The Nordic biogas model: Conceptualization, societal effects, and policy recommendations

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ABSTRACT

Because biogas systems may take many forms, utilizing different feedstock and finding different end uses for the biogas, it becomes difficult to produce explanations, inferences, and conclusions about biogas systems in general, which is why concepts for specific types of biogas systems are needed. This paper introduces the concept of the Nordic biogas model, an urban waste-based biogas system where biogas is upgraded to biomethane and used as transport fuel and the digestate applied as biofertilizer on farmland. The Nordic biogas model has three functions, namely, renewable transport fuel production, waste management service, and biofertilizer production that all bring secondary and tertiary positive societal effects, such as reduced climate gas emissions and productivity benefits to industry. This has implications for environmental and sustainability assessment of the Nordic biogas model as the multi-functionality must be considered when choosing reference scenarios, system boundary, and indicators to use within assessments. Finally, the paper discusses policy recommendations for supporting the implementation of the Nordic biogas model. Such policy should respect the multi-functionality of the Nordic biogas model by creating coherent policy mixes that neither neglect nor over-compensate for the multi-functionality of the Nordic biogas model.

1. Introduction

Cities are facing increasing environmental pressure in the form of air pollution, climate change, and waste build-up. Simultaneously, rural areas are facing their own environmental pressures, such as eutrophication, soil-carbon loss, and an import dependency on mineral fertilizer and protein fodder. Partly, this can be linked to the linear flow of resources from rural areas to cities where food is predominantly produced in rural areas and consumed in cities where it eventually becomes solid waste and sewage [46]. The nutrients extracted from the soil to produce the food is largely lost in this system and the waste produced may create environmental issues for the city unless it is well-managed [47]. The loss of nutrients in the system also contributes to the requirement of substantial imports of nutrients to many agricultural areas around the world. Biogas systems may play an important part in reconnecting this potentially circular flow through their ability to produce biofertilizer from organic waste, which enables nutrients to return to the soil [1]. Furthermore, biogas systems may contribute toward overcoming other urban environmental issues by taking care of organic waste while producing renewable fuel [85], which may reduce air pollutants [45] and climate gas emissions when compared to fossil fuels [20].

However, not all types of biogas systems bring these positive effects as biogas systems may take many forms; for example, one may use different kinds of substrates (see, e.g., [8]), utilize different digestion technologies (see, e.g., [38]), and find different kind of end uses for the biogas (see, e.g., [21,78]). This multiplicity means that it is very difficult to infer general conclusions that hold for all types of biogas systems. To support such general inferences there is a need for precise and well-defined concepts that enables concise language use when discussing different types of biogas systems and their respective drawbacks and benefits. Furthermore, precisely defined concepts are an important part of explaining the context of research results, which helps with understanding the transferability of such results. In addition, they make policy discussions more efficient and could enable more direct policy interventions. One example of a biogas-specific concept is the Biogasdoneright™ concept, a concept used for biogas systems that
Similarly, this paper seeks to develop a concept for a specific biogas system, this system, unlike the Biogasdoneright™ system, represents a type of biogas system that developed around urban waste management in the Nordic countries with the first examples occurring in the 1990s (see, e.g., [15,72,86]).

This biogas system is referred to as the Nordic biogas model (NBM) and it is characterized by three characteristics: First, the substrate is typically classified as an urban waste, where common substrates include household food waste, wastewater, sewage sludge, and food industrial waste. Second, the biogas is upgraded to biomethane and used for transportation purposes. Third, the digestate is applied to farmlands as biofertilizer. These three characteristics of the NBM means that it is inherently multi-functional, enabling effective waste management, generating renewable transportation fuel, and producing renewable biofertilizer. The model thereby provides three primary societal services, or functions, which generate positive secondary and tertiary societal effects. Examples of these indirect effects are reduced greenhouse gas emissions [45], reduced need for fossil fuels [85], the possibility to recycle nutrients [24,84], and productivity benefits to industries [40]. However, the multi-functionality is not only an advantage of the NBM, it may also complicate its identity. In a society with a fragmented governance and policy structure, people may be looking for a waste treatment option, a fossil-free fuel, or a renewable organic fertilizer separately, but few are searching for solutions to these three challenges at the same time [37]. Furthermore, in a narrow environmental assessment, the multi-functionality is typically missed, and a biomethane transport fuel may perform no better than other renewable fuel alternatives (see, e.g., [81]). Moreover, organic waste fractions, which are the substrates used in the NBM, are often quite a small fraction of a country’s biomass reserve and throughput and may be an even smaller part of their energy potential (see, e.g., [87]). This means that in top-down energy potential studies, the NBM may appear insignificant from an energy perspective (see, e.g., [66]); however, this leaves out other sustainability-related aspects and neglects future potential that may come out of further research and innovation.

