-model geeft inzicht in de duurzaamheid van specifieke bio-vergistingsketens en helpt bij het aangeven van opties voor verbetering en optimalisatie. De resultaten van het model worden uitgedrukt in vier indicatoren van duurzaamheid namelijk: 1) de economische kosten in Net Present Value (NPV) en de terugverdientijd; 2) de efficiëntie in geïnvesteerde energie tegenover de geproduceerde energie ofwel de [P]EROI; 3) de CO2-voetafdruk uitgedrukt in opwarmingspotentieel 100 jaar schaal (GWP100); en 4) de milieu-impact in EcoPoints (Pt) wat alle impact op het milieu bevat (bijvoorbeeld menselijke gezondheid, opraken van grondstoffen en biodiversiteit). De modulaire aanpak in het EBS-model verdeelt de bio-vergistingsketen in individuele fysieke processen, waardoor het model transparanter, flexibeler in gebruik is en programmeerbaar is voor verschillende bio-vergistingsketens. De modulaire aanpak kan gezien worden als het opsplitsen van taken in blokjes, bijvoorbeeld: transport, opslag, biogasproductie, opwaardering naar groen gas. Per blokje wordt een taak beschreven en vervolgens gelinkt aan de voorgaande en opvolgende blokje, waarmee een keten van blokjes wordt gemaakt die bijvoorbeeld biogas produceert. Het voorgaande maakt het onderzoek naar de verschillende aspecten van een bio-vergistingsketen mogelijk. Om het EBS-model te valideren (zie hoofdstuk 4), is een validatie- en verificatiemethode (V&V) onderzocht, specifiek geselecteerd voor en toegepast op de validatie van het EBS-model. Door het gebruik van deze methode worden fouten in het model opgelost, de sterke en zwakke punten van het model gevonden en het concept van het model getest en versterkt. Het belangrijkste resultaat van het V&V-proces geeft aan dat het EBS-model gevalideerd is. Echter, het model moet worden beschouwd als een expertmodel en mag alleen gebruikt worden door ervaren gebruikers met kennis van het vakgebied.

Stap 2: Het meten van de milieuduurzaamheid van verschillende biomassastromen en het bio-vergistingsproces

Door het gebruik van de in stap 1 beschreven nieuwe methode en het EBS-model, is de energie-efficiëntie en duurzaamheid van een bio-vergistingsketen, die op de boerderijschaal groen gas produceert, geanalyseerd en geëvalueerd (zie hoofdstuk 5). Binnen de analyse is rekening gehouden met het volgende: het gebruik van vijf biomassagrondstoffen (mais, gras, bieten/aardappeltoppen, stro en bodemverbeteraars), opwaardering van biogas naar groen gas, vervanging van de huidige biomassa-afvalbeheerroutes en de daarbij behorende energie en milieu impact en het transport van de biomassagrondstoffen. Voorbeelden van huidige biomassa-afvalroutes zijn het maaien en laten liggen van biomassa of het afvoeren en verbranden ervan. De resultaten van dit onderzoek geven aan dat vanuit een energie-efficiënt en duurzaamheidsoogpunt bio-vergisting het best gebruikt kan worden voor de verwerking van lokaal beschikbare afval-biomassastromen. Dit heeft als extra voordeel dat er energie wordt geproduceerd. Transportafstanden van alle biomassagrondstoffen behoren niet meer dan 150 kilometer te bedragen. Daarboven zullen de emissies en milieueffecten die van Gronings aardgas (als referentie gebruikt) overtreffen. Het gebruik van groen gas als brandstof kan de aanvaardbare transportafstand tot meer dan 300 km verhogen. Daarbinnen kan optimalisatie de duurzaamheid van het gehele proces aanzienlijk verbeteren; bijvoorbeeld in de vorm van interne energieproductie en gebruik in de bio-vergistingsketen, vrachtwagens rijdend op groen gas, en mitigatie. Verder bevordert het gebruik van afval-biomassastromen als co-substraat de duurzaamheid van het systeem. De bovengenoemde optimalisatie, waar energie wordt gebruikt om het proces te bekrachtigen, zal echter resulteren in minder groen gas dat in het gasnet wordt geïnjecteerd, omdat het groen gas gedeeltelijk intern wordt geconsumeerd.

Stap 3: Het bepalen van de mogelijke biomassa-reststromen en de daaruit geproduceerde energie

Voor de volgende stap binnen de analyse van de bio-vergistingsketen ligt de nadruk op biogasproductie gebruik makend van lokaal beschikbare biomassagrondstoffen zoals co-substraten, waarbij intensieve landbouw voor de productie van biomassa, lange transportafstanden van biomassa en energiedragers worden vermeden (zie hoofdstuk 6). Binnen het onderzoek zijn vijf gemeenten in Noord-Nederland (Groningen, Hoogeveen, Noordenveld, Ten Boer en Eemsmond) geanalyseerd op de beschikbaarheid van lokale biomassa-afvalstromen. Vervolgens is met behulp van het EBS-model de efficiëntie en milieuduurzaamheid van drie biogas-opwaardeerketens (productie van groen gas, warmtekrachtkoppeling en afvalbeheer) geanalyseerd die gebruik maken van de lokaal aanwezige biomassa-afvalstromen. De groengasketen produceert voornamelijk groen gas, met dezelfde kwaliteit als aardgas, en dit groene gas wordt geïnjecteerd in het aardgasnet. De warmtekrachtkoppeling (WKK) produceert elektriciteit en warmte waarbij de elektriciteit na intern gebruik wordt geïnjecteerd in het elektriciteitsnet. De warmte wordt intern gebruikt voor het biogas productie proces. Daarnaast kan (indien mogelijk) de overige warmte worden gebruikt in een warmtenet. Afvalbeheer combineert meerdere elementen om de duurzaamheid te maximaliseren, namelijk; een kleine WKK die de warmte en elektriciteit voor het proces produceert; omzetting van groen gas in brandstof; en het opwaarderen van de overblijvende digistaat naar groene kunstmest ter vervanging van fossiele kunstmest. Overige energie uit dit proces wordt als groen gas geïnjecteerd in het gasnet. De gemiddelde nuttige energie die uiteindelijk door de bio-vergisters geproduceerd wordt is echter aanzienlijk lager dan de theoretisch aanwezige energie in de beschikbare biomassa-afvalstromen. Dit is vaak als gevolg van de slechte kwaliteit van biomassa en de moeilijke oogstomstandigheden. Van de theoretisch aanwezige energie in de beschikbare biomassa-afvalstromen kan gemiddeld in de drie bio-vergistingsketens; 73% worden omgezet in groen gas; 57% worden omgezet in warmte en kracht; en 44% worden omgezet in groen gas in het afvalbeheertraject waar aanvullend groene brandstof en kunstmest wordt geproduceerd. Vanuit dit perspectief heeft groen gas de voorkeur voor het bereiken van productiedoelen, omdat deze de grootste hoeveelheid energie uit de biomassa omzet in groen gas. Echter, kijkend naar milieuduurzaamheid presteert het afvalbeheertraject beter. Voornamelijk omdat het afvalbeheertraject een hogere efficiëntie heeft met lagere emissies en milieueffecten. De belangrijkste lessen die kunnen worden getrokken uit de resultaten, zijn tweeledig. Ten eerste: er is een aanzienlijke kloof tussen bio-energiepotentieel en netto-energiewinst. Ten tweede: er is een kloof tussen top-down-regelgeving en daadwerkelijke emissiereductie en duurzaamheid. Deze kloof kan veroorzaakt worden door het gebrek aan kennis bij de regelvormende partijen omtrent de werkelijke haalbare emissiereducties door bio-vergisters. Binnen deze kaders zijn er gefundeerde beslissingen en stabiel beleid nodig over de beste manier om de beperkte beschikbaarheid van biomassa op de meest effectieve en duurzame wijze te benutten in de nabije en verre toekomst. Dit aangezien biogas een ondersteunende rol kan spelen bij de integratie van andere hernieuwbare bronnen in lokale gedecentraliseerde energiesystemen als een flexibele en opslagbare energiebron. Daarop aanvullend, is het vergistingsproces is zeer geschikt voor de behandeling van lokaal beschikbare bioafvalstromen.

