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The role of life cycle assessment in the sustainable transition to a decarbonised gas network through green gas production

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ABSTRACT

Green gas is a promising renewable energy carrier compatible with existing gas networks, whose environmental impact and capacity to decarbonise the energy sector is evaluated by life cycle assessment (LCA). This articles reviews 42 LCAs applied to biomethane, produced by anaerobic digestion, and bio-SNG, produced by gasification and methanation, discussing the main methodological choices and their effects on the results, and highlighting the limits of the use of LCA as a stand-alone approach in real-case applications. While uncertainty analysis was performed in 34 of the reviewed studies, only 3 studies integrated the LCA with process modelling or geospatial modelling. The lack of data for pre-commercial or newly-commercialised technologies has necessitated to the introduction of thermodynamic models giving mass and energy flows, especially in the case of bio-SNG. Limits due to geospatial case-specific constraints have been overcome by two studies introducing geographical information systems (GIS) based models to evaluate the impact of green gas production system on a regional level. Facility siting and sizing has been also found to be fundamentally important in evaluating the trade-off between profitability and environmental impact. Finally, this work highlights the need for a hybrid LCA, in which LCA is integrated with thermodynamic models of the process, GIS-based infrastructure design, and uncertainty quantification, in order to inform stakeholders of the economic, environmental and energy potential of green gas production systems.

1. Introduction

1.1. Background

In a business-as-usual projection, world energy consumption is estimated to increase by 28% from 2015 (607 EJ) to 2040 (777 EJ), with a consequential increase by 34% of world energy-related CO_2 emissions, from 33.9 to 42.7 billion metric tons [1]. In 2014, the Intergovernmental Panel on Climate Change (IPCC) identified the energy supply sector as the largest contributor to anthropogenic global CO_2 emissions (approximately 35%) and criticised the limited research on integration of low-carbon technology, such as sustainability, site-specificity and efficiency of large-scale deployment of bioenergy, which can play a critical role in mitigation [2]. In 2015, the Paris Agreement [3] committed signatory countries to hold the increase in global average temperature to below 2 °C above pre-industrial levels, and to invest in greenhouse gas emissions (GHG) mitigation pathways.

According to the U.S. Energy Information Administration (EIA), natural gas will account for the largest portion in the increase of world primary energy consumption from 2012 to 2040 [4]. Under governmental pressure to reduce CO_2 emissions, natural gas may displace more carbon-intensive fuels [4]. In 2015, seven European gas transmission system operators, Energynet.dk (Denmark), Fluxys Belgium, Gasunie (Netherlands), GRTgaz (France), Swedegas (Sweden), Gaznat (Switzerland) and ONTRAS (Germany), signed a joint declaration proclaiming the aim to establish 100% CO_2-neutral gas supplies by 2050 [5].

Gas networks can have a critical role in decarbonising the future energy system [6]. Existing gas infrastructures are valuable and strategic assets capable of delivering significant quantities of energy for many applications: power generation, industrial heat and chemicals, building heat and transport [2]. Current fluctuations in gas demand are significant, but can be successfully handled by the storage flexibility of the grid infrastructure. Conversely, the capability of electricity network systems to respond to energy demand fluctuations is more technically challenging and expensive [7]. Pathways to decarbonise the gas

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Nomenclature table

AD	Anaerobic digestion
Bio-SNG	Biomass derived synthetic natural gas
CHP	Combined heat and power
GIS	Geographic information system
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
TM	Thermodynamic model
UQ	Uncertainty quantification

network include the production of hydrogen (via power-to-gas systems), biomethane (via anaerobic digestion (AD)), biomass derived synthetic natural gas (bio-SNG) (via gasification), and carbon capture and storage (CCS) [7].

Biomethane and bio-SNG have a chemical composition very similar to natural gas, so are chemically compatible with the existing gas infrastructure. They are referred to as green gas in this article. Feedstocks for green gas production consist of wastes and purpose-grown crops. Wet feedstocks are typically suited to AD, whilst dry or woody feedstocks are more suited to gasification [8]. AD can use very low and negative cost feedstocks such as food waste and animal slurries (i.e. the operator is paid to take the waste). This makes it economical as an efficient waste management technique, able to reduce local air and water emissions, as well as providing a nutrient-rich by-product known as digestate that can be used as organic fertiliser [9].