Biogas systems of the NBM kind represents a major part of biogas production in especially Sweden and Norway and while they are not the most prominent type of biogas system in other Nordic countries, they are still more common in those countries than in the rest of the world (although there are examples of it in other parts of the world as well), which is why it is given this particular name. The Nordic label, however, does not mean that this is a concept to be used to describe biogas systems or biogas development in the Nordic countries (as the biogas landscape of the Nordic countries will, and is, developing and changing), it, as previously stated, denotes a biogas system that utilizes urban organic waste to produce biofertilizer and biomethane for transport. Choosing the Nordic label is simply following the common naming convention of naming something after the geographical area where it was developed.

While examples of the NBM are common in the Nordic countries, it is a biogas system with global relevance. In theory, it should be applicable everywhere there is: (i) significant amounts of organic waste, (ii) a need for transportation, and (iii) surrounding farmlands (or other areas able to utilize plant nutrients). These three aspects hold true for almost every city in the world. However, there are barriers to the diffusion of the NBM, which are, for example, tied to lack of knowledge about the functions and societal effects of the NBM [63] and policy incoherence [52]. Therefore, the aim of this paper is to describe how the multi-functionality of the NBM impacts how the societal effects of the NBM should be assessed and to discuss how policy aimed at supporting the implementation of the NBM can be constructed considering the NBM’s wide embeddedness in different policy areas. In doing this, we first present the societal functions and indirect effects of the NBM from a general perspective relevant to a global audience (Section 3). This lays the foundation for a deliberation on the assessment of the societal effects of the NBM’s three functions through system assessment in local, case specific, contexts (Section 4), which leads to a discussion on how policy can be designed that considers the beneficial societal effects of the NBM and its wide embeddedness in different sectors (Section 5).

2. Method

This paper is a synthesis of results and conclusions from research studies, conferences, and seminars on real-world examples of the NBM. Included within these are interviews, case studies, and meetings where various aspects about the NBM has been discussed. This research has been done within the context of the Swedish Biogas Research Center (BRC), which is a competence centre established for developing knowledge on resource-efficient biogas systems and their successful implementation [7]. Research is performed in a triple-helix model where academia, industry, and public organisations are involved and the BRC involves five department at two Swedish Universities (Linköping University and the Swedish University of Agricultural Sciences) and around 40 partner and member organisations that are actively engaged in co-creating knowledge on various biogas-related topics [6]. The environmental and societal effects of biogas systems and how policy could support the implementation of resource-efficient biogas systems have been studied within the BRC since its inception in 2012. From this library of works, knowledge was gathered and synthesized regarding the NBM’s multiple functions and societal effects and how policies can be designed to facilitate the development of real-world examples of the NBM. A short-list of this library of works as well as seminars and conferences where the authors of this paper has developed and discussed the NBM concept can be found in Appendix A. It is from these studies, conference, and seminars that this paper has sprung.

Throughout these activities, many researchers and societal actors within the BRC have observed a need to develop concepts and concise language to differentiate different types of biogas systems from each other because this enables inferences and explanations about particular biogas systems, which simplifies communication and dissemination of information. As one of the foremost arenas for research on real world examples of the NBM, we believe that our experience and the knowledge we have helped create within the BRC puts us in a unique position to define such a concept for biogas systems that utilize urban waste as feedstock and produce transport fuel and biofertilizer. Furthermore, to show how such a concept enables higher level discussions and inferences about the NBM and allows the research discussion to move from discussing individual case studies toward a more general and abstract discussion, this paper presents the functions of the NBM and provides insight related to how policy can be formulated to support this type of biogas system.