Stap 4: Het optimaliseren van de energiehuishouding van boerderijen door het gebruik van een bio-vergister

Ten slotte wordt de nadruk gelegd op de verdere optimalisatie van de bio-vergistingsketen in combinatie met het landbouwproces. Hierbij wordt gebruik gemaakt van het concept "industriële symbiose" in combinatie met het EBS-model (zie hoofdstuk 7). Binnen industriële symbiose wordt getracht alle energie en materiaalstromen optimaal te benutten en deze waar mogelijk zoveel mogelijk her te gebruiken door bijvoorbeeld opwaardering en verwaarding. Het optimaliseren van de bio-vergistingsketen omvat het gebruik van lokaal beschikbare biomassa-afvalstromen als co-substraten en een selectie van verbeteringsopties die afzonderlijk en/of gecombineerd in een symbiotisch systeem worden toegepast. Resultaten tonen aan dat bij het implementeren van individuele verbeteringsopties positieve effecten op de indicatoren waar te nemen zijn. De gerealiseerde verbetering is echter vaak significant voor slechts een of twee van de vier indicatoren die worden gebruikt in de nieuwe aanpak (energie-efficiëntie, carbon footprint, milieueffecten en kosten). Daarom leidt het focussen op individuele factoren niet noodzakelijk tot optimale oplossingen. Een symbiotisch systeem dat meerdere verbeteringsopties combineert, kan aanzienlijke verbeteringen realiseren voor alle indicatoren. Toegepast in een theoretische case studie, waarbij een samenwerking van landbouwbedrijven (akkerbouw en veehouderij), biomassa delen en gezamenlijk een symbiotische bio-vergister beheren, kan een aanzienlijke vermindering van energieverbruik, broeikasgasemissies, milieueffecten en jaarlijkse uitgaven worden bereikt; in vergelijking met de sommatie van alle impacten voor dezelfde landbouwbedrijven zonder een bio-vergister. De grootste impact-reducties en economische voordelen kunnen worden behaald wanneer een overschot aan mest beschikbaar is om te worden verwerkt tot groene meststof ter vervanging van fossiele meststoffen. Daarnaast gebruikt de coöperatie ongeveer de helft van de geproduceerde energie intern om de energie- en brandstofbehoeften te vervangen en groene mest te produceren. Resterend groen gas, elektriciteit en warmte kan worden verkocht ter vervanging van fossiele energiebronnen. Het toepassen van het bovengenoemde symbiotische concept op de Nederlandse landbouwsector kan helpen om de gestelde doelstellingen voor hernieuwbare energie en broeikasgasreductie, aangegeven door de Nederlandse landbouwsector voor het jaar 2020, te bereiken.

Vervolgonderzoek

In dit onderzoek zijn niet alle door Elkinton en in het PESTEL-raamwerk beschreven elementen verwerkt in de nieuwe designmethode. Wel is er binnen dit onderzoek een begin gemaakt aan drie aanvullende elementen, die met behulp van vervolgonderzoek aan de hiervoor beschreven meetmethode kunnen worden toegevoegd.

STAP 5: Binnen een energiesysteem is balans tussen vraag en aanbod een belangrijk element. Balans vertaalt zich naar betrouwbaarheid, wat betekend hoeveel procent van de tijd energie voor ons beschikbaar is. In Nederland, bijvoorbeeld, is de betrouwbaarheid van het elektriciteits- en aardgasnet boven de 99%. Nu kunnen sommige hernieuwbare bronnen deze balans verstoren. Dat komt vooral omdat deze bronnen moeilijk stuurbaar zijn. Voorbeelden daarvan zijn zonnepanelen en windturbines die alleen energie produceren bij zon of wind. Deze productie is dan evenredig aan de hoeveelheid zon en wind. Daarnaast zijn er ook technieken, waaronder bio-vergisting of energie-opslag, die wel stuurbaar zijn en de balans kunnen verbeteren. Binnen deze context is het belangrijk om de impact van een combinatie van duurzame technieken (REPPs) op de balans van het lokale energiesysteem te kunnen meten. Daarom is er in dit onderzoek een voorstel gedaan waarmee op uurbasis de balans kan worden gemodelleerd en gekwantificeerd. Dit wordt gedaan op basis van de belastingduurkromme, die de amplitude van de vraag per uur aangeeft, van de hoogste amplitude tot de laagste als een functie van de tijd, verdeeld over een jaar. De belastingduurkromme geeft aan wat de balans is van het gemodelleerde systeem. De hiervoor genoemde indicator kan de netbeheerders informeren over balans en netstabiliteit, maar ook opties aanreiken om de balans in het energienet te verbeteren en optimaliseren (zie hoofdstuk 8).

STAP 6: Het samenvatten van de expressies van duurzaamheid (Productie, Planeet, Ruimte, Winst, Balans) in een duidelijk overzicht resulteert in een label dat de duurzaamheid van het gemeten REPP of een combinatie van REPPs weergeeft. Dit overzicht van de duurzaamheid van een REPP kan helpen bij het planning- en besluitvormingsproces en kan worden gebruikt om individuele REPPs of gecombineerde systemen te vergelijken of te optimaliseren (zie hoofdstuk 8).

