Analysis of the potential for biogas upgrading to syngas via catalytic reforming in the United Kingdom

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A B S T R A C T

The UK faces unprecedented environmental challenges which require urgent action. The promotion of renewable energy sources is a promising solution to tackle these challenges. Among these, syngas production from biogas via dry reforming of methane shows great potential as a green alternative to meet global environmental goals. The purpose of this work is to estimate the potential of syngas production from biogas in the UK and its profitability. To estimate the syngas production, we present an overview of methane dry reforming to syngas. This analysis reveals that nickel/alumina catalysts are the most popular choice for the mentioned reaction. Afterwards, the potential biogas production in the UK is obtained. Both set of data are subsequently combined to estimate the potential for syngas production from biomass in the UK. A techno-economic analysis is performed to estimate the syngas price to reach profitability. This analysis reveals syngas prices ranging from 1.15 to 1.56 €/m^3 to overcome production costs, which is higher than producing syngas from traditional fossil fuels. Further analysis has also been conducted to estimate the production of different utilisation routes for said syngas including biofuel, methanol and electricity.

1. Introduction

1.1. Background

Fossil fuel scarcity as well as mitigation of greenhouse gas (GHG) emissions are among the greatest scientific challenges of our era [1]. Increasing the renewable share in the global energy production pool, and other options such as Carbon Capture and Storage/Utilization (CCS/CCU [2]), will play a crucial role to tackle said issues in the near future. As a matter of fact, only 17.8% of the global electricity generation comes from renewable origin energy at present [3]. With the objective of reducing emissions by 80% across all sectors by 2050 with respect to 1990 levels [4], investment in renewables has led to the UK having the sixth greatest renewable energy installed capacity as of 2018 [5]. The UK investment in renewables reached 0.8% of the GDP in 2015 [6,7] and forecasts are that the investment in renewables will rise in the upcoming decades. The above might nevertheless not be enough to achieve the proposed target.

Among the renewable options, biogas is at present the greatest contributor to renewable energy production globally [8,9]. Biogas results from the anaerobic digestion of biodegradable matter and is comprised of CH_4 and CO_2 mainly [10]. Composition varies depending on feedstock, although a percentage ratio (CH_4:CO_2) of 60 to 40% is considered a standard value [11,12]. There are three main routes for biogas utilisation after its production (Fig. 1B), which are as follows: i) It can be upgraded to biomethane by CO_2 separation, thus obtaining a nearly pure CH_4 stream which can replace natural gas [13,14], ii) burnt to produce green electricity in a combined heat and power (CHP) system [15,16], or iii) upgraded to high added value products such as syngas via dry reforming of methane (DRM) [17,18]. Syngas is a fuel gas mixture consisting mainly of hydrogen and carbon monoxide. Further, syngas can be employed as intermediary to produce commodities such as methanol [19] and long-chain hydrocarbons [20] via the Fischer-Tropsch (FT) process, or for green electricity generation in solid oxide fuel cells (SOFC) [21,22] (Fig. 1C). Biogas can be also directly fed to SOFC units [23,24]. Nonetheless, biogas upgrading to syngas provides more flexibility to produce chemicals or electricity [25]. This allows to

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Parameter list

Q_{bio}	Biogas Production Estimated m^3/h
a_i	Biogas Yield m^3/t
T	Processing Capacity t/a
f_i	Correction Factor –
NPV	Net Present Value €
PI	Profitability Index €/€
I_t	Cash Inflows €
O_t	Cash Outflows €
r_d	Discount Rate %
n	Lifetime of the project years
t	Time years
C_{inv}	Investment Cost €
R_{syngas}	Syngas Revenues €
Q_{syngas}	Syngas Flow m^3/h
p_{syngas}	Syngas Price €/m^3
C_{loan}	Loan Cost €
C_{il}	Loan Interest Cost €
n_l	Period of the Loan years
r_{int}	Interest rate %

C_{prev}	Investment Cost Reference €
Q_{prev}	Capacity Reference m^3/h
C_{mo}	Maintenance and Overhead Cost €
C_{df}	Depreciation Cost €
C_{ins}	Insurance Cost €
C_{inst}	Installation Cost €
C_{ut}	Utilities Cost €
n_{wh}	Working Hours H
C_{uut}	Unitary Cost of Utilities €/m^3
C_{lab}	Labour Cost €
C_{labu}	Unitary Labour Cost €/worker
n_{op}	Number of Workers Worker
C_{cat}	Catalyst Cost €
Q_{cat}	Amount of Catalyst kg
p_{cat}	Catalyst Price €/kg
WHSV	Weight Hourly Space Velocity L/(g h)
p_{cat-Rh}	Rhodium Catalyst Price €/kg
p_{cat-Ru}	Ruthenium Catalyst Price €/kg
p_{Rh}	Rhodium Price €/kg
p_{Ru}	Ruthenium Price €/kg
p_{Al}	Alumina Price €/kg

adapt the production to the market needs.

Syngas proves a strong candidate for boosting the production of renewable energy [26], and is therefore a promising alternative for biofuel and green electricity production. This work evaluates the potential for syngas production from biogas in the UK via DRM and its techno-economic analysis. To the best of author's knowledge, this is the first work in which the production of syngas from biogas and its economic feasibility is analysed through a case study.

1.2. Workflow and objective

The objective of this work is to analyze the potential for syngas production from biogas via catalytic reaction in the UK. The workflow (Fig. 2) to achieve said goal is, in the following order:

- Overview of catalytic upgrading of biogas to syngas via DRM, focusing on the most technologically feasible catalysts for this reaction.
- Assessment of biogas production from biodegradable matter in the UK.
- Assessment of potential syngas capacity production from biogas following the catalysts reviewed in the first step.
- Techno-economic assessment of DRM to produce syngas, evaluating the syngas price needed to reach profitability under several scenarios.