3. Functions of Nordic biogas models

In anaerobic digestion (AD) organic materials are converted into an energy-rich gas made up of methane, carbon dioxide, and various trace
gases (biogas) while also leaving a nutrient-rich digestate (biofertilizer). This is the core technology of all biogas systems, including the NBM. As previously stated, the NBM provides three functions to society (see Fig. 1) and while each of these functions can be substituted by another solution on a one-to-one basis, it is difficult to find another solution able to provide all services as part of an integrated system. In this section, the individual functions of the NBM are presented and compared to the most common alternatives within each functional area to give some background on the rationale behind the effects associated with each service of the NBM.

### 3.1. Waste management

The NBM can be used for treating both solid organic waste and wastewater. Other solid organic waste options are, for example, landfill, incineration, or composting, while the main other wastewater management option is aerobic digestion. When comparing AD to Landfills, it is important to note that landfills are large contributors of methane leaks while AD systems have potentially much less methane emissions [61]. Moreover, compared to incineration, AD generally has lower acidifying and eutrophying emissions [34]. In addition to these emission factors, another positive of AD is the possibility to recover nutrients, which is not yet possible from landfills or incineration. On the other hand, when compared to composting, AD enables energy recovery, which is not possible for composting solutions.

As a wastewater management option, anaerobic solutions have the same level of purification for oxidizable pollutants, capable of achieving the same levels of chemical oxygen demand (COD) as aerobic wastewater management but the anaerobic option has a lower demand for chemicals and urea, a lower energy need, and less sludge volumes to dispose of [62,64]. The drawback of anaerobic wastewater management is the sensitive microbial community, which is typically more sensitive to disturbances than its aerobic counterparts [80].

### 3.2. Vehicle fuel

In the NBM, the biogas is utilized as a vehicle fuel. To do this the biogas is upgraded (cleaned from CO2 and trace gases). The upgraded biogas is hereafter referred to as biomethane and represents a fossil-free fuel [85], which reduces particle and NOx emissions [14,53,88] as well as engine noise compared to diesel vehicles [76]. Compared to electric vehicles, the main benefit with biomethane vehicles is that they provide a clean and fossil-free fuel alternative without the negative environmental and social impact tied to the rare earth elements and metals contained in the batteries needed for electric mobility (see, e.g., [35,65,71]). Biomethane may also have better climate performance than electric vehicles, depending on how the electricity used for transportation is generated [39]. The volumetric energy density is lower in biomethane than diesel, but by liquefying the gas, the volumetric energy density increases (compared to compressed biomethane) and can even become comparable to diesel, although the liquefied biomethane typically requires larger storage tanks than diesel [18]. Due to the local nature of the NBM, it may also increase the energy security of a region or country, although this is somewhat dependent on the source of the organic matter being digested.

### 3.3. Fertilizer

The fertilizing function is achieved through the use of the digestate, which can replace mineral fertilizers in both industry and farming practices [31]. When used for this application, the digestate is usually referred to as a biofertilizer. Mineral fertilizers are often produced through energy-demanding processes, as is the case for nitrogen [33], or through mining finite resources, as is the case for phosphorous [16]. Biofertilizer application, on the other hand, represents a circular flow of nutrients that can reduce the environmental impact of agricultural practices. In many agricultural areas around the world, mineral fertilizers are imported, meaning that the NBM can enable the (partial) self-sufficiency of nutrients for these regions. Before application, the digestate should go through a quality control where the nutrient content as well as unwanted particles and heavy metals are measured. Depending on incoming substrates to the biogas plant, the digestate can even be approved for organic farming. Biofertilizer usually has a high content of easily available nitrogen [17] and may enhance topsoil management through an increase in soil organic carbon and available plant nutrients [5]. As soils receive a more diverse nutrient composition, they become more resilient to changes in climate [73]; in some cases, biofertilizer can also have an inhibitory effect on some plant pathogens [79]. The possibility to apply biofertilizer can sometimes be constrained depending on whether there are any pollutants in the biofertilizer. This can be a problem for any type of biofertilizer but is especially a common problem for NBM solutions based on wastewater since wastewater often include many substances that may be problematic if they are spread on farmland, such as human pathogens, pharmaceuticals, and heavy metals [12]. Even so, there are technical solutions to remove pollutants and the nutrient recovery from wastewater can be an important contribution to the nutrient balance in many regions of the world [82].