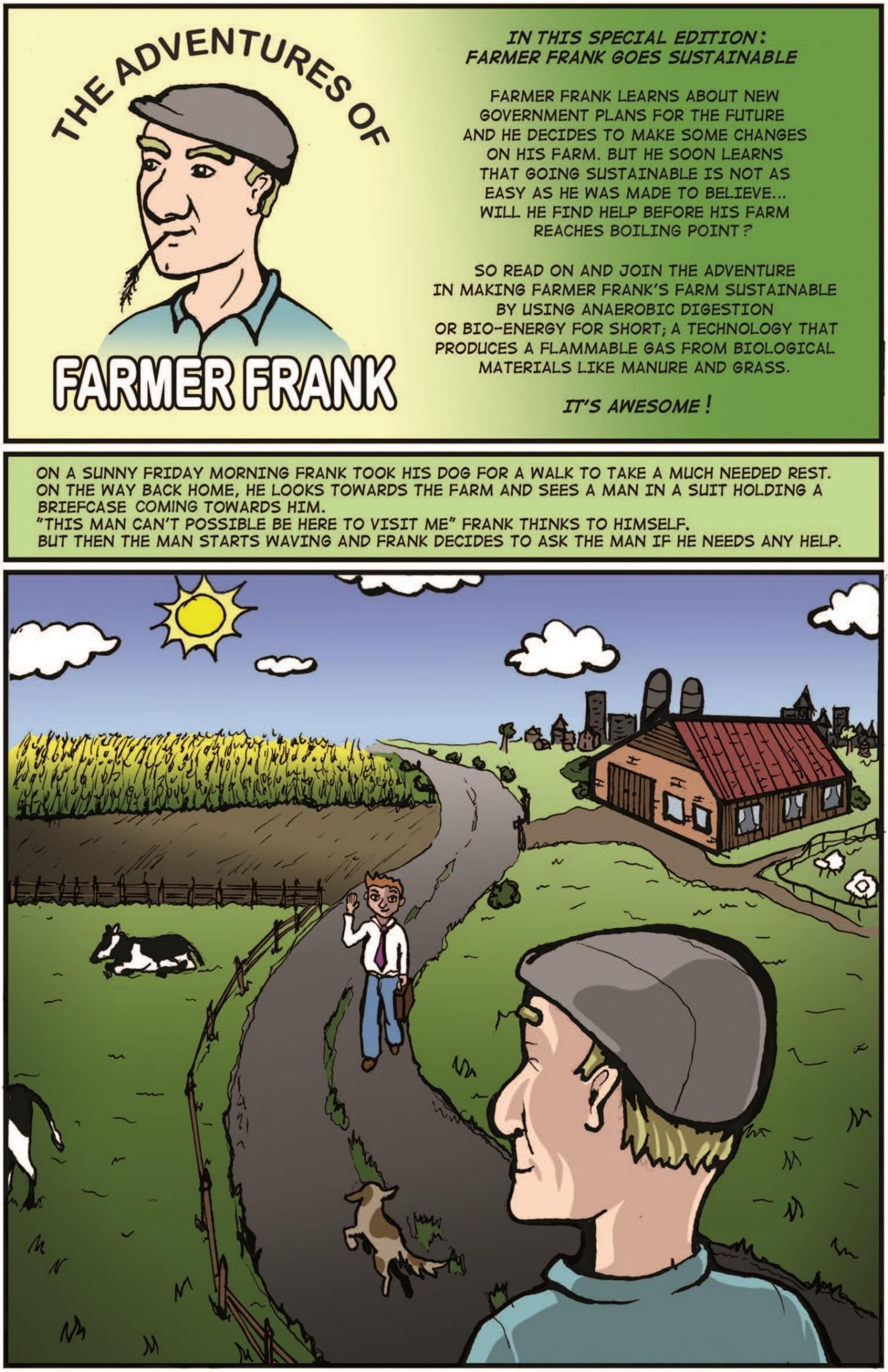
STAP 7: Sociale effecten zijn zeer moeilijk te kwantificeren met behulp van fysieke modellering. Ook zijn ze vaak gebaseerd op een culminatie van ecologische, economische, ruimtelijke en sociale indrukken die de mening over een specifieke kwestie vormen. Daarbinnen is opinie (een mening over een bepaald onderwerp) vaak ook gebaseerd op discussie over het desbetreffende onderwerp en in dat perspectief kan een link worden gelegd met de andere indicatoren voor duurzaamheid. Daarbinnen kunnen kwantificeerbare eigenschappen van REPPs (Planeet, Winst, Ruimte, Balans) worden gebruikt in een sociale activiteit om de mening over een specifieke kwestie te meten en zelfs te beïnvloeden. De bovengenoemde link is verder onderzocht door de ontwikkeling van een "serious game" genaamd de "We-Energy Game". Deze game is gebaseerd op de indicatoren van duurzaamheid die in deze paragraaf zijn besproken. Deze praktische oplossing wordt gebruikt voor het starten en begeleiden van de discussie over integratie van duurzame energie in lokale gemeenschappen en kan bijdragen aan het creëren van bewustwording en draagvlak binnen lokale gemeenschappen (zie hoofdstuk 8).

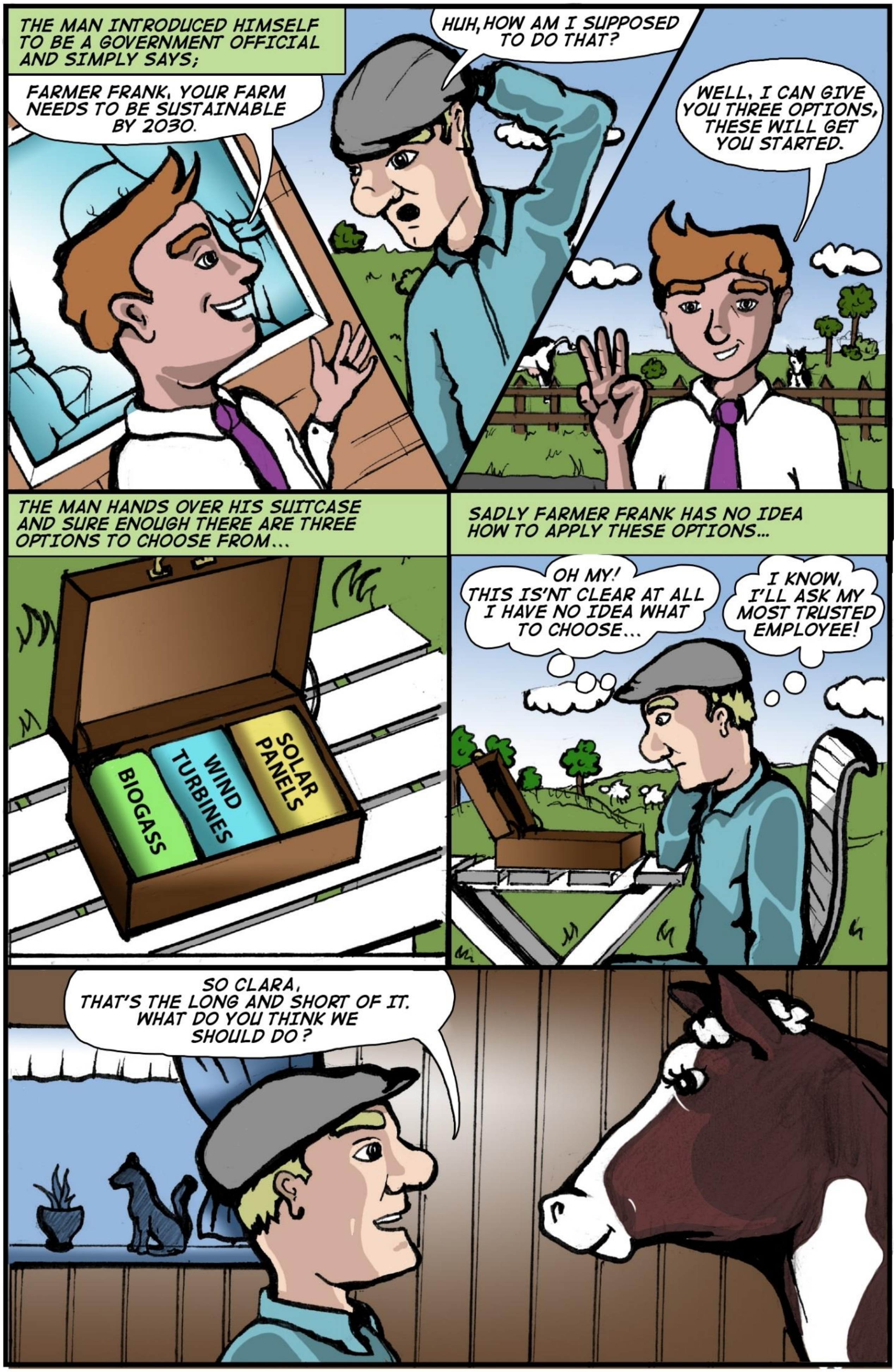
Reflectie: Ontwikkeling en mogelijk gebruik van de nieuwe methode

