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Designing a green gas supply to meet regional seasonal demand – An operations research case study

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HIGHLIGHTS

- A green gas supply was modeled to cover a season dependent gas demand.
- Non-continuous biogas production is important to meet season dependent gas demand.
- Increasing replacement of natural gas by green gas does not always increase costs.

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ABSTRACT

One of the issues concerning the replacement of natural gas by green gas is the seasonal pattern of the gas demand. When constant production is assumed, this may limit the injected quantity of green gas into a gas grid to the level of the minimum gas demand in summer. A procedure was proposed to increase the gas demand coverage in a geographical region, i.e., the extent to which natural gas demand is replaced by green gas. This was done by modeling flexibility into farm-scale green gas supply chains. The procedure comprises two steps. In the first step, the types and number of green gas production units are determined, based on a desired gas demand coverage. The production types comprise time-varying biogas production, non-continuous biogas production (only in winter periods with each digester having a specified production time) and constant production including seasonal gas storage. In the second step locations of production units and injection stations are calculated, using mixed integer linear programming with cost price minimization being the objective. Five scenarios were defined with increasing gas demand coverage, representing a possible future development in natural gas replacement. The results show that production locations differ for each scenario, but are connected to a selection of injection stations, at least in the considered geographical region under the assumed preconditions. The cost price is mainly determined by the type of digesters needed. Increasing gas demand coverage does not necessarily mean a much higher cost price.

1. Introduction

Several studies assess bioenergy potential and costs on a global, continental or national level. Relatively few describe the spatial distribution of bioenergy production potential and the costs of bioenergy supply within a defined small geographical region [1], although the number of studies in this field is increasing (e.g., [2–5]). The benefits of gaining quantitative knowledge of possible plant locations, plant scales and logistics to decrease costs were discussed previously ([6,7]). Research in the field of local or regional energy supply gives a better understanding of the implications of a national or more global energy policy. This is illustrated by studies investigating the benefits and costs of increasing levels of regional energy self-sufficiency ([8–10]). Three closely related principles in this respect are the use of renewable energy resources within a region rather than energy imports, decentralization of the energy system (from national to regional), and increase in the energy efficiency of the supply and the demand side.

Published studies on facility location problems give insight in possible modeling approaches and relevant preconditions depending on the area considered, and the results show where to build facilities. A number of studies exist in which geographical locations of bioenergy plants are calculated for larger regions or countries, under specified boundary conditions, e.g., power plants and

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Nomenclature

ABS	agent based simulation
CHP	combined heat and power
DSO	distribution system operator
GDC	gas demand coverage, i.e., the percentage of a concrete natural gas demand pattern replaced by green gas
GIS	geographical information system
GP	goal programming
Green gas	biogas upgraded to natural gas quality, in literature also referred to as biomethane. Upgrading comprises cleaning (e.g., removing H_2S) and removing CO_2, resulting in burning properties equivalent to natural gas (in our case Dutch quality gas with Wobbe Index 43.46–44.41 MJ/Nm^3)
GRS	gas receiving station, where gas from the transport grid enters the distribution grid, and the pressure of the gas is reduced from 40 bar to 8 bar
LP	linear programming
MILP	mixed integer linear programming
Nm^3	normal cubic meter (at standardized conditions $p = 1.01325$ bar, $T = 273.15$ K)
SSF	seasonal swing factor, defined by the maximum hourly gas demand divided by the minimum hourly gas demand in a year [–]. *SSF* = 1 means a constant gas demand

factories in a Spanish region [11], ethanol refineries in Sweden [12]. Some studies take yearly changes in demand or demographic developments into account, (e.g. [13,14]), but studies predominantly consider supply and demand in a more or less static way, i.e., the long-term supply of biomass and demand for bioenergy are considered constant in time. Usually, seasonal differences between supply and demand are not addressed. Moreover, published studies mainly comprise production of electricity or fuels like ethanol or methanol.