### 3.4. System level effects

The NBM is a local solution that brings local employment and industrial development into urban and rural areas. The NBM can also connect urban and rural areas as the waste (primarily sourced from cities) provides nutrients for farmlands, which in turn provides food for the city. As the NBM often collects substrate from the local area and distributes biofertilizer locally, it is likely that the total need for transportation is reduced compared to importing mineral fertilizers and other biofuel substrates, such as palm oil, wheat, or maize. In addition, the NBM can contribute to several international, national, and regional sustainability goals, such as reducing climate change, recycling nutrients, improving waste management, reducing nutrient leakages, reducing air pollution, and improving energy and food security.
There are also examples of anaerobic digestion increasing the competitiveness of industries that receive a cheaper and safer waste management solution [40].

4. Assessing the Nordic biogas model

This section focuses on how system assessments, such as such as life cycle assessment, cost-benefit analysis, and multi-criteria assessment of the NBM should be performed. With the term “system assessment” we mean methods that aim to assess the societal or environmental (sometimes both) effects of socio-technical systems. The methods employed for this purpose have also been called environmental system analysis tools or sustainability assessment tools [32,69]. The multiple benefits of the NBM presented in Section 3 presents some challenges for this type of assessment since the multiple functions of the NBM require assessments to employ sufficiently broad system boundaries to include all three main functions of the NBM. If one would focus on one of the primary functions of the NBM, that is, either vehicle fuel production, waste management service, or fertilizer production, there is a risk that positive and negative societal and environmental effects tied to the other functionalities are not accounted for. In this section, a few insights about how to perform valid system assessments of the NBM are presented based on the multiple studies that have been done within the BRC (see Appendix A). This is done because environmental or sustainability assessments results are often used to justify policy intervention and technological implementation. Therefore, ensuring that they are correctly performed
becomes of importance to the diffusion of the NBM.

4.1. Reference scenario

The many functions of the NBM present challenges for comparative system assessments since the reference scenario will require substitutes for each function. Normally, when focusing on comparing one function, for example, vehicle fuels, one could imagine comparing different fuel production systems with vehicles running on different fuels (see, e.g., [68]). However, at the system level, one needs to compare the NBM with regard to all its functions, that is, vehicle fuel production, waste management service, and fertilizer production. This means that the comparison may instead become, for example, the NBM compared to gasoline fuel production and use, composting of household waste, aerobic wastewater management, and mineral fertilizer production and use. In Fig. 2, the different functional comparisons and what that means for a system-level comparison are illustrated.

4.2. Life cycle perspective and system boundary

From a life cycle perspective, how and where the different functions are provided throughout the life cycle of the NBM becomes important. To include all functions of the NBM in system assessments, broad system boundaries are needed. Systems may also include substitutions, that is, that other technologies are replaced by the introduction of the NBM, which is included through system expansion. Because system boundaries should be chosen to include all significant parts of a system in regard to the aim of the assessment [50] and will impact the result of any subsequent analysis (see, e.g., [27]), it is of importance to choose a boundary that includes all relevant processes that affect the societal or environmental effect of the NBM. Based on this, this section aims at explaining why certain system boundaries are inadequate or adequate for the assessment of the NBM. This is done through the description and discussion of four different system boundaries that have been used for the assessment of the NBM. These four boundaries are illustrated in Fig. 3.