De huidige veronderstelling dat hernieuwbare bronnen zoals biomassa, zon of wind ook duurzaam zijn, wat gelijk staat aan geen broeikasgasemissies of milieu-impact, kan en zal wijzen op een verkeerde prikkel voor een duurzaam systeem. Kijkend vanuit dit perspectief wordt het hoofddoel, namelijk reductie van broeikasgasemissies, mogelijk niet bereikt. Om een duurzaam systeem te bereiken, moeten regelgeving en subsidiëring voor REPPs gelijke waarden geven aan energie-efficiëntie, emissies en milieu-impact als aan economische aspecten om de duurzame energieproductie te bevorderen. Op deze manier is het mogelijk om te werken aan een duurzame toekomst in plaats van simpelweg te werken aan een hernieuwbare toekomst. Daarbinnen moet regulering geen vooraf bepaalde beslissingen nemen over welke bronnen duurzaam zijn. Dit ook, omdat elke REPP een andere milieu-impact heeft, gebaseerd op de factoren van duurzaamheid die in dit proefschrift worden besproken (zie hoofdstuk 8). Binnen deze kaders is het van belang dat de duurzaamheid van REPPs duidelijk en transparant gemeten kunnen worden, zodat er goed geïnformeerde keuzes gemaakt kunnen worden.

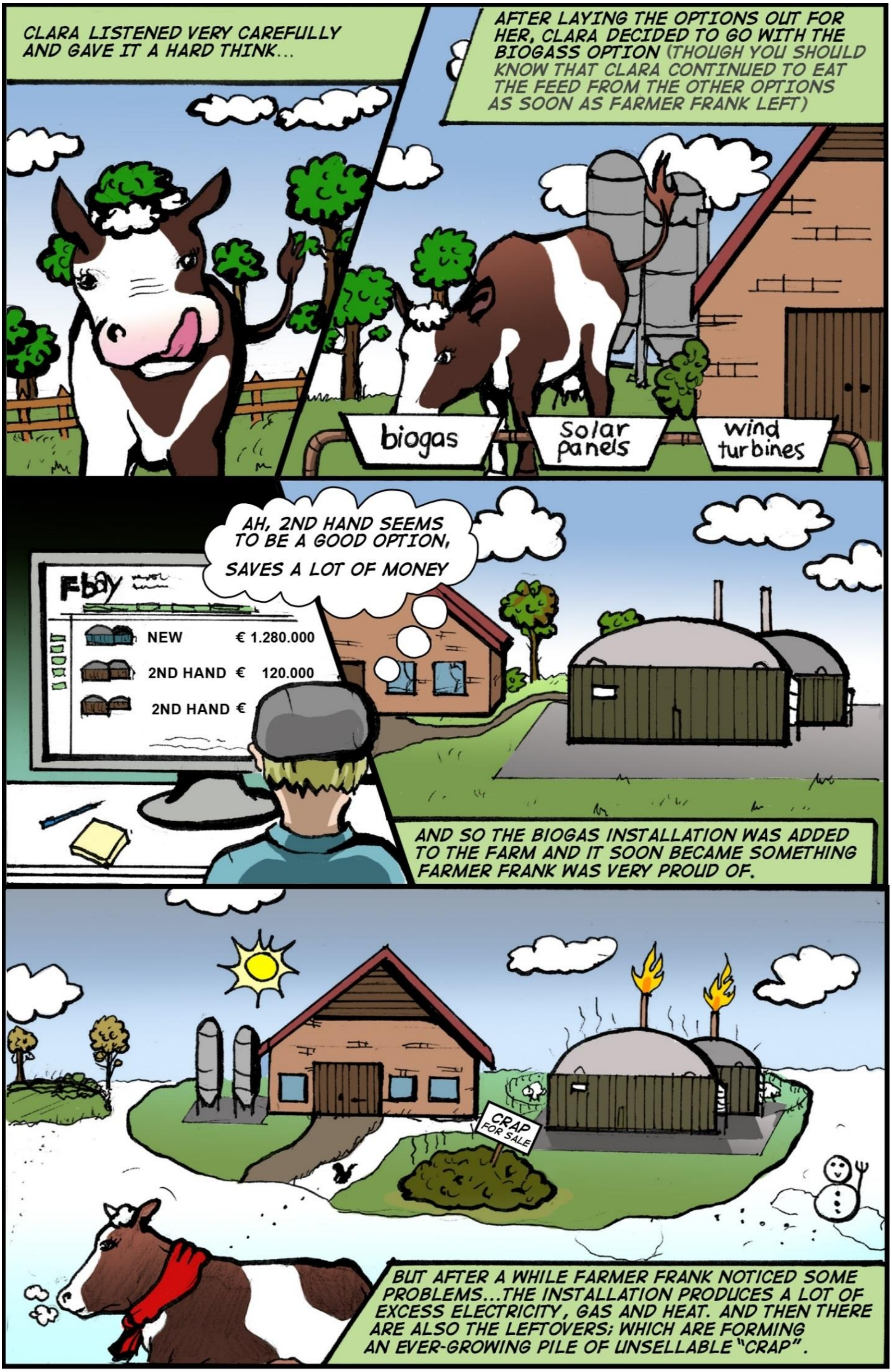
De versnelling van de integratie van hernieuwbare energie en de overgang naar een duurzame circulaire economie is ook grotendeels een sociaal proces. Hierbij hebben stakeholders de behoefte om bewust, correct en transparant geïnformeerd en betrokken te worden bij het proces. Om dat te bereiken is het leveren van kennis alleen niet voldoende. Stakeholders moeten de urgentie begrijpen en, belangrijker nog, deelnemen aan het ontwerp- en implementatieproces van hernieuwbare technologieën. REPPs zullen in veel opzichten een significante invloed hebben op hun omgeving. Daarom moet er voor een toekomstige, duurzame circulaire economie een multi-perspectief en multi-stakeholdersbenadering worden geïnitieerd om zo benadeling of onredelijke bevoordeling van individuele belanghebbenden te voorkomen. Verder is het van belang om ook de discussie over de energietransitie duurzaam te maken. Dit omdat de levensstijl die vandaag wordt geleefd (consumptiegedrag) en de beslissingen die morgen worden genomen nog vele jaren zullen na-echoën en daarom ook grote van invloed zijn op de volgende generaties. Het erkennen van het belang van de belanghebbenden binnen het concept van duurzaamheid en het informeren van deze belanghebbenden met transparante en duidelijke informatie kan helpen bij het voeren van goede discussies, het nemen van goede beslissingen en het vormen van goed beleid. Van belang is dat de juiste informatie over de duurzaamheid, maar ook over de geografische plaatsing op het juiste moment in de discussie wordt aangereikt aan de stakeholders. Dat kan uiteindelijk de integratie van REPPs en daarmee de overgang naar een duurzame circulaire samenleving versnellen.