In this paper we focus on bioenergy in the form of green gas, with the aim to calculate biogas plant locations in a sub-municipality scale rural region in The Netherlands. Possibilities for green gas production are strongly dependent on the geographical region considered. A simple, local green gas supply chain may consist of co-digestion of one co-substrate type with available dairy cattle manure, upgrading the produced biogas to natural gas quality, and injection of the upgraded gas into the natural gas grid at injection stations. Such a supply chain may represent the activities of one farmer, and was earlier investigated [15]. The costs of such a supply chain can be calculated by summing the costs of each process step. Even when cost functions are not linear or non-continuous, because of differing technologies or scale-dependent cost functions, the costs per Nm^3 green gas can be determined. The cost price calculation is slightly expanded when two or more injection stations to choose from are present in the same geographical region. A network of more digesters and injection stations rapidly increases the number of possibilities of plant locations and connections, and thus the number of calculations for an optimization.

Meeting a varying seasonal gas demand was investigated in a study where the gas demand in a region was modeled by a sine function [16]. A seasonal swing factor (*SSF*) was defined, being the maximum hourly gas demand divided by the minimum hourly gas demand in one year, based on this sine function. An *SSF* = 1 means a constant gas demand during a year. The higher the *SSF*, the greater the challenge to match demand and supply. In the mentioned study *SSF*'s ranging from 1.2 to over 20 were found, depending on consumer type. If a geographical region is considered with a known hourly gas demand, *SSF* = 1, and a known natural gas grid, then the green gas might be relatively cheap if large scale plants are possible, provided that there are no limitations on available biomass or grid entry capacities. Optimal plant locations can then be calculated resulting in a minimum cost price. At larger *SSF* (e.g., *SSF* = 12) the minimum hourly gas demand may be relatively low. If constant gas production is assumed without storage, large scale plants may not be possible, implying cost price increase. Up to date, the minimum hourly gas demand is, in combination with a constant supply, considered to be a limiting factor for replacement of natural gas by green gas (e.g., [17,18]). The question arises whether the choice of the locations in a given region is influenced by the extent to which a supply chain has to cope with a given *SSF*, i.e., the extent to which the gas demand has to be covered by green gas. The above considerations justify a more in-depth geographical analysis of promising locations to build green gas supply chains. I.e., given a known, time-varying gas demand in a geographical region, how can optimal production locations and connections between production locations and injection stations be determined? The central research question considered in this study is therefore:

Given a geographical region with a known seasonal gas demand (and thus *SSF*), and possible geographical locations for production plants and gas injection stations, which combination of locations gives the lowest cost price when defined shares of the gas demand, i.e., gas demand coverage (*GDC*, up to 100%), have to be met by green gas?

Sub questions to be answered are:

1. How can feasible geographical locations and capacities of green gas production units and injection stations be defined in this region?
2. How to model a flexible green gas supply chain? Flexible means that the green gas output of the chain can be varied in time to meet seasonal differences in gas demand. More specific, based on Bekkering et al. [16], which choices must be made between flexible biogas production, gas storage and multiple digesters?

The research is novel in the sense that not only biogas plant and injection station locations in a defined geographical region are calculated in a case study under the condition of (partially) following the seasonal gas demand, but that also the sensitivity of these locations to increase in natural gas replacement is investigated. The intention of answering the research question is to gain a better understanding of possible developments in locally or regionally matching supply and demand. And more specifically, insight is gained in whether requirements on the GDC, which may be a political decision, would influence investment decisions.

To the authors' knowledge no literature exists which defines at which geographical scale energy supply should be considered. E.g., Meyer et al. [2] and Burgess et al. [3] chose a geographical area for their calculations, but no explanation was given what this choice was based on. It is not clear how large such a geographical region should be, although political divisions might be determinative [9]. Investigations for green gas injection have been done for a selected region in the north of The Netherlands [19]. The potential of manure in this region was investigated, but not specified per farm. In