The first boundary to be discussed is the tank-to-wheel boundary. This boundary includes only impacts generated from the vehicle, such as tail-pipe emissions or noise, and is used, for example, when emission test cycle data is used as the indicator for emissions in assessments. An example of this is the declared carbon emission values of cars sold in the EU. This boundary is not suitable for the environmental or sustainability assessment of the NBM because it excludes emissions generated by the NBM and the reference alternative(s) in other areas of the life cycle (see, e.g., [20;56;57] for an overview of sustainability-related effects). The second boundary is the well-to-tank boundary. In this boundary, the impact generated by the combustion of the biomethane is instead excluded (while production-related impact is included), which means it is not recommended for use in assessments of the NBM because the vehicle impacts are still important to the societal and environmental effects of the NBM. The third boundary shown in Fig. 3 is the well-to-wheel I boundary. In this boundary, the entire life cycle is included; however, it does not include substitution impacts, often because the assessment is focused on a single function. This boundary was used in, for example, the original EU renewable energy directive (RED I) standard for emissions accounting. As discussed in Section 4.1, all three functions of the NBM are needed to accurately describe its system impact, and therefore this boundary is also inadequate. Finally, the well-to-wheel II boundary is the boundary that the authors recommend for use in assessing the NBM, as it includes the impact of the entire life cycle and all three functions of the NBM, enabling a valid assessment. The most prominent use of this type of boundary is when adhering to the ISO standard for life cycle assessments [51], which is why it is typically used in many life cycle assessments being performed. For a life cycle assessment practitioner, this may seem obvious but there are many occurrences where the more narrow system boundaries described above have been applied, which is why this point is underlined here.

To exemplify and illustrate that the inclusion of the three functions of the NBM and their substitution effects have profound importance regarding the analysis of its sustainability effects a simplified example of the climate performance of an NBM system is shown in Fig. 4. The life cycle climate performance of an NBM system may, for example, include (i) emissions related to its production, (ii) fossil fuel substitution, (iii) substitution of mineral fertilizer, (iv) soil carbon build-up, and (v) avoided emissions from organic waste in landfills. For instance, in EU’s first renewable energy directive (RED I), only the first two were included, which leaves out a large part of the potential climate impact. In this example, the fertilizer, soil carbon build-up, and waste management related services make up about two thirds of the net climate impact (see Appendix B for data and data sources).
The multiple functions of the NBM and its associated effects also impact the indicator selection process of system assessment methods. The indicator selection process is of high importance to the result of system assessment studies. When deliberating about what indicators to include for the assessment of the NBM, each function of the NBM will need representation by specific indicators. If, for example, when performing an environmental assessment, one only includes the vehicle fuel or transportation service, it may only be relevant to analyse when performing an environmental assessment, one only includes the NBM will need representation by specific indicators. If, for example, 

Huttunen et al. [48] calling for greater policy coherence to different societal services, it tends to be affected by many different pollutants (such as NO\textsubscript{x}, PM, and SO\textsubscript{2}) from the vehicle, and perhaps run-off pollutants from tires and paint. Including biofertilizer production, in addition to fuel production, may mean that indicators related to, for example, soil quality, nutrient leakage from farmland, and nutrient recycling may become relevant to the assessment (see, e.g., [56]). Finally, inclusion of the waste management service may mean that, for instance, indicators concerning pollutant leakage and the performance (i.e., the purification rate) of wastewater management technologies may become relevant. It is not our purpose with this paper to suggest a list of indicators since what constitutes sustainability will (and should) be different depending on the stakeholders involved and the context within which technologies are studied [3,26,55]. What we aim to instil, however, is the idea that all functions of the NBM and their respective costs and benefits should be deliberated upon when selecting indicators. Sometimes this may include all indicators mentioned above (and more); other times, some indicators may be excluded due to them being irrelevant to the decision at hand or that the context means that effects within a specific indicator are negligible. The deliberation and transparent exclusion of indicators is preferred over missing indicators or arbitrary exclusions.

5. Policy implications and discussion

In many countries, it is common to set policies related to societal service provisions, for example, energy, water, or food or related to different sectors, for example, agriculture, manufacturing, or transportation [44]. Since the NBM crosses different sectors and provides different societal services, it tends to be affected by many different policy areas and affect several different actors. These actors range from waste managers to biogas producers and from car producers to regional or municipal authorities. This cross-sectoral attribute creates confusion for businesses trying to establish real-world examples of the NBM, something that has been highlighted previously in literature, with, for example, Huttunen et al. [48] calling for greater policy coherence to increase biogas production in Finland. Similarly, Pfau et al. [74] call for policy coherence between bio-economy policies and renewable energy policies to enable the growth of biogas systems that may contribute positively to both domains but are currently hampered by diverging and narrow goals. Finally, Gustafsson and Anderberg [37] echo these sentiments, stating that current biogas policy is patchy and ineffective.