To meet the proposed scope, this work is organised as follows. We begin by overviewing biogas upgrading to syngas via DRM (section 1.3). Secondly, an explanation of the methodology is presented (section 2). Afterwards, the results obtained in our work are presented and discussed in section 3. The potential biogas production from waste in the UK is
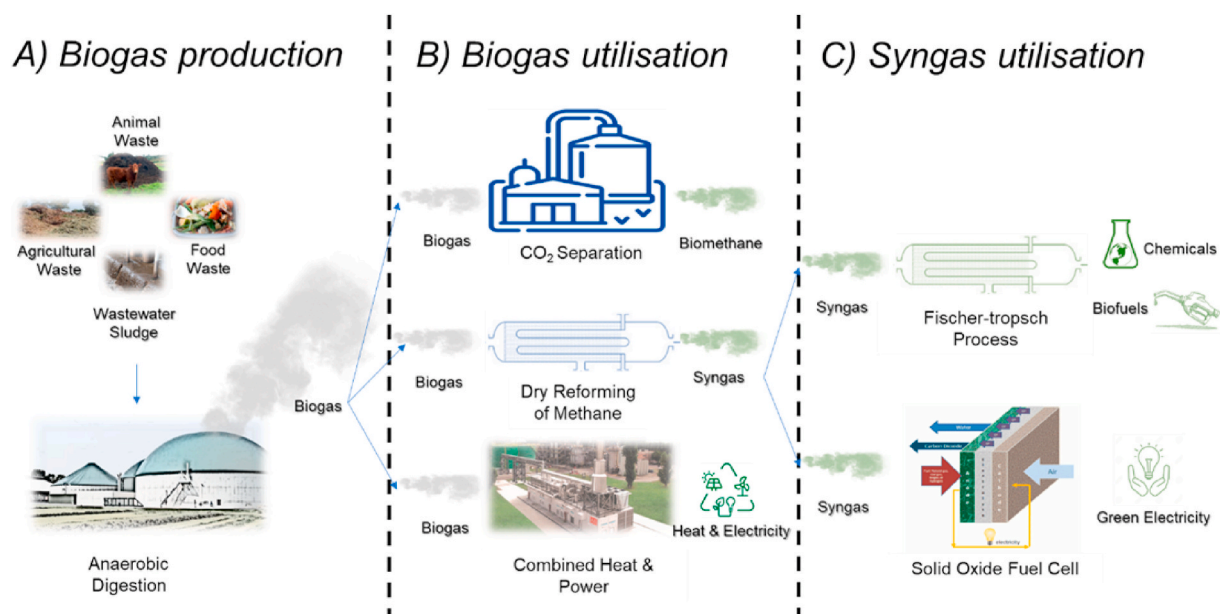

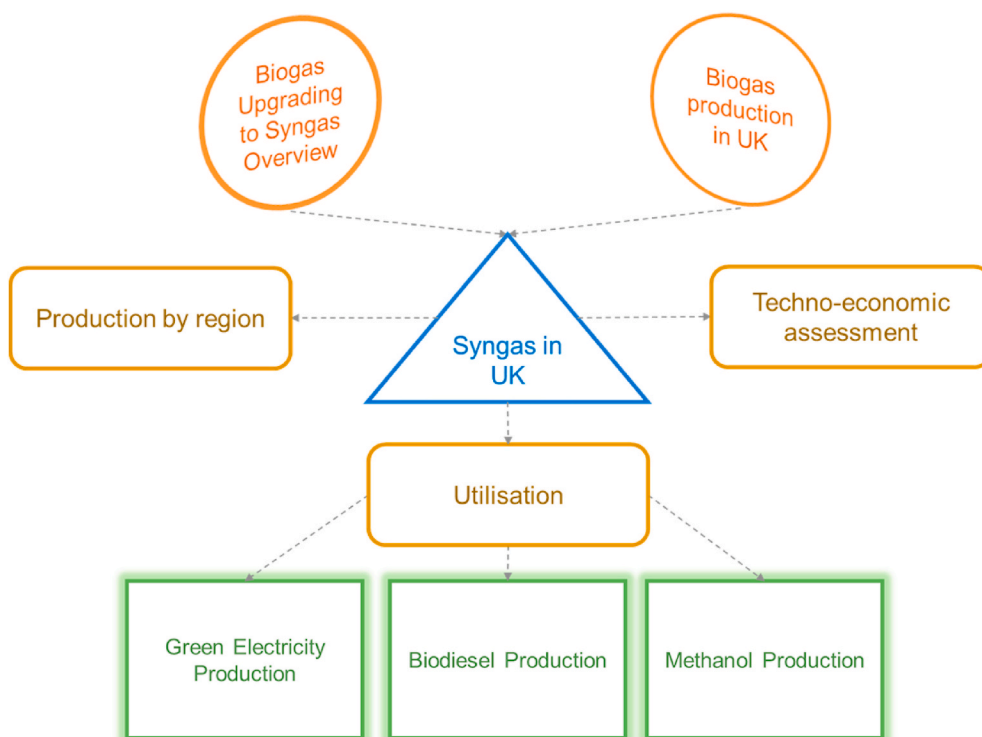**Fig. 1.** Biogas utilisation routes.

Fig. 2. Proposed workflow.

addressed in section 3.1. Both the catalytic works reviewed, and the biogas production data collected find a synergy in section 3.2, where the analysis of potential syngas production from biogas in the UK via DRM is carried out. Section 3.3 presents the results of the economic analysis performed, where estimating a syngas price is the objective of all the scenarios evaluated. Finally, section 3.4 shows an estimation of the production of electricity, green diesel and methanol from syngas in the UK.