Elkington en PESTEL bevestigen beide de aanwezigheid aan van meerdere hoofdelementen (of belanghebbenden) binnen duurzaamheid. De nieuwe methode die is beschreven in dit onderzoek is een combinatie van de bestaande benaderingen en methoden die de Triple Bottom Line, PESTEL, MEFA en aLCA samenbrengen om de duurzaamheid van REPPs te meten. De combinatie van de bovengenoemde onafhankelijke methoden stelt de nieuwe benadering in staat om te werken met een multi-perspectiefbenadering die elk specifiek element kwantificeert. De aanpak die in dit proefschrift is ontwikkeld in combinatie met de suggesties voor het uiten van balans en mensen (zie hoofdstuk 8) levert een waardevolle en stevige basis voor het evalueren van de duurzaamheid van REPPs en het communiceren van de resultaten aan belangrijke stakeholders in het besluitvormingsproces. Tot slot: Laten we weloverwogen beslissingen nemen over de duurzaamheid van ons gemeenschappelijke huis om onze toekomst en die van vele generaties te beschermen.

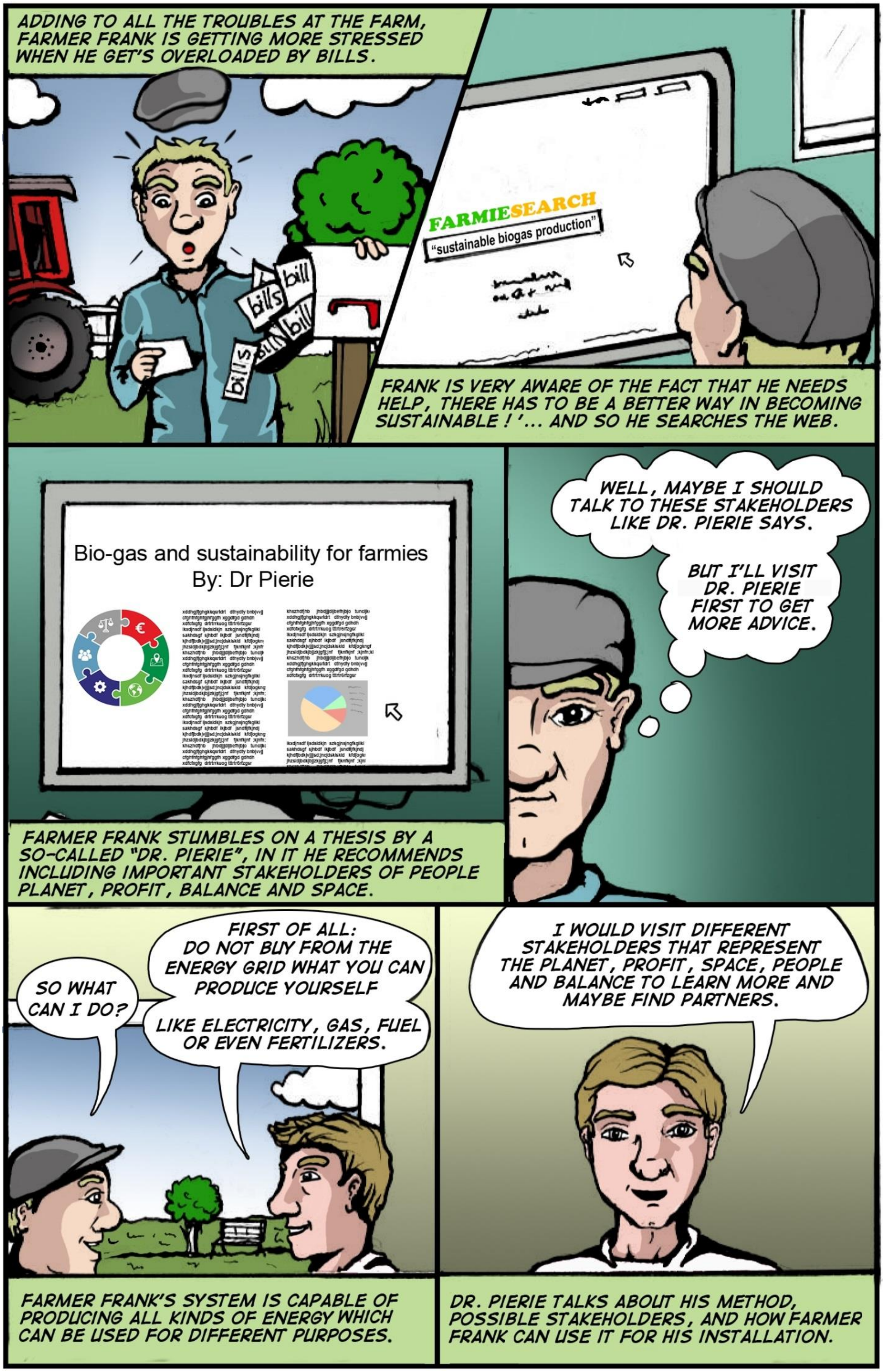

THE ADVENTURES OF
FARMER FRANK
IN THIS SPECIAL EDITION:
FARMER FRANK GOES SUSTAINABLE
FARMER FRANK LEARNS ABOUT NEW GOVERNMENT PLANS FOR THE FUTURE AND HE DECIDES TO MAKE SOME CHANGES ON HIS FARM. BUT HE SOON LEARNS THAT GOING SUSTAINABLE IS NOT AS EASY AS HE WAS MADE TO BELIEVE... WILL HE FIND HELP BEFORE HIS FARM REACHES BOILING POINT?
SO READ ON AND JOIN THE ADVENTURE IN MAKING FARMER FRANK'S FARM SUSTAINABLE BY USING ANAEROBIC DIGESTION OR BIO-ENERGY FOR SHORT; A TECHNOLOGY THAT PRODUCES A FLAMMABLE GAS FROM BIOLOGICAL MATERIALS LIKE MANURE AND GRASS.
IT'S AWESOME!
ON A SUNNY FRIDAY MORNING FRANK TOOK HIS DOG FOR A WALK TO TAKE A MUCH NEEDED REST. ON THE WAY BACK HOME, HE LOOKS TOWARDS THE FARM AND SEES A MAN IN A SUIT HOLDING A BRIEFCASE COMING TOWARDS HIM.
"THIS MAN CAN'T POSSIBLE BE HERE TO VISIT ME" FRANK THINKS TO HIMSELF.
BUT THEN THE MAN STARTS WAVING AND FRANK DECIDES TO ASK THE MAN IF HE NEEDS ANY HELP.