The idea of including the broader set of functions and effects of the NBM do not only hold implications for strategic policies but also for subsidy schemes, tax reliefs, and other kinds of economic regulation. If one chooses to give a subsidy or tax relief to the NBM due to its socio-economic or environmental benefits, one should consider that these socio-economic and environmental benefits stem from the different functions of the NBM and occur at different parts of the life cycle. This is illustrated in Table 1, where a few selected areas based on Swedish environmental and development goals are divided into production-related and consumption-related effects (based on [57]). Thus, subsidies may need to be spread over the life cycle to ensure that all functions are given to the inhabitants of the region or nation that pay for the subsidy. For example, if a nation would subsidize the NBM by giving tax relief to the fuel, the function of waste management and biofertilizer production may occur outside the nation paying for the subsidy, resulting in inefficient subsidy schemes. As of 2022, this is the case in Sweden, where biomethane as a vehicle fuel has a lower tax than fossil fuels due to its environmental and socio-economic benefits, but almost a third of the biomethane consumed in Sweden is imported from Denmark, meaning that Sweden is paying for environmental and socio-economic benefits and societal services in Denmark. In Denmark, they have adopted an opposite subsidy scheme, namely, paying a subsidy to the producers of biomethane through feed-in tariffs. This biomethane is then exported to Sweden, and environmental and socio-economic benefits related to the consumption of biogas are paid for by Denmark, while the benefits occur in Sweden. This also results in a double subsidy, whereby biogas possibly receives too much of a subsidy. If, instead, both nations were to subsidize the different functions and their respective benefits, no double subsidizing would occur, and it would ensure that benefits paid for by a nation occur within that nation.

A way to foster such coherent policy formulation could be through framing the NBM in a way that includes all three functions since civil servants and politicians would then be made aware that the NBM is more than simply a waste management or energy conversion technology. The accurate framing of the NBM is also important because the framing of technologies can influence their performance and effects (cf. [49]). Therefore, in order for the effects of the NBM to be properly communicated and understood, it must be framed in a broad way, one which can encompass the many different functions and indirect effects of the NBM. In literature, an emerging trend is to frame the NBM as a sustainability solution [30];[86], a framing where the diversity of the NBM’s functions and effects can be included and one which is also recommended here.

6. Conclusions

Biogas systems can contribute toward solving many environmental and societal issues in both rural and urban areas, but because biogas systems may take many different forms, with very different societal effects, there is a need for concepts to differentiate between different biogas systems. This paper describes one such concept, the Nordic biogas model (NBM). The NBM denotes an urban waste-based biogas system where the digestate is used as biofertilizer and the biogas is upgraded to biomethane and used in transportation. It was first developed in the Nordic countries, which is why it is given this specific name, although nowadays examples can be found across the globe. The NBM may contribute with several societal benefits in the form of effective waste management, nutrient recycling, reduced greenhouse gas emissions, enhanced soil health, and improved food and energy security.

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4 Sustainability solution, in this case, refers to a solution that aims to contribute toward solving several sustainability-related challenges. It does not mean that the solution is sustainable or more sustainable than possible alternatives.
Therefore, the NBM should not be framed solely as an energy, agriculture, or waste management solution. It is all three simultaneously, and it is suggested that it is framed as a sustainability solution.

The accurate capturing of this broad set of societal effects requires system assessments to be performed in a way that includes all three functions of the NBM and their relevant impacts. This has implications for what reference alternatives to select, what system boundary to choose, and what indicators to use for assessments. When it comes to reference scenarios, any reference scenario comparing the NBM needs to include at least one alternative for each of the NBM’s main functions, namely, a waste management alternative, a fertilizer alternative, and a fuel alternative. As for the system boundary, it should be sufficiently broad to include all the three main functions of the NBM (and any potential substitutions) and its main life cycle stages. Finally, when selecting indicators for system assessments of the NBM, all three main functions and their associated impact need to be represented by indicators in the assessment (or deliberately and transparently excluded together with the reason for the exclusion).