1.3. Overview of dry reforming methane route

Catalytic paths for biogas upgrading have been traditionally carried out via the DRM reaction, which reads
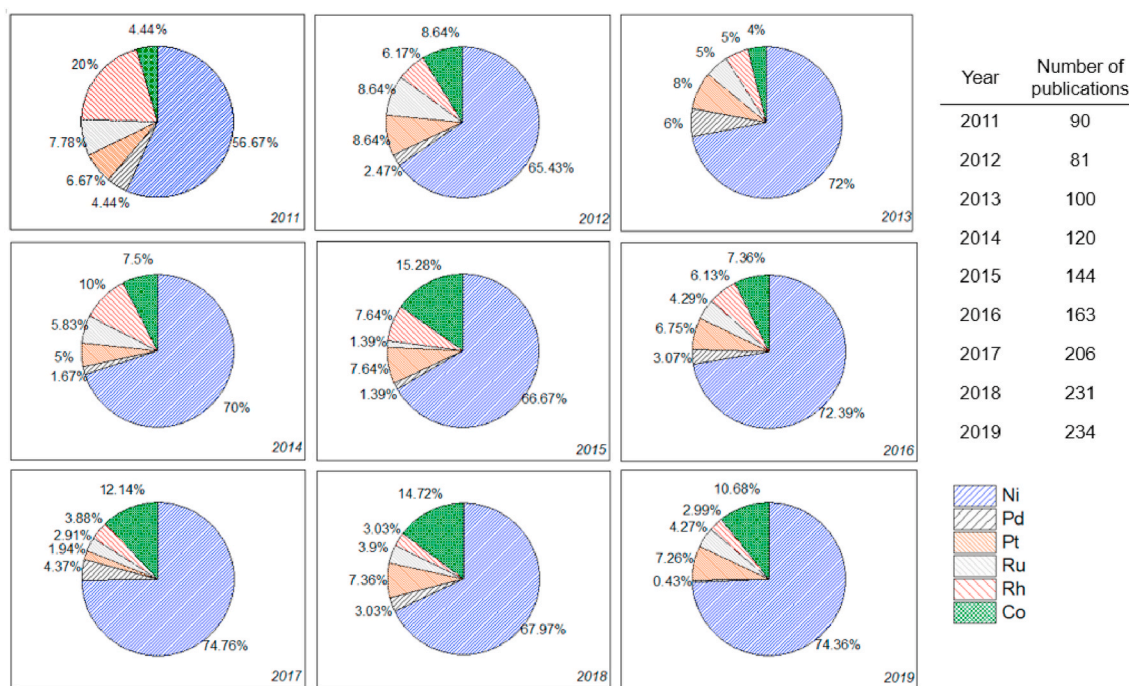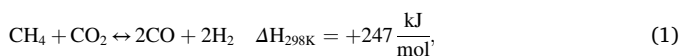

Fig. 3. Number of publications per year for different active phases for DRM. Data collected from Scopus—keywords: dry reforming methane & active phase material, i.e. Ni).

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \quad \Delta H_{298K} = +247 \frac{kJ}{mol}, \tag{1}$$

In this reaction, CO_2 and CH_4 (both considered as major GHG) are transformed into syngas (a highly valuable intermediate for the production of fuels, chemicals or green electricity [27,28]). DRM is an endothermic reaction and the reactants involved present high stability. Therefore, high reaction temperatures as well as catalysts are needed to achieve acceptable yields. The reaction temperatures for DRM reaction ranges typically from 600 °C to 900 °C [15]. Acceptable CH_4 conversions (60–65%) and H_2 yields (50–60%) are obtained within said range. To avoid catalyst deactivation caused to carbon deposition, high temperature (*ca.* 900 °C) is preferred over the low temperature (*ca.* 600 °C) [15, 29]. The catalysts chosen are crucial, too. A comprehensive literature survey has been carried out to determine the most common catalysts for DRM. Fig. 3 and Fig. 4 reveal, respectively, the active phase and the supporting material used for DRM reaction in published studies from 2011 to 2019.

As shown in Fig. 3, Ni-based catalysts are commonplace. Indeed, Ni is far from the second material most employed for DRM purposes, which is Co. The reason behind the success of Ni is economic, as Ni is cheaper and presents higher availability than noble metals such as Pd and Pt [27]. Besides its lower price, Ni is preferred over other similar metals (i.e. Co) because its global production is higher and the conversion and selectivity obtained are similar than that of Co [30,31]. This makes Ni-based catalysts of great interest for DRM reaction from an industrial point of view. Moreover, Ni presents good stability for long-term operations when operated at equilibrium conversions. In those cases where even higher stability is needed, Rh or Ru can be used [32,33], although the utilisation of the latter two entails higher costs than the use of Pd and Pt. Fig. 3 also reveals that further diversity in terms of active phase research is needed. The search of alternative metals which may present similar results to those given by Ni could reduce the catalytic dependant of this active phase.

Regarding the supporting material, Fig. 4 reveals that Al_2O_3 dominates. Al_2O_3 provides high surface area as well as adequate thermal and mechanical properties, which are essential for the catalytic reaction [34]. Other reasons are its price and availability. Since Ni and Al_2O_3 are the most feasible active phase and supporting material for DRM reaction, many studies have focused on improving their performance [17, 35–38].
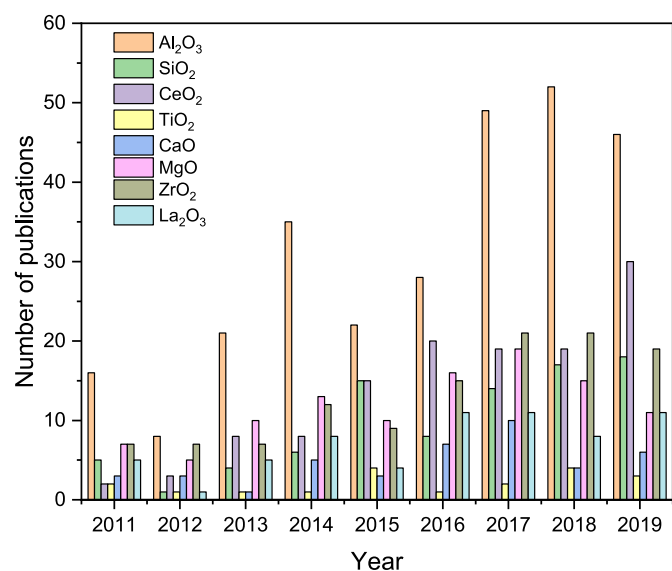
Even though, from an industrial perspective, Ni/Al_2O_3 is the most appropriate catalyst because of its low cost and availability, scaling-up towards commercialisation for DRM remains challenging [18]. The main drawback of Ni-based catalysts is deactivation at the reaction temperatures needed for DRM. Ni deactivation is mainly caused by carbon deposition, which can happen either by CH_4 decomposition or through the Boudouard reaction (catalysts deactivation by blocking catalyst active sites) [39]. Some strategies can be adopted to improve the activity and stability of Ni-based catalysts comprehensively review by Boldrin et al. [40].

Bimetallic catalysts have also been investigated. To reduce carbon deposition, the combination of Ni and Co as active phases has proved effective [41–43]. Indeed, as reported by Arora and Prasad [39], conversions for DRM using bimetallic Ni–Co catalysts are greater than those obtained with stand-alone Ni catalysts. Ni has been also combined with Pt [44], Sn [45], Ru [46] or Pd [47] to form bimetallic catalysts. Even if the overall performance of bimetallic catalysts is greater, there is an obvious extra-cost related to the catalyst manufacturing [48].