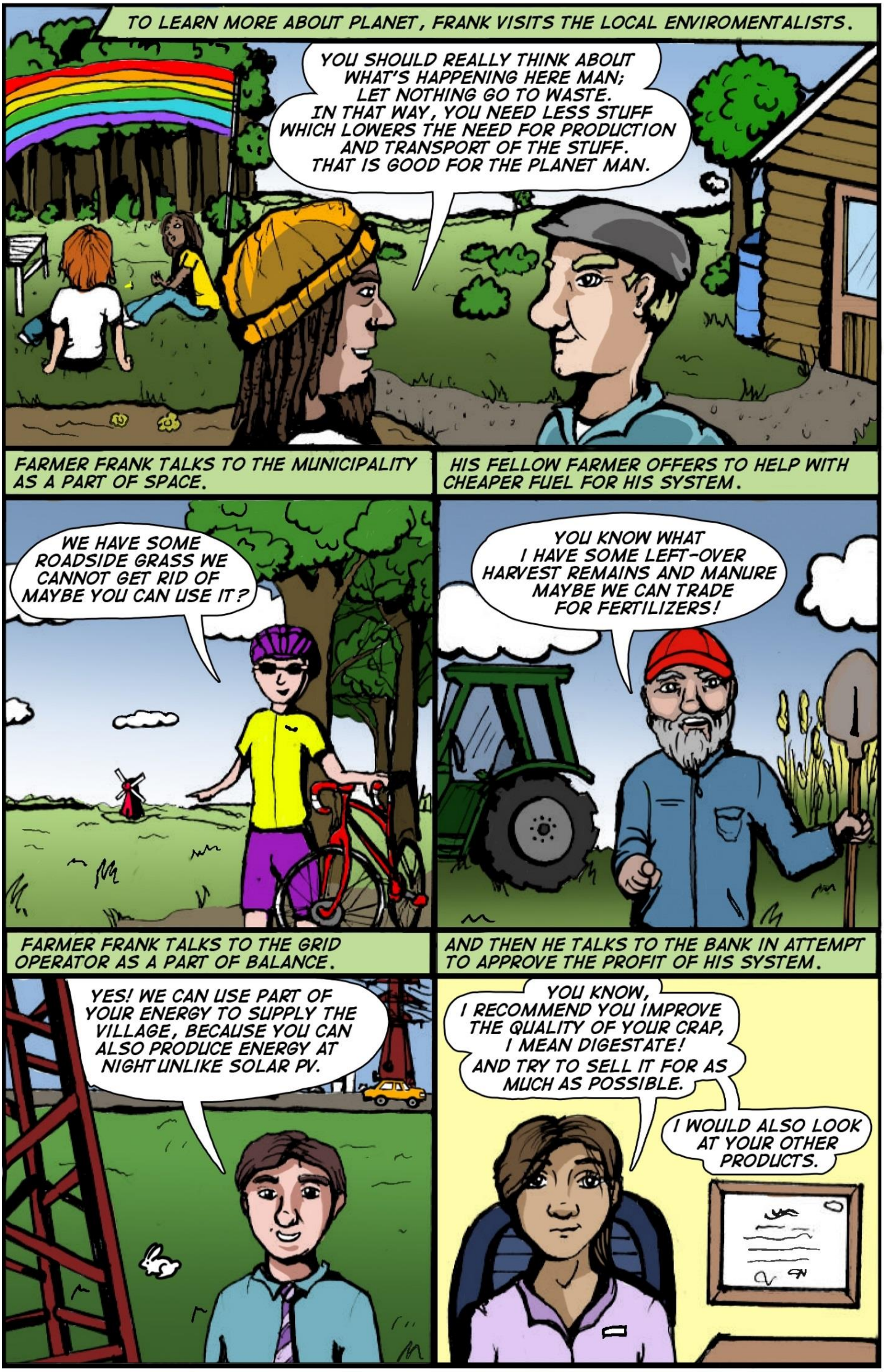


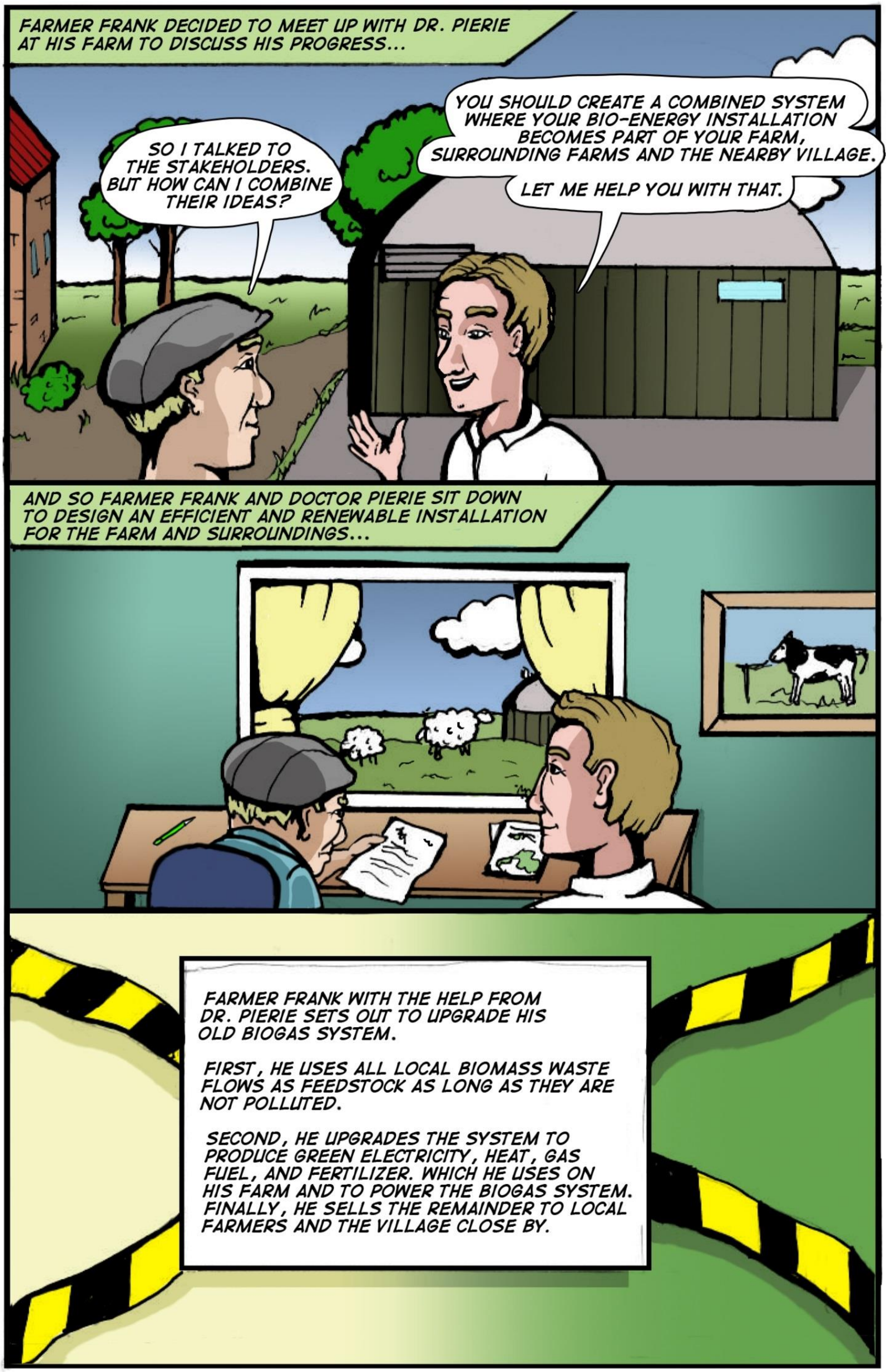
FARMER FRANK



CLARA LISTENED VERY CAREFULLY AND GAVE IT A HARD THINK...
AFTER LAYING THE OPTIONS OUT FOR HER, CLARA DECIDED TO GO WITH THE BIOGASS OPTION (THOUGH YOU SHOULD KNOW THAT CLARA CONTINUED TO EAT THE FEED FROM THE OTHER OPTIONS AS SOON AS FARMER FRANK LEFT)
biogas
solar panels
wind turbines
AH, 2ND HAND SEEMS TO BE A GOOD OPTION,
SAVES A LOT OF MONEY
Fbay
NEW € 1.280.000
2ND HAND € 120.000
2ND HAND €
AND SO THE BIOGAS INSTALLATION WAS ADDED TO THE FARM AND IT SOON BECAME SOMETHING FARMER FRANK WAS VERY PROUD OF.
CRAP FOR SALE
BUT AFTER A WHILE FARMER FRANK NOTICED SOME PROBLEMS...THE INSTALLATION PRODUCES A LOT OF EXCESS ELECTRICITY, GAS AND HEAT. AND THEN THERE ARE ALSO THE LEFTOVERS; WHICH ARE FORMING AN EVER-GROWING PILE OF UNSELLABLE "CRAP".


ADDING TO ALL THE TROUBLES AT THE FARM, FARMER FRANK IS GETTING MORE STRESSED WHEN HE GET'S OVERLOADED BY BILLS.
bill
bills
bill
bills
bill
FARMIESEARCH
"sustainable biogas production"
FRANK IS VERY AWARE OF THE FACT THAT HE NEEDS HELP, THERE HAS TO BE A BETTER WAY IN BECOMING SUSTAINABLE ! '... AND SO HE SEARCHES THE WEB.
Bio-gas and sustainability for farmies
By: Dr Pierie
FARMER FRANK STUMBLES ON A THESIS BY A SO-CALLED "DR. PIERIE", IN IT HE RECOMMENDS INCLUDING IMPORTANT STAKEHOLDERS OF PEOPLE PLANET, PROFIT, BALANCE AND SPACE.
WELL, MAYBE I SHOULD TALK TO THESE STAKEHOLDERS LIKE DR. PIERIE SAYS.
BUT I'LL VISIT DR. PIERIE FIRST TO GET MORE ADVICE.
