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Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region

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HIGHLIGHTS

- The total theoretical biomethane resource of grass silage in a region was estimated.
- A theoretical biomethane resource of ca. 138 PJ was identified.
- An optimisation model determined profitable biomethane facility locations.
- Profitable plants produced 12 PJ of biomethane, 8.6% of the theoretical resource.
- Approximately 22% of industrial gas demand could be supplied by profitable plants.

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ABSTRACT

The total theoretical biomethane resource of cattle slurry and grass silage in Ireland was estimated using the most up to date spatially explicit data available. The cattle slurry resource (9.6 PJ) was predominantly found in southern and north-eastern regions while the grass silage resource (128.4 PJ) was more concentrated in western regions. The total biomethane resource of cattle slurry and grass silage was equivalent to 6% and 76% of total natural gas consumption in Ireland in 2014/15, respectively. A sequential optimisation model was run to determine where to source cattle slurry and grass silage from, for 42 potential biomethane plant locations in Ireland. The concept was to maximise plant net present value (NPV) and develop locations in order of plant profitability. The impact of plant size, grass silage price, volatile solids ratio (VSR) of grass silage to cattle slurry, and incentive per unit energy of biomethane was assessed in 81 separate scenarios. The results indicated that total biomethane production from plants with a positive NPV ranged from 3.51 PJ/a to 12.19 PJ/a, considerably less than the total resource. The levelised cost of energy (LCOE) of plants was also calculated and ranged from ca. 50.2 €/MW h to ca. 109 €/MW h depending on the various plant parameters. LCOE decreased with increased plant size and ratio of grass silage to cattle slurry. The relationship between grass silage price and LCOE was assessed. In the median scenario (33 €/t_{wwt} grass silage, VSR of 4, 75,000 t_{wwt}/a plant size, 60 €/MW h incentive) cattle slurry was sourced within 6.4 km of the facility while grass silage was sourced within 10.5 km of the facility. A high level assessment of the carbon dioxide intensity of biomethane from the median scenario was conducted and showed a potential greenhouse gas reduction of 74–79% when compared to natural gas.

1. Introduction

The total final consumption (TFC) of energy in transport in Ireland in 2013 was approximately 173 PJ, of which 97% was imported petroleum fossil fuels [1]. Thermal energy consumption was 187 PJ, or 34% of total primary energy requirement [1]. Ireland has an obligation to ensure that 10% of energy in transport and 12% of thermal energy is sourced from renewable sources by 2020 [2,3]. Biomethane production through the anaerobic digestion of biodegradable matter is a potential pathway to meeting such renewable energy targets using indigenous feedstock. Use of biomethane can also mitigate greenhouse gas emissions from agriculture through improved manure and slurry management, and contribute to the 20% national reduction target in the non-

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emissions trading sector relative to 2005. The use of biomethane as an energy source can also contribute toward meeting the 20% reduction in total greenhouse gas emissions relative to 1990 levels, by offsetting the use of fossil fuels. Within the EU, seven natural gas grid operators have agreed to supply 100% carbon neutral gas by 2050, with anaerobic digestion (AD) being a key component in achieving this [4]. Gas Networks Ireland (GNI), the owner and operator of the natural gas network in Ireland has targeted 20% renewable gas in the network by 2030, with an interim goal of 21.5 PJ of renewable gas by 2024 [5].

Feedstock suitable for use in AD includes biodegradable materials with high moisture content such as household organic waste, agricultural residues and slurries, grass silage, energy crops, and macro algae (seaweed). The scientific literature suggests a potentially significant resource of biomethane associated with grass silage and cattle slurry in Ireland [6–8], which could contribute more than 26% of the projected energy consumption in transportation in 2020 [6]. Studies to date have only provided an overall national resource; no spatially explicit studies have been undertaken, no potential build order of biomethane facilities whilst considering financial viability has been developed. An assessment of sub-regions within Ireland for development of a biomethane industry has been conducted [9] however the financial viability of the plants was not assessed.

Internationally the development of a biomethane industry, whilst taking into consideration the location of potential feedstocks, has been assessed by Bojesen for the case of Denmark; the feedstock assessed was slurries from animal husbandry [10,11]. The work by Bojesen utilised a p-median solution to determine the allocation of feedstock sources to potential biogas facilities, plant profitability was not considered, and the impact of feedstock mix was not assessed. Work by Hohn et al. assessed the resource potential of biogas in southern Finland and also determined potential locations for biogas facilities, again by solving a p-median problem which minimised the total transportation cost of feedstock to the proposed biogas facilities [12]. The impact of feedstock mixture on the energy production of facilities was not assessed. The most profitable plant, in terms of NPV, was not determined by either Bojesen et al. or Hohn et al.; a potential build order of plants ranked in terms of profitability was not developed by either. Chinese et al. investigated the impact of changing bioenergy promotion schemes in Italy on the agricultural biogas industry, by considering plant size, feedstock supply, feedstock mix, and digestate disposal [13]. The work by Chinese et al. did not consider the impact of varying ratios of feedstock, and it did not develop a potential build order of biogas facilities.