Modifications on the supporting material for Ni-based catalysts have been studied, too. Al_2O_3 has been compared with MgO, TiO_2, SiO_2, ZrO_2, and La_2O_3–ZrO_2 Ni-based catalysts [49], evidencing greater performances than that of other supporting materials, hence giving rise to further opportunities to improve traditional Ni/Al_2O_3 catalysts [17]. Ni-based catalysts can also be promoted with alkaline species such as CaO or MgO to enhance the thermal stability of the ensemble and tune the acid-base properties [50]. For instance, promoting Ni–Al_2O_3 catalysts with CaO can provide better overall performance by preventing deactivation [51]. Depending on the effect sought, the use of these CaO or MgO promoters on Ni-based catalysts enhances other properties such as basicity or oxygen storage capacity [18,27]. ZrO_2 and CeO_2 have also been explored to improve Ni-based resistance against deactivation or carbonation [52–56].

Based on the information above, the catalysts selected to perform the present study are Ni/Al_2O_3, $Ni/CaO–Al_2O_3$, $Ni–Sn/Al_2O_3$, Ru/Al_2O_3, Rh/Al_2O_3 and $Ru/Ce–ZrO_2$. All of the possibilities concerning active phase or supporting material are covered.

2. Methodology

2.1. Assessment of biogas production in the UK

The objective of this section is to calculate the potential for biogas production from biomass in the UK. Data on existing anaerobic digestion biomass plants have been gathered from 'The Official Information Portal on Anaerobic Digestion' [57], a database which classifies every biomass processing plant which involves anaerobic digestion in the UK by type of output, location, processing capacity, and feedstock composition. Nonetheless, said database does not provide biogas capacities and therefore, these have been estimated. Regarding types of output, the database classifies the plants according to CHP and biomethane production. The majority of biomethane production plants have been built in the last decade and therefore, these have not reached full depreciation. On the other hand, CHP systems have been in operation for a longer amount of time and are therefore likely to have reached full depreciation. In this sense, retrofitting CHP plants can be a cheaper alternative than the retrofit of biomethane plants. For this reason, only those producing CHP have been considered in our calculation [58]. The location of each biomass processing plant has been used to calculate the potential for biogas production per UK region.

The biogas that could be potentially produced Q_{bio} (Eqn. (2)) by one of the biomass processing plants is approximated by the expression

$$Q_{bio} = \sum_{i=1}^{N} \left(a_i \frac{T}{f_i} \right), \tag{2}$$

where N is the number of types of feedstock entering the plant, a_i is the

Fig. 4. Number of publications per year for different supporting materials for DRM. Data collected from Scopus—keywords: dry reforming methane & supporting material, i.e. Al_2O_3.

biogas yield of each type of feedstock in m^3/t (Table 1), T is the processing capacity of each plant given by the database cited above in tons per annum [57], and f_i is a correction factor equal to the number of types of feedstock being processed by a given plant and explained as follows.

The database given in Ref. [57] does not provide the amount of each type of feedstock processed, and therefore, the total processing capacity in tons of biomass, which is indeed provided, was split equally per type of feedstock in the absence of any further data. Thus, if the feedstock of the biomass plant is composed by only one type of waste, the percentage of this waste was 100%, yielding a correction factor $f_i=1$. In those instances where two types of waste were used, the percentage of each waste was 50% each ($f_i=2$), and so on. This value can be considered as a weighted mean. The working hours assumed were 8000 h per annum.

2.2. Assessment of syngas production from biogas via dry reforming of methane in the UK

The potential syngas production capacity in the UK via DRM was estimated by using the biogas production obtained in section 2.1 and a selection of $Ni-Al_2O_3$ catalysts as discussed in section 1.3. Six catalysts were selected for comparison. This allowed further discussion regarding the correlation between the catalyst used and the syngas production potential. The first catalyst chosen was Ni/Al_2O_3, since it is the most extended catalyst for DRM, as explained in section 1.3. Ni/Al_2O_3 constitutes the base case scenario for comparison in this study. The promotion of the supporting material was considered selecting $Ni/CaO-Al_2O_3$. The combination of different metals as the active phase was also studied. For this purpose, we incorporated $Ni-Sn/Al_2O_3$ to our analysis. Higher price metals such as Rh and Ru were also included in this syngas production estimation for comparison. Rh/Al_2O_3 and Ru/Al_2O_3 were selected since, as previously explained in section 1.3, these active phases also provide longer life span. Finally, the DRM performance of a very different – more expensive – catalyst ($Ru/Ce-ZrO_2$) was also included. The materials Ru, Ce and Zr were selected because of the higher efficiencies they provide although their prices are much higher than Ni and Al_2O_3. The approximated CH_4 conversion (Table 2) was the parameter considered to estimate syngas production with each catalyst.

Table 1
Biogas production values from different feedstocks employed in this work.

Feedstock	Biogas production (m^3/t)	References for calculations
Animal manure	92	[59]
Energy crops	186	[60–62]
Grass silage	39	[63–65]
Maize silage	96	[66]
Vegetable & fruit waste	51	[67]
Sugar beet	34	[68,69]
Wholecrop wheat	40	[70]
Food waste	119	[71,72]
Potato waste	70	[73]
Organic fraction of MSW	88	[74]
Poultry manure	71	[75]
Cattle manure	50	[76–78]
Brewery waste	34	[79]
Dairy waste	40	[80]
Ryegrass	46-70[a]	[81,82]
Cattle slurry	25	[57,83]
Brewery wastewater	52	[84]
Cheese waste	14-31[a]	[85,86]
Coffee waste	20	[87]
Confectionary production waste	38	[88]
Distillery wastes	39	[89]
Farm yard manures	75	[90]
Potato peelings	21	[91]
Livestock bedding	20	[92]

Authors selected the data in order to be on the conservative side.
[a] Contradictory values were found in the literature for this feedstock.

Table 2
Catalysts selected to estimate the syngas capacity in the UK.

Catalyst	CH_4 conversion (%)	Reference
Ni/Al_2O_3	60	[37]
$Ni/CaO-Al_2O_3$	58	[95]
$Ni-Sn/Al_2O_3$	63	[45]
Ru/Al_2O_3	63	[32]
Rh/Al_2O_3	67	[33]
$Ru/Ce-ZrO_2$	65	[96]

Moreover, full separation of the reacted and unreacted components was assumed [93,94]. The separated flow, which still contains CH_4, was assumed to be burnt to produce thermal energy.