SO WHAT CAN I DO?
FIRST OF ALL: DO NOT BUY FROM THE ENERGY GRID WHAT YOU CAN PRODUCE YOURSELF
LIKE ELECTRICITY, GAS, FUEL OR EVEN FERTILIZERS.
FARMER FRANK'S SYSTEM IS CAPABLE OF PRODUCING ALL KINDS OF ENERGY WHICH CAN BE USED FOR DIFFERENT PURPOSES.
I WOULD VISIT DIFFERENT STAKEHOLDERS THAT REPRESENT THE PLANET, PROFIT, SPACE, PEOPLE AND BALANCE TO LEARN MORE AND MAYBE FIND PARTNERS.
DR. PIERIE TALKS ABOUT HIS METHOD, POSSIBLE STAKEHOLDERS, AND HOW FARMER FRANK CAN USE IT FOR HIS INSTALLATION.


TO LEARN MORE ABOUT PLANET, FRANK VISITS THE LOCAL ENVIROMENTALISTS.
YOU SHOULD REALLY THINK ABOUT WHAT'S HAPPENING HERE MAN; LET NOTHING GO TO WASTE. IN THAT WAY, YOU NEED LESS STUFF WHICH LOWERS THE NEED FOR PRODUCTION AND TRANSPORT OF THE STUFF. THAT IS GOOD FOR THE PLANET MAN.
FARMER FRANK TALKS TO THE MUNICIPALITY AS A PART OF SPACE.
WE HAVE SOME ROADSIDE GRASS WE CANNOT GET RID OF MAYBE YOU CAN USE IT?
HIS FELLOW FARMER OFFERS TO HELP WITH CHEAPER FUEL FOR HIS SYSTEM.
YOU KNOW WHAT I HAVE SOME LEFT-OVER HARVEST REMAINS AND MANURE MAYBE WE CAN TRADE FOR FERTILIZERS!
FARMER FRANK TALKS TO THE GRID OPERATOR AS A PART OF BALANCE.
YES! WE CAN USE PART OF YOUR ENERGY TO SUPPLY THE VILLAGE, BECAUSE YOU CAN ALSO PRODUCE ENERGY AT NIGHT UNLIKE SOLAR PV.
AND THEN HE TALKS TO THE BANK IN ATTEMPT TO APPROVE THE PROFIT OF HIS SYSTEM.
YOU KNOW, I RECOMMEND YOU IMPROVE THE QUALITY OF YOUR CRAP, I MEAN DIGESTATE! AND TRY TO SELL IT FOR AS MUCH AS POSSIBLE.
I WOULD ALSO LOOK AT YOUR OTHER PRODUCTS.