Finally, the paper suggests a few policy considerations based on the fact that the multi-functionality of the NBM has implications for policy-making. First, it is important to ensure that policy that affects the implementation and operation of the NBM is coherent across sectors so that the multi-functionality is neither penalized nor overly compensated for. Currently, diverging goals set in different policy areas are hindering the development of the NBM, even though the NBM would contribute positively in many of these areas. Furthermore, policy formulation needs to consider where positive or negative effects occur in the life cycle and where that part of the life cycle is geographically located to ensure that subsidies or tax reliefs that are given to businesses result in positive effects in the country that pays for the subsidy. Hence, policy that supports the NBM may need to be divided between production support and consumption support since some societal benefits are tied to the production of biogas, while others are tied to the consumption of it.

Table A1
A list of publications, conferences, and seminars from which the synthesized conclusions of the manuscript is based on.

<table>
<thead>
<tr>
<th>Year</th>
<th>Type</th>
<th>Methods</th>
<th>Title</th>
<th>Reference</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>2013</td>
<td>Scientific</td>
<td>Literature review, document studies</td>
<td>Biofuels for transportation in 2030: feedstock and production plants in a Swedish county</td>
<td>[28]</td>
<td>Study on the potential for biofuel production, where the NBM was one production pathway studied</td>
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<td>2016</td>
<td>Report</td>
<td>Literature review</td>
<td>The role of biogas solutions in the circular and bio-based economy</td>
<td>[41]</td>
<td>A study on the societal impact of the NBM through the lens of the Agenda 2030 SDGs</td>
</tr>
<tr>
<td>2018</td>
<td>Pre-study</td>
<td>Workshops, interviews</td>
<td>A pre-study on a Swedish arena for internationalization of biogas solutions</td>
<td>N/A</td>
<td>25 companies met in a workshop series to develop the offer of internationalization of the Nordic model for biogas solutions</td>
</tr>
<tr>
<td>2018</td>
<td>Scientific</td>
<td>Literature review, interviews</td>
<td>The role of biogas solutions in sustainable biorefineries</td>
<td>[40]</td>
<td>An analysis of the role of the NBM in biorefinery setups</td>
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<td>2019</td>
<td>Scientific</td>
<td>Case studies, literature review</td>
<td>Assessing the potential, performance and feasibility of urban solutions: Methodological considerations and learnings from biogas solutions</td>
<td>[59]</td>
<td>A deliberation and discussion on how to perform multi-dimensional assessments based on case studies of the NBM</td>
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<tr>
<td>2019</td>
<td>Report</td>
<td>Literature review</td>
<td>Samhällseffekter av alternativa drivmedel (eng. ‘Societal effects of alternative fuels’, author’s own translation)</td>
<td>[57]</td>
<td>An analysis and description of the societal effects of different alternative fuels in the Swedish county of Östergötland, where biomethane produced through an NBM setup was one option analysed</td>
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<td>2019</td>
<td>Conference</td>
<td>N/A</td>
<td>7th Nordic biogas conference: The “next wave” in biogas!</td>
<td>[70]</td>
<td>Conference where seminars and presentation where held by the authors on the NBM</td>
</tr>
<tr>
<td>2020</td>
<td>Scientific</td>
<td>Case study, interviews, workshops</td>
<td>Assessment of by-product valorisation in a Swedish wheat-based biorefinery</td>
<td>[42]</td>
<td>An environmental assessment of different ways to valorize by-products in a biorefinery, where the NBM is one pathway that is assessed</td>
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<tr>
<td>2020</td>
<td>Scientific</td>
<td>Workshops, literature review</td>
<td>Developing biogas systems in Norköping, Sweden: An industrial symbiosis intervention</td>
<td>[60]</td>
<td>A description and discussion about an intervention to facilitate the NBM in a local setting</td>
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<td>2021</td>
<td>Conference</td>
<td>N/A</td>
<td>Biogas 2021: Guldtruschen</td>
<td>[77]</td>
<td>Presentations of narratives, challenges and opportunities of biogas solutions, including the NBM, in Sweden</td>