Reaction conditions such as temperature, reactants ratio and space velocity are provided in the selected references and overall these conditions represent a good picture of DRM studies in catalysis literature.

2.3. Economic model for syngas production in the UK

The objective of the economic evaluation was to estimate the price of a cubic meter of syngas to make the DRM alternative profitable. Thus, the economic model performed follows the Discounted Cash Flow (DCF) method, which allows to estimate the profitability of engineering projects. Among the alternative indicators of DCF method, the Net Present Value (NPV) and the Profitability Index (PI) were chosen as these are the most recommended for preliminary profitability evaluations [97]. The first indicator (NPV) reveals the positive or negative sign of the project. The PI indicator in turn, estimates the value returned per unit of investment. The calculation of these indicators was carried out following Eqns (3) and (4), where I_t represents the cash inflows and O_t means the cash outflows. The rest of parameters are the discount rate (r_d), the lifetime of the project (n), and the investment cost (C_{inv}). I_t and O_t were calculated through Eqns (5) and (6) respectively. The only revenue of this evaluation is the syngas selling R_{syngas}, calculated by means of Eqn. (7), which is composed by the syngas flow obtained from biogas Q_{syngas} and the syngas price p_{syngas}. The syngas composition set is $H_2:CO$ ratio equal to 1. The set of equations used are:

$$NPV = \sum_{t=0}^{n} \frac{I_t - O_t}{(1 + r_d)^t}, \tag{3}$$

$$PI = \frac{\sum_{t=0}^{n} \frac{I_t - O_t}{(1+r_d)^t}}{C_{inv}}, \tag{4}$$

$$I_t = R_{syngas}, \tag{5}$$

$$O_t = C_{loan} + C_{il} + C_{mo} + C_{df} + C_{ins} + C_{inst} + C_{ut} + C_{cat} + C_{lab}, \tag{6}$$

and

$$R_{syngas} = Q_{syngas} * p_{syngas}. \tag{7}$$

The outflows estimation (Eqn. (6)) contains the costs explained below. The investment C_{inv} was assumed to be covered by a loan C_{loan} considering payment of interest C_{il}. Eqns (8) and (9) have been used to estimate these costs, where n_l is the loan period, t the actual year, and r_{int} the interest rate. C_{inv} was estimated following the six-tenths rule [98], in which the investment cost can be estimated from previous investment cost of similar plants (Eqn (10)). To this end, the investment cost of previous studies C_{prev} and capacities of previous studies Q_{prev} were used to correlate with our capacities [99]. A Conversion ratio of 1.10 between (US Dollar to Euro) was considered. Maintenance & overhead C_{mo}, depreciation C_{df}, insurance C_{ins} and installation C_{inst} costs, were estimated as a percentage of the previous costs (Eqns (11)–(14)) [100]. The cost of the utilities C_{ut} needed for syngas production from biogas was calculated using Eqn (15), where Q_{syngas} is annualized with the number

of working hours per year n_{wh} and multiplied by the unitary cost of utilities C_{uut}. A conversion factor of 0.0111 MWh/m^3 and updating percentage of 6.5% were used [101]. Labour cost C_{lab} calculations imply the multiplication of the unitary labour cost C_{labu} by the number of operators n_{op} (Eqn (16)). Finally, the catalyst cost C_{cat} was calculated using Eqn (17), in which Q_{cat} is the amount of catalyst needed and p_{cat} is the catalyst price. Q_{cat} was calculated considering the weight hourly space velocity (WHSV) and the biogas flow Q_{bio} to be treated. The following are the equations used to obtain the variables mentioned above:

$$C_{loan} = \frac{C_{inv}}{n_l}, \quad (8)$$

$$C_{il} = [C_{inv} - C_{loan}*(t+1)]*r_{int}, \quad (9)$$

$$C_{inv} = C_{prev} * \left(\frac{Q_{syngas}}{Q_{prev}}\right)^{0.6}, \quad (10)$$

$$C_{mo} = C_{inv}*p_{mo}, \quad (11)$$

$$C_{df} = C_{loan}*p_{df}, \quad (12)$$

$$C_{ins} = C_{inv}*p_{ins}, \quad (13)$$

$$C_{inst} = C_{inv}*p_{inst}, \quad (14)$$

$$C_{ut} = Q_{syngas}*n_{wh}*C_{uut}, \quad (15)$$

$$C_{lab} = C_{labu}*n_{op}, \quad (16)$$

and

$$C_{cat} = Q_{cat}*p_{cat}. \quad (17)$$

As Ni/Al$_2$O$_3$ is the most used catalyst (see section 1.3), it was considered as the baseline catalyst. Specifically, a 10% Ni catalyst was chosen in agreement with standard compositions [45,102]. An economic comparison of the catalyst selected was later performed, choosing Ru/Al$_2$O$_3$ and Rh/Al$_2$O$_3$ catalysts as these have proved more stable for long-term operations. Furthermore, Ru/Al$_2$O$_3$ and Rh/Al$_2$O$_3$ provide higher conversions as shown in section 2.2. Specifically, a 2% Rh catalyst and 3% Ru catalyst were selected in accordance with previous studies [32,33]. Considering their relative stability for long-term operations, we assume a catalyst life span of 12 months for Ni, 18 months for Ru and 36 months for Rh. For Ni/Al$_2$O$_3$, commercial prices were found as it is a well stablished catalyst in the industry. For Ru/Al$_2$O$_3$ and Rh/Al$_2$O$_3$, a price per kg of catalyst was estimated in agreement with Eqns (18) and (19). For this purpose, we assume the catalyst price as the costs of the raw materials (p_{Rh}, p_{Ru} and p_{Al}) and the percentage of each in the catalysts as:

$$p_{cat-Rh} = 0.02*p_{Rh} + 0.98*p_{Al}, \quad (18)$$

and

$$p_{cat-Ru} = 0.03*p_{Ru} + 0.97*p_{Al}. \quad (19)$$

Table 3 collects the economic inputs employed for the techno-economic evaluation.

As previously mentioned, our economic analysis focused on syngas price to reach profitability. To this end, five biogas plant sizes were studied in agreement with the results presented in section 3.1, where biogas production in the UK is analysed. Afterwards, a deeper evaluation was performed, including the catalyst selected and catalyst raw material prices. The model presented here has some limitations, which are: (1) The reference chosen to estimate the investment costs was based on a capacity greater than the capacities considered here. This could lead to broaden the overall error. Nonetheless, as there is a lack of information concerning this point, the estimation was performed by applying the six-

Table 3
Economic inputs used in the techno-economic evaluation.