Better whole-systems modelling analysis is needed, grounded in the practical reality of gas network decarbonisation options, to provide a stronger evidence base for decision makers. This will enable quantification of the economic costs and benefits of different gas network decarbonisation options, and to establish the conditions needed for a positive business case for investment in these options [2].

1.2. LCA state-of-the-art

1.2.1. Normative framework

The primary driver for assessing the role of gas networks in future energy systems is to consider their roles in achieving climate targets. The most widely adopted systematic technique to assess GHG emissions and overall environmental impact of a product or process is life cycle assessment (LCA) [10]. Today LCA is the main methodological reference for guiding sustainability policies and design of energy solutions [11]. In standards ISO 14040-14044:2006 [12,13], LCA is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" and it includes four phases [10]. These four phases are: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation. The goal and scope definition includes the motivation of the study, the intended application and audience, and the description of system boundaries. The system boundaries identify the confinement of the system under investigation and they include all the activities involved in the production system [13], from the input raw material (feedstock) to the final use of the end-product (green gas). The extension of the system boundaries can go from cradle (i.e. raw material supply) to grave (i.e. end of life) and even back to cradle again when consideration is taken of reuse-recovery-recycling potential. In other words, cradle-to-grave defines the full life cycle of the product, whereas cradle-to-gate considers the partial life of the product. For example, cradle-to-gate analysis could end at green gas production, with no consideration on its final use. Besides these definitions, it is good practice to list all of the activities comprised in the LCA, which usually include: planting and collection/harvesting of the resources, transport, conversion, distribution and, in the case of cradle-to-grave boundaries, end use of the main product and waste disposal. The LCI is a compilation of the inputs (resources) and the outputs (emissions) of the system studied over its life cycle. The LCIA quantifies the potential environmental impacts of the studied system. Baseline impact categories, defined by SETAC Working Group on Impact Assessment [10], include: depletion of abiotic resources, impact of land use, global warming potential, ozone depletion, human toxicity, ecotoxicity, photo-oxidant formation, acidification and eutrophication. Besides baseline impact categories, there are also study-specific categories that may merit inclusion depending on the goal and scope of the LCA study and whether appropriate data are available (e.g. impacts of ionising radiation, loss of biodiversity). Additionally, there are other impact categories that are not standardized, such as depletion of biotic sources. In the Interpretation phase, the results from the previous phases are discussed in relation to the goal and scope [14].

1.2.2. Emerging approaches

For the purpose of integrating emerging low carbon technologies into the existing gas grid infrastructure, environmental impact analysis of the systems is necessary but not sufficient. Consideration must be given to the economic and energy assessments of the energy system, which provides, with the environmental impact, a holistic view on the sustainability of the transition [15]. Economic and energy analyses of green gas production systems depend on the technology used and the infrastructure design, which determine the input-output flows of energy and material.

The design of the infrastructure depends on site specific data, such as the position of the gas grid and injection sites, and distance of the energy conversion plant from the resources. Regionalization of the environmental impact assessment has been a subject of interest recently in LCA practice [16]. LCA is not usually intended to be a regional or spatially disaggregated approach, but the scattered nature of biomass availability and its integration with existing energy infrastructure necessitate a spatially representative LCA. Geographic information systems (GIS) are a set of techniques that combine geography and information technology and allow the user to build geographically explicit models. GIS integrated with LCA takes account of heterogeneity of a territory on a number of levels: resource distribution, transport distances (between resources and conversion plants, and/or between conversion plants and demand sites), plant siting, and sizing. GIS is essential for system design for two scopes:

- Spatially-distributed resource assessment, which derives from actual data, based on census or measurements, or models, involving parameters affecting yield [17].
- Spatially-dependent plant siting and sizing, which depends on an optimization algorithm, constraints, and an objective function [18].

Hiloidhari et al. [19] reviewed the role and the application of GIS for assessments, logistics and plant design, with particular focus on agricultural residues. Plant siting and sizing are performed through optimization of the supply chain, which consists of the stages included in the system boundaries defined in the scope of the LCA. The objective function of the optimization can be defined in the scope of the LCA. Examples of this include maximization of profitability, or minimization of environmental impact, or both in multi-criteria optimization, in which results are presented as a set of Pareto-optimal solutions, which expose the trade-offs [18]. Yue et al. [20] performed a review that highlighted the different alternatives and state-of-the-art of supply chain optimization for aquatic and terrestrial biomass. When a spatially-explicit model is necessary for the design of the system and it enriches the inventory, it also asks questions about the spatial