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Published in:
Applied Energy

DOI:
[10.1016/j.apenergy.2015.10.037](https://doi.org/10.1016/j.apenergy.2015.10.037)

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Pierie, F., Bekkering, J., Benders, R. M. J., van Gemert, W. J. T., & Moll, H. C. (2016). A new approach for measuring the environmental sustainability of renewable energy production systems: Focused on the modelling of green gas production pathways. *Applied Energy*, 162, 131-138.
<https://doi.org/10.1016/j.apenergy.2015.10.037>

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

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HIGHLIGHTS

- A new approach for, an understandable and comparable Life Cycle Analysis.
- Included in the approach a method for handling complexity and integrating temporal dynamics.
- Sustainability expressed in three clear and comparable indicators.
- The new approach structures and clarifies the Life Cycle Inventory and Analysis process.

ARTICLE INFO

Article history:

Received 4 June 2015

Received in revised form 11 September 2015

Accepted 5 October 2015

Available online 11 November 2015

Keywords:

Biogas

Green gas

Bio-methane

Life Cycle Analysis (LCA)

Environmental impact

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.

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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

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Nomenclature

AD	anaerobic digestion	(P)EROI	Process Energy Returned On Invested
CHP	combined heat and power	GWP100	Global Warming Potential 100 year scale
oDM	organic dry matter	Pt	Environmental impact in EcoPoint
FM	fresh matter	LCI	Life Cycle Inventory
GJ	giga joule	LCA	Life Cycle Analysis
MJ	mega joule	aLCA	Attributed Life Cycle Analysis
Mg	mega gram (equivalent to metric tonne)	MFA	Material Flow Analysis
PED	Primary Energy Demand	MEFA	Material and Energy Flow Analysis
Nm ³	normal cubic meter	kgCO ₂ eq	kilograms of carbon dioxide equivalent

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 [1]. 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 [2–4]. 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 [5]. 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 [6].

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 [7]. Results of these studies indicate either: Energy Input to Output Ratio [7]; Primary Energy Demand (PED) per functional unit [6]; or Primary Energy Input to Output Ratio (PEIO) [8]. The focus of the LCA approach lies in the analysis of environmental impacts of a product, a process, or a system [6]. 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 [9]. 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 [10,11]. In measuring the environmental sustainability of biogas production systems the amount and types of indicators differ between studies, ranging from on average five [5,6,12–15], to ten [16,17], up to eighteen [9,11]. 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 [10]. Studies also

tend to focus on specific fields within the biogas production pathway, e.g. feedstocks, specific biogas technologies or specific biogas end uses [16]. This high level of detail and wide variability in both scope and indicators makes the interpretation and comparison of the various results difficult [16]. 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 [18–20]. 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 [1,20,21].

Within this context, what is lacking is a systematic method for generating and identifying sustainable solutions [22–24]. The transition towards renewable energy requires a clear and understandable insight into the environmental consequences of producing renewable energy [5,23]. 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 [25,26]. Therefore, we address this issue as part of the Flexigas project [27]. 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. 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

Fig. 1. The main modules and sub-modules used in an example green gas production pathway.

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. [28], (Fig. 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 [29]. 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” [30]. 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.

2.1. 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. 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. 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. 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.

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) [31]), 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” [7]. 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 modelling (or planning) process.

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 [32]. 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 [33,34]. 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 [1]. 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 [35] and the transition towards renewable energy production could increase the amount of intermittent production present in the decentralized smart energy system [25,26].

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.

2.3. The sub-module

Within each sub-module, one main physical process of the green gas production pathway is described (Fig. 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 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), level one and level two will be determined through the use of the MEFA methodology (explained in Sections 2.3.1 and 2.3.2), where level three and four will use the aLCA methodology (explained in Sections 2.3.3 and 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 Sections 2.3.1–2.3.4 the four levels in the sub-module will be discussed more explicitly using the structure depicted in Fig. 2.

2.3.1. Level one: Primary flows

Within the metabolism concept primary mass flows are defined as raw materials (e.g., biomass, biogas, di-gestate 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) [36], 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 [29].”

The MEFA framework is used for determining the primary flows and the direct energy and material flows described in Section 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 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. 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,

Fig. 2. Structure of a single sub-module based on dynamic MFA/MEFA/LCA.

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 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.

(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. 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 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. 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.

2.3.2. 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 [29]. The MEFA concept is integrated into the sub-module using the following factors (the letters in Fig. 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).

(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 3). The direct impacts are mostly calculated using the Attributed Life Cycle Analysis (aLCA) method, which will be explained in the following section.

(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 3).

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:

Table 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	[38–40]

Table 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	[41]
Direct carbon footprint	3.2820	kgCO ₂ eq/kg	[41]
Direct environmental impact	0.0397	Pt/kg	[41]

Table 1

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

Biogas potential manure	Nm ³ /Mg oDM	Source
Biogas potential	300.00	[28]
Methane content (CH ₄)	180.00	[28]
Nitrogen (N ₂)	6.00	[37]
Oxygen (O ₂)	3.00	[37]
Ammonia (NH ₃)	0.30	[37]
Hydrogen sulphide (H ₂ S)	0.03	[37]
Carbon dioxide (CO ₂) (Remainder)	110.67	[37]

“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” [6].

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 coincide with the letters in the explanation).

(L) Direct functional flows: The main inputs into the LCA level (Fig. 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 dataset 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 4 are consumed and emitted for producing and transporting 1 kg of diesel (direct functional unit).

(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 4).

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 2.3.3). 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 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 5).

Table 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	[42]
Indirect carbon footprint	0.6000	kgCO ₂ eq/kg	[42]
Indirect environmental impact	0.1800	Pt/kg	[42]

Table 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	[42]
Embodied carbon footprint	518.00	kgCO ₂ eq/kW	[42]
Embodied environmental impact	150.00	Pt/kW	[42]

^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 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.

3. Environmental impact indicators

The resulting environmental sustainability will be expressed in three known indicators which correlate with the definition of “strong sustainability” [43], wherein environmental quality precedes social prosperity and then economic prosperity [43,44]. 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 ecosystems, nature, and human health. The three units will be expressed per Gigajoule of energy produced (e.g. kgCO₂eq/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.

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 [45]). To determine the (P)EROI factor for a green gas production pathway, both the process energy invested and the energy returned must 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 [45]. 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, [46]).

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 [47–49]. However, there are many different types of greenhouse gases 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 [47]. The carbon footprint is expressed in carbon dioxide equivalents (CO₂eq) using the relevant 100-year global warming potential scale or GWP100 [47]. 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.

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 [50]. 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 [41]. 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 [41]."

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.

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.

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 green gas production pathway. 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 [25,26]. 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 modelling 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.

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