Variable	Value	Reference
N	20	Assumed
r_d (%)	10	[97]
C_{prev} (k€)	29240	[99]
Q_{prev} (m^3/h)	87986	[99]
n_l (y)	15	[103]
r_{int} (%)	10	[104]
p_{mo} (%)	10	[105,106]
p_{df} (%)	20	[97,105]
p_{ins} (%)	1	[103]
p_{inst} (%)	20	[107]
n_{wh} (h/y)	8000	Assumed
C_{uut} (€/kWh)	0.084	[108]
C_{labu} (€/y/worker)	62400	[109]
n_{op} (worker)	50 m^3/h – 3	[100]
	100 m^3/h – 4	
	250 m^3/h – 5	
	500 m^3/h – 6	
	1000 m^3/h – 8	
WHSV (L/g h)	120	[37]
p_{cat-Ni} (€/kg)	32.18	[104]
p_{Rh} (€/kg)	215410	[110]
p_{Ru} (€/kg)	8158	[110]
p_{Al} (€/kg)	0.295	[111]

tenths rule; (2) The cost of the catalysts is based on the costs of the active phase (as explained before), which is usually much greater than the supporting material; (3) The catalyst life span was assumed, as there is no way to know the real life span of these catalysts at industrial scale; (4) The WHSV was assumed at the value given above for all the catalyst. This assumption was taken for comparison. Selecting the same WHSV for all the catalysts implies setting a fixed reactor volume. Therefore, the influence on the economic performance will be produced only by the nature of the catalyst. As authors are aware of these limitations, at the end of the economic estimation (section 3.3), a sensitivity analysis has been included. In this analysis, the scaling factor used for the six-tenths rule, WHSV and catalyst life span are varied to verify its overall influence on the economic estimation.

2.4. Assessment of utilisation routes for syngas

Three scenarios were considered in our analysis for its utilisation (Fig. 1). The first included the conversion of syngas to electricity through a SOFC process. The second estimates the production of green diesel as a potential biofuel product from syngas through the Fischer-Tropsch route. The last scenario considers the production of methanol from syngas. For these three scenarios, the starting point is the syngas production obtained with Ni/Al$_2$O$_3$, which is analysed in section 3.2. The selection was based on the commercial availability of these catalysts, as well as in its relatively low price. Table 4 collects a brief explanation of each scenario as well as their assumptions. Some of the extra data needed for the calculation are indicated below. For the electricity production estimation, the enthalpy of combustion for H$_2$ and

Table 4
Scenarios explored for syngas utilization.

Scenario	Goal	Assumptions	References for data
1	Electricity production through SOFC	- Yield from available enthalpy of syngas to electricity: 50%. Typical range: 30–74%	[116–119]
2	Biofuel production through Fischer-Tropsch	- Yield from syngas to Biofuel based on H$_2$ conversion: 55% Typical range: 40–70%	[120,121]
3	Methanol production	- Yield from syngas to methanol: 20% Typical range: 15–25%	[115,122, 123]

CO were −286 kJ/mol and −283 kJ/mol respectively [112]. Toe conversion factor of green diesel is 0.88 [113], and the density of green diesel was 0.86 t/m^3 [114]. Methanol density was selected at standard conditions (0.792 t/m^3). For these estimations, a H_2/CO ratio of 1 was assumed, even though different values can be found in the literature [115]. This is an important parameter to consider as adding hydrogen/water to increase the ratio will entail higher costs.

3. Results and discussion

3.1. Biogas production in the UK

The data obtained were gathered in an additional database, extension of that in Ref. [57]. The reader can access the expanded database on the following Open Science Framework link https://osf.io/6hr8b/?view_only=1a6e993a9ff447059274797507f1bad1. The biogas production capacity was subsequently collated and classified by UK region. In total, 391 biogas production plants were analysed. As the result of the estimation, the potential for biogas production by region in the UK was obtained (Fig. 5). The biogas production results obtained would increase should biogas production from waste – biomass costs decrease. Nonetheless, not only costs play a key role but also the feedstock availability. As shown in Fig. 5, the East of England possesses the highest biogas production capacity, followed by the East Midlands and Scotland. There are therefore two potential-biogas-production hotspots in UK: one in Scotland, and another in the regions to the north east of London (i.e. East Midlands, West Midlands, and East of England). In addition, the regions with the greatest biogas production potential are those with a gross value added (GVA) below the UK average (12%) [124]. GVA can be defined as the economic macro-magnitude that measures the value generated by a group of producers in an economic area, ultimately collecting the value added to goods and services in the different stages of the production process. The GVA of East Midlands (EM) was 5.7% of that of the UK in 2016 [124] (9th position over the twelve regions) and that of the West Midlands (WM) was 7.2% (7th position) [124]. The production of syngas from biogas in said regions could therefore constitute a boost to the local economy in addition to the increase in renewables needed to meet the target pointed out in the introduction to this

document. Also, the geographic distribution of biogas production potential from biomass depicted in Fig. 5 could help with logistic plans. Regarding the capacities of the biogas plants studied, Fig. 6 reveals the percentage distribution by plant size. Biogas production plants have been classified in this work as small (up to 250 m^3/h), medium (500 m^3/h) and large scale (1000 m^3/h) [100,125]. There is a predominance of small to medium plants (50–500 m^3/h), adding an 84% of the total. In view of Fig. 6, the following biogas plant sizes were chosen as representative of the UK outlook for biogas production: 50, 100, 250, 500 and 1000 m^3/h. These data are necessary for the techno-economic analysis carried out in section 3.3.