The profitable operation of a potential biomethane facility requires a sufficient financial incentive; determining this required incentive is crucial.

The innovation in this paper is that it provides a method to assess, and undertakes an exemplar analysis of, potential locations for anaerobic digesters for biomethane production and grid injection and ranks them in terms of financial viability whilst considering plant size, feedstock price, feedstock source, transportation cost, potential incentive value, and feedstock mix. No such work has been reported previously in scientific literature to the authors' best knowledge at the time this work was carried out. The region chosen for this analysis was Ireland, in which there is currently no large scale biomethane industry. Grass silage and cattle slurry were selected for this assessment owing to their large resource in Ireland. This work is aimed at policy makers, engineers, planners, and developers involved in the establishment of biomethane industries.

The methodology developed herein could be applied to any region in order to determine the total theoretical biomethane resource, and develop a potential build order to biomethane facilities ranked in terms of profitability. The objectives of this work are to:

(1) Determine the total theoretical biomethane potential of cattle slurry and grass silage on a regional level and highlight the regions of greatest resource.
(2) Calculate the total biomethane production from potential plants for a range of silage prices, premium or incentive levels, volatile solids ratios (VSRs) of grass silage to cattle slurry, and plant sizes using an optimisation model which maximises plant profitability.
(3) Develop cost curves outlining the quantity of biomethane which can be produced at a given levelised cost of energy.
(4) Outline a potential build order of plants for a given scenario and assess the source locations of grass silage and cattle slurry used in the constructed plants.
(5) Assess the relationship between resource and financially viable resource.

2. Methodology

2.1. Calculation of cattle slurry resource

The total resource of cattle slurry in terms of wet tonnes (t_{wwt}) was calculated at each ED (electoral division, the smallest regions for which such data was available) according to Eq. (1) based on prior work by the authors [14]. The most up to date data (June 2010) on bovine livestock for each ED was sourced from the Central Statistics Office (CSO) on May 20th 2015.

Eq. (1); cattle slurry resource per electoral division (m_j^{CS}):

$$m_j^{CS} = N_{cows,dairy}Y_{cows,dairy} + N_{cows,other}Y_{cows,other} + N_{cattle\geqslant 2}Y_{cattle\geqslant 2} + N_{cattle1-2}Y_{cattle1-2} + N_{cattle\leqslant 1}Y_{cattle\leqslant 1} \quad (1)$$

In Eq. (1) N_ϑ is the number of livestock type ϑ in an ED, Y_ϑ is the annual slurry production per head of livestock of type ϑ. The annual slurry yield per head of bovine livestock was taken from Hennessy et al. [15]. The dry solids (DS_{CS}) content and volatile solids (VS_{CS}) content of cattle slurry was taken to be 8.35%$_{wwt}$ and 6.23%$_{wwt}$, respectively, an average of values obtained for Irish dairy cattle slurry in literature [6,16,17]. The total methane yield per ED was found using a specific methane yield (SMY) of 143LCH_4/kgVS [16], while the total energy resource was determined using a calorific value of 37.78 MJ/Nm^3CH_4.

2.2. Calculation of grass silage resource

The total area of land in each ED allocated to grassland pasture and silage production was sourced from the CSO. The annual production of dry matter (DM) grass from pasture, grass silage from land dedicated to grass silage production, and grassland allocated to hay production was calculated using the methodology outlined in McEniry et al. [18] as shown in Eq. (2). An assumption that maximum nitrogen fertiliser application (to the limit permitted by the EU Nitrates Directive) was used.

Eq. (2); grass dry matter resource per ED (m_i^{GS}):

$$\begin{aligned} m_i^{GS} = {} & A_{grass} * \left(F_{SG1} * Y_{SG1}^{grass} + F_{SG2} * Y_{SG2}^{grass} + F_{SG3} * Y_{SG3}^{grass}\right) \\ & + A_{silage} * F_{1cut} * \left(F_{SG1} * Y_{SG1,1cut}^{silage} + F_{SG2} * Y_{SG2,1cut}^{silage} + F_{SG3} * Y_{SG3,1cut}^{silage}\right) \\ & + A_{silage} * F_{2cut} * \left(F_{SG1} * Y_{SG1,2cut}^{silage} + F_{SG2} * Y_{SG2,2cut}^{silage} + F_{SG3} * Y_{SG3,2cut}^{silage}\right) \\ & + A_{hay} * \left(F_{SG1} * Y_{SG1}^{hay} + F_{SG2} * Y_{SG2}^{hay} + F_{SG3} * Y_{SG3}^{hay}\right) \end{aligned} \quad (2)$$

In Eq. (2) A_k is the area of land under grass type k. Different soil groups yield different quantities of grass, grass for silage, and grass for hay [18]. The fractions of land area in each soil group (F_{SG1}, F_{SG2},