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<tr>
<td>2021</td>
<td>Scientific</td>
<td>Interviews, case study</td>
<td>Advancing the circular economy through organic by-product valorisation: a multi-criteria assessment of a wheat-based biorefinery</td>
<td>[43]</td>
<td>A multi-dimensional assessment of different ways to valorize by-products in a biorefinery is performed, where the NBM is one pathway that is assessed</td>
</tr>
<tr>
<td>2021</td>
<td>Scientific</td>
<td>Literature review, document study, workshops</td>
<td>Using national environmental objectives in green public procurement: Method development and application on transport procurement in Sweden</td>
<td>[56]</td>
<td>A study on how assessments of different alternatives can be integrated in green public procurement, where biomethane produced through the NBM is one assessed option</td>
</tr>
<tr>
<td>2021</td>
<td>Scientific</td>
<td>Case study, interviews</td>
<td>The role of biogas solutions for enhanced nutrient recovery in biobased industries: Three case studies from different industrial sectors</td>
<td>[31]</td>
<td>Three case studies on how the NBM can enhance nutrient recycling in biobased industries</td>
</tr>
<tr>
<td>2021-2022</td>
<td>Research planning</td>
<td>Meetings, seminars</td>
<td>Dialogue with Swedish biogas actors about their needs and expectations for research in the perspective of different alternative fuels in the Swedish county of Östergötland</td>
<td>N/A</td>
<td>27 one-hour interviews contributing to the research agenda of the Biogas Research Center</td>
</tr>
<tr>
<td>2022</td>
<td>Report</td>
<td>Workshops</td>
<td>Världens bästa biogassystem: et BRC innovationsprojekt (eng. ‘World’s best biogas system: a BRC innovation project’, author’s own translation)</td>
<td>[58]</td>
<td>A case study on the potential for implementation of various types of biogas systems (including the NBM) in the Swedish county of Södermanland</td>
</tr>
<tr>
<td>2022</td>
<td>Knowledge dissemination</td>
<td>Lectures, meetings</td>
<td>Meetings with local and regional actors about biogas development</td>
<td>N/A</td>
<td>13 meetings containing a lecture and discussions with local and regional politicians, civil servants, and industry representatives in southern and mid Sweden about conditions for development of biogas systems, including NBM-type systems</td>
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<tr>
<td>Table B1</td>
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</tr>
<tr>
<td><strong>Emission category</strong></td>
<td><strong>Climate impact (kg CO₂-eq./per-year)</strong></td>
<td><strong>References</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production of biogas</td>
<td>7.1</td>
<td>[4,13]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel substitution</td>
<td>−29.4</td>
<td>[29]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biofertilizer substitution</td>
<td>−3.4</td>
<td>[9–10,83]</td>
<td></td>
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<tr>
<td>Soil carbon build-up</td>
<td>−3.5</td>
<td>[67, 75]</td>
<td></td>
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<td>Landfill methane leakage avoidance</td>
<td>−34.3</td>
<td>[25]</td>
<td></td>
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</table>

**CRediT authorship contribution statement**

Axel Lindfors: Conceptualization, Investigation, Resources, Writing – original draft, Writing – review & editing. Linda Hagman: Resources, Writing – original draft, Writing – review & editing. Mats Eklund: Conceptualization, Investigation, Resources, Writing – review & editing.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Appendix A**

In Table A1, a list of publications, conferences, and seminars can be found that have engaged researchers and practitioners on different topics in relation to the Nordic biogas model within the Swedish Biogas Research Center.

**Appendix B**

Supporting data and references for Fig. 4. The climate impact for each emission category has been extracted from the references found in Table B1. The production of biogas represents an increase in climate impact while the other emission categories reduce climate emissions, either through substitution effects, carbon storage effects, or avoidance of methane leakage.

**References**

[29] Gustafsson M, Ammenberg J, Murphy JD. A perspective on the state of the biogas industry from selected member countries, IEA Bioenergy Task 37, IEA Bioenergy Task 37, 2022.