3.2. Syngas production in the UK via dry reforming of methane

The results obtained for the syngas production estimation are plotted in Fig. 7. A total of 155,703 m^3/h of syngas can be obtained if the baseline catalyst, i.e. Ni/Al_2O_3, is chosen. In terms of production, similar
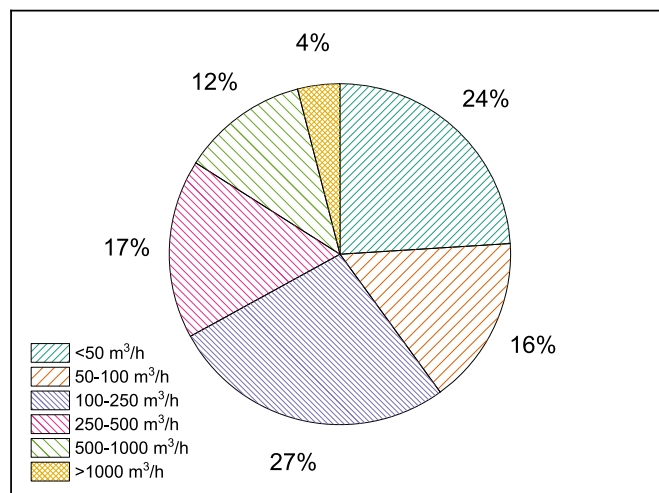
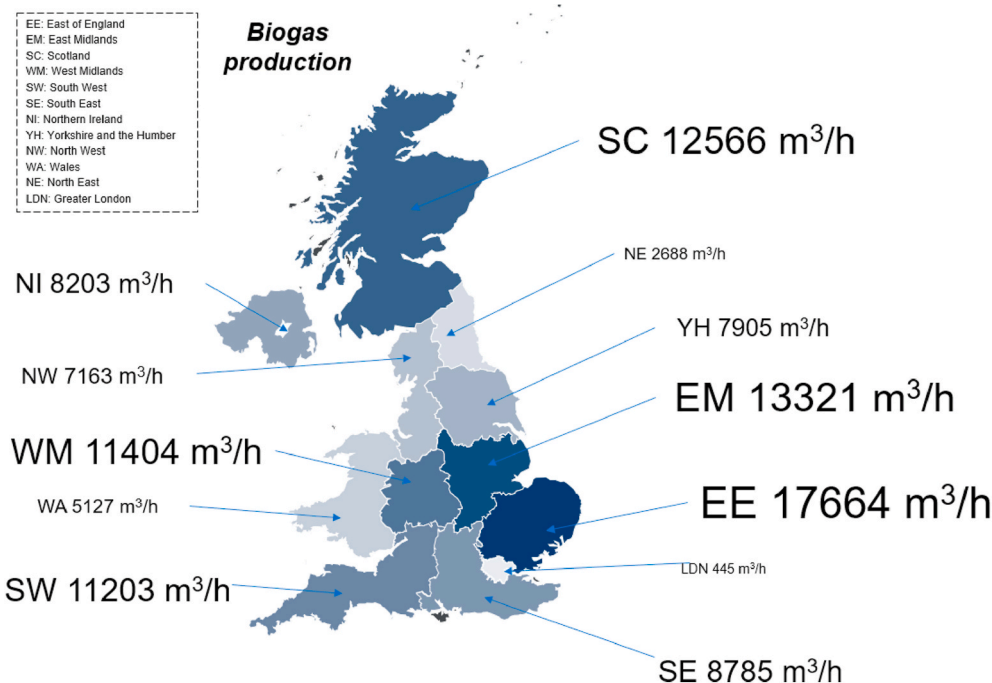**Fig. 6.** distribution by biogas production plant size in the UK.

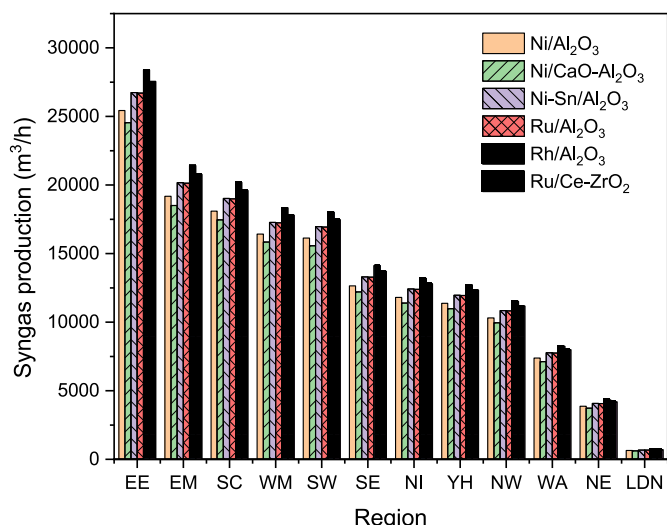**Fig. 5.** Biogas production estimation in the UK by region.

Fig. 7. Syngas production with different catalysts by region.

supporting material consumption for catalyst manufacturing, the amounts needed are less important than economic performance but still a key factor to discuss the feasibility of our proposal. As an example, Ni and Al_2O_3 needs for syngas production were estimated. According to Charisiou et al. [37], 0.6 L/h of biogas feed reacts over 0.005 g of an 8% Ni–92%Al_2O_3 catalyst. Thus, for a biogas flowrate of 108,127 m^3/h, 346 t Ni and 3979 t Al_2O_3 would be needed per year. The production of Ni in the UK was 39,100 t in 2014 [126]. Therefore, only a 1% of the total Ni production would be needed for biogas upgrading to syngas. Certainly, for Al_2O_3, the amount needed (3979 t/y) would be higher and overseas supply would be needed. Indeed, the demand could be covered by the yearly production of Al_2O_3 in West Europe (5738 t in 2019 [127]), and that of China (71,282 t in 2019).

3.3. Techno-economic analysis of syngas production from biogas

Fig. 8 showcases the economic results obtained in our analysis. The evolution of the indicators chosen (NPV and PI) with syngas price for the five selected sizes is plotted in Fig. 8A and B respectively. Fig. 8C shows the minimum syngas price to reach an NPV equal to zero for the selected biogas plant sizes. Alternatively, this syngas price can be considered the minimum price to cover overall costs. As shown, the syngas price per cubic meter needed to achieve profitable scenarios decreases as long as biogas plant size increases. This is a direct consequence of the economy of scale. Indeed, as can be seen in Fig. 8A, NPV value of smaller plants is higher than larger plants for the lower syngas price. This result is inverted due to the greater slope of the larger plants, which allow them to reach profitable scenarios at lower prices. The results obtained for the evolution of PI with syngas price show similar trends.