FARMER FRANK DECIDED TO MEET UP WITH DR. PIERIE AT HIS FARM TO DISCUSS HIS PROGRESS...
SO I TALKED TO THE STAKEHOLDERS. BUT HOW CAN I COMBINE THEIR IDEAS?
YOU SHOULD CREATE A COMBINED SYSTEM WHERE YOUR BIO-ENERGY INSTALLATION BECOMES PART OF YOUR FARM, SURROUNDING FARMS AND THE NEARBY VILLAGE.
LET ME HELP YOU WITH THAT.
AND SO FARMER FRANK AND DOCTOR PIERIE SIT DOWN TO DESIGN AN EFFICIENT AND RENEWABLE INSTALLATION FOR THE FARM AND SURROUNDINGS...
FARMER FRANK WITH THE HELP FROM DR. PIERIE SETS OUT TO UPGRADE HIS OLD BIOGAS SYSTEM.
FIRST, HE USES ALL LOCAL BIOMASS WASTE FLOWS AS FEEDSTOCK AS LONG AS THEY ARE NOT POLLUTED.
SECOND, HE UPGRADES THE SYSTEM TO PRODUCE GREEN ELECTRICITY, HEAT, GAS FUEL, AND FERTILIZER. WHICH HE USES ON HIS FARM AND TO POWER THE BIOGAS SYSTEM. FINALLY, HE SELLS THE REMAINDER TO LOCAL FARMERS AND THE VILLAGE CLOSE BY.

AFTER ANOTHER FEW WEEKS OF OPTIMIZATION THE FARM TURNED OUT MUCH BETTER THEN FARMER FRANK COULD HOPE FOR.

THE GOVERNMENT IS HAPPY,
HIS FELLOW FARMERS ARE HAPPY,
AND HIS NEIGHBORS BENEFIT FROM HIS HEAT, GAS AND ELECTRICITY.

NOW HE IS THE ONE SENDING BILLS.
FARMER FRANK COULDN'T BE MORE PROUD.

DRAWING: LEONIE BELT
COLOUR: MARCEL VAN DER SLEEN
WRITTEN BY: FRANK PIERIE

ARTWORK

Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

D I P L O M A

For specialised PhD training

The Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment
(SENSE) declares that

Frank Pierie

born on 20 August 1982 in Groningen, The Netherlands

has successfully fulfilled all requirements of the
Educational Programme of SENSE.

Groningen, 5 October 2018

On behalf of the SENSE board — Prof. dr. Huub Rijnaarts

the SENSE Director of Education — Dr. Ad van Dommelen

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

The SENSE Research School declares that **Frank Pierie** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 48.7 EC, including the following activities:

Selection of SENSE PhD Courses

- Environmental research in context (2011)
- Research in context activity: 'Setting up alumni network SENSE' (2013)
- SENSE writing week (2013)
- Grasping Sustainability (2013)

Selection of other PhD and Advanced MSc Courses

- Summer school RUG EIRSS, RuG Groningen (2012)
- Writing skills English, Hanze University of Applied Sciences(2012)
- Summer school SENSE, Utrecht University (2013)

Selection of Management and Didactic Skills Training

- Lecturer of various courses at Hanze University of Applied Sciences (2012-2018) on topics such as Sustainability, Biogas, Energy Systems, Global Change and others
- Presentation given at the master class 'Future Energy infrastructure' at the Energy Delta Convention, Groningen (2012)
- Organizing workshops and keynote presentation SENSE Summer School (2013)
- Organizing and maintaining journal club at Hanze University of Applied Sciences (2013-2015)
- Developing and teaching MSc course 'Models & Scenarios for Strategic Decision Making' for the European Master program 'Sustainable Energy System Management'(2014-2018)

Selection of Oral Presentations

- *An integrated approach for a dynamic energy and environmental system analysis of biogas production pathways.* Biogas Science, 26-30 October 2014, Vienna, Austria
- *Young professionals and energy transition*. K4I, 17-20 November 2014, Brussels, Belgium
- *Optimizing the sustainability of Biogas production pathways.* Flexigas symposium, 8 December 2014, Groningen, The Netherlands
- *Spatial and environmental assessment of energy potentials for Anaerobic Digestion production systems applied to the Netherlands.* European Biomass Conference and Exhibition (EUBC&E), 6-9 June 2016, Amsterdam, the Netherlands

SENSE Coordinator PhD Education

Dr. Peter Vermeulen

SCIENTIFIC CONTRIBUTIONS

ARTICLES

1) Pierie F, van Someren CEJ, Benders RMJ, Bekkering J, van Gemert WJT, Moll HC. Environmental and energy system analysis of bio-methane production pathways: A comparison between feedstocks and process optimizations. Appl Energy 2015; 160: 456-66.

2) Pierie F, Bekkering J, Benders RMJ, van Gemert WJT, Moll HC. A new approach for measuring the environmental sustainability of renewable energy production systems: Focused on the modelling of green gas production pathways. Appl Energy 2016; 162: 131-8.

3) Pierie F, Benders RMJ, Bekkering J, van Gemert WJT, Moll HC. Lessons from spatial and environmental assessment of energy potentials for Anaerobic Digestion production systems applied to the Netherlands. Appl Energy 2016; 176: 233-44.

4) Pierie F, Dsouza A, van Someren EC, Benders MR, van Gemert JW, Moll CH. Improving the Sustainability of Farming Practices through the Use of a Symbiotic Approach for Anaerobic Digestion and Digestate Processing. Resources 2017; 6.

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1) Pierie F, van Someren CEJ, Bekkering J, Benders RMJ, van Gemert WJT, Moll HC. The Development, Validation and Initial Results of an Integrated Model for Determining the Environmental Sustainability of Biogas Production Pathways 2016; 24th European Biomass Conference and Exhibition: 1411,1411 - 1421.

2) Rajagopal M, Wijbrandi W, Pierie F. Flexible Biogas Chain Simulator 2013; WRTEC.

PRESENTATIONS AT INTERNATIONAL CONFERENCES

1) An integrated approach for a dynamic energy and environmental system analysis of biogas production pathways. Biogas Science, 26-30 October 2014, Vienna, Austria

2) Optimizing the sustainability of Biogas production pathways. Flexigas symposium, 08 December 2014, Groningen, The Netherlands

3) Spatial and environmental assessment of energy potentials for Anaerobic Digestion production systems applied to the Netherlands. European Biomass Conference and Exhibition (EUBC&E), 06-09 June 2016, Amsterdam, the Netherlands

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Frank Pierie

Optimizing the sustainability of complex (renewable) energy production pathways:

Applied to farm scale biogas production pathways

To avoid energy scarcity as well as climate change, a transition towards a sustainable society must be initiated. Within this context, governmental bodies and/or companies often note sustainability as an end goal, for instance as a green circular economy. However, if sustainability cannot be clearly defined as an end goal or measured uniformly and transparently, then the direction and progress towards this goal can only be roughly followed. A clear understanding of and a transparent, uniform measuring technique for sustainability are hence required for sustainable and circular (renewable) energy production pathways (REPPs), as society is asking for an integrated and understandable overview of the decision-making and planning process towards a future sustainable energy system. Therefore, within this dissertation, a new approach is proposed for measuring and optimizing the sustainability of REPPs; it is useful for the analysis, comparison, and optimization of REPP systems on all elements of sustainability. The new approach is applied and tested on a case based on farm-scale, anaerobic digestion (AD), biogas production pathways.