According to our analysis, the minimum syngas (bio-syngas) price to reach profitability is 1.15 €/m^3 for 1000 m^3/h plant sizes. This value is rather high in comparison with other energy vectors such as biomethane or natural gas. For example, the costs of biomethane production varies from 0.54 to 0.73 €/m^3 [128], which is half the price calculated here.
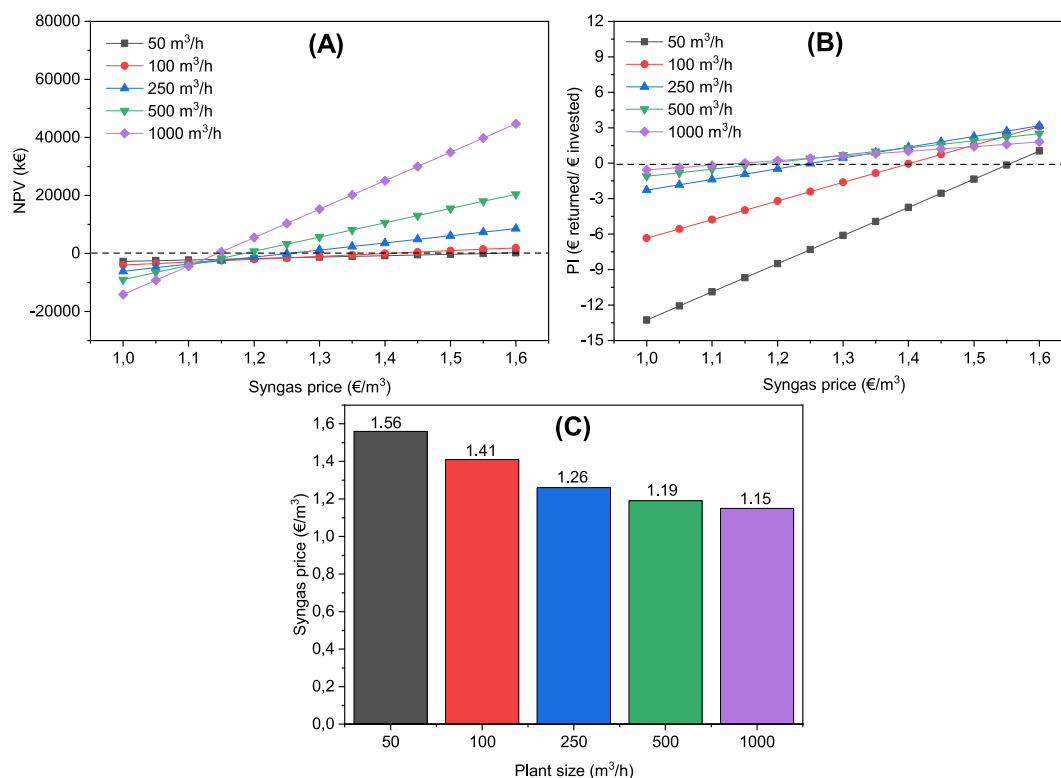
conclusions to the previous section can be extracted. The modification of the supporting material via the incorporation of CaO prevents catalyst deactivation [51], but it causes a reduction of 5450 m^3/h in the total syngas production. Using a bimetallic Ni-based catalyst (Ni–Sn) the DRM performance improves, but an extra cost must be assumed as discussed previously. The utilization of a novel metal (Ru or Rh), provides higher productions and longer life span. The same result is obtained when catalysts formed by less available elements, such as Ru or Ce, are selected. These elements improve the syngas production by 8% (168, 678 m^3/h) with respect to the baseline catalyst. For these latest assumptions, the cost of catalyst manufacturing would be accordingly higher. Our results indicate that an optimization study for DRM performance – catalyst costs is needed. In terms of active phase and

Fig. 8. Economic results of syngas from biogas via DRM using Ni/Al_2O_3 catalyst: (A) NPV evaluation for different syngas prices and plant sizes; (B) PI evaluation for different syngas prices and plant sizes; and (C) Syngas prices for NPV equal to zero scenarios.

Therefore, biomethane production from biogas may be a more interesting alternative from an economic point of view. Comparing to the prices of producing syngas by traditional fossil fuels, the results presented here are far from being competitive. Producing syngas from natural gas via gasification costs around 0.08 €/m^3 [129]. This reveals that further research is needed to low syngas producing cost by DRM. In some countries, such as Italy or Germany, there are governmental incentives for the production of renewable energy carriers. For instance, biogas production is incentivised in Germany with a premium price for kWh produced (14.73–16.73 cents/kWh) [130]. Another example of governmental incentives can be found in Italy, where 61 €/MWh are paid for injecting biomethane to the grid [130]. This incentive strategy could be also of great interest for bio-syngas production in those countries where the promotion of renewable energy is a priority.

The cost breakdown shows that catalysts price is the most influencing cost (i.e. 49% for 250 m^3/h), followed by labour (26% for 250 m^3/h), loan (14% for 250 m^3/h) and M&O (9% for 250 m^3/h). Fig. 9 reveals the economic influence of the catalyst selected for 100 and 250 m^3/h plant sizes. The sizes selected were in agreement with the higher percentage presented in Fig. 6, as biogas plants up to 250 m^3/h represent 67% of the total. As shown in Fig. 9, the selection of a noble metal-based catalyst may provide both more stability for long-term operation and higher efficiency, but still Ni/Al$_2$O$_3$ is more economically appealing for syngas production. Indeed, the use of Ru/Al$_2$O$_3$ catalyst increases the syngas price needed to reach NPV zero by 35%. When Rh/Al$_2$O$_3$ is selected, the syngas price increases by 671%. This dramatic increase is caused by the cost of the raw materials which form the catalyst. In this direction, Fig. 10 shows the syngas price evolution with the cost reduction of Ru and Rh raw material prices. The analysis was performed for 250 m^3/h plant size and as in Fig. 9 the syngas price corresponds to NPV equal to zero. One can observe that the reduction of the Ru raw material price should be 70% to achieve the syngas prices obtained with Ni-based catalyst. In the case of Rh raw material price, even at 80% cost reduction, the syngas price is still far from the obtained with Ni/Al$_2$O$_3$ catalysts. These results confirm that Ni/Al$_2$O$_3$ catalysts have no economic competitors for DRM reaction.

Finally, to study the influence of some important parameters assumed and thus to provide a wider analysis, a sensitivity analysis was performed (Fig. 11). The parameters included are: WHSV (Fig. 11A), catalyst life span (Fig. 11B), and the scaling factor used for the six-tenths rule to estimate the investment costs (Fig. 11C). To compare with the previous results, the target economic output is syngas price per cubic meter to reach an NPV equal to zero. As shown in Fig. 11A and 11.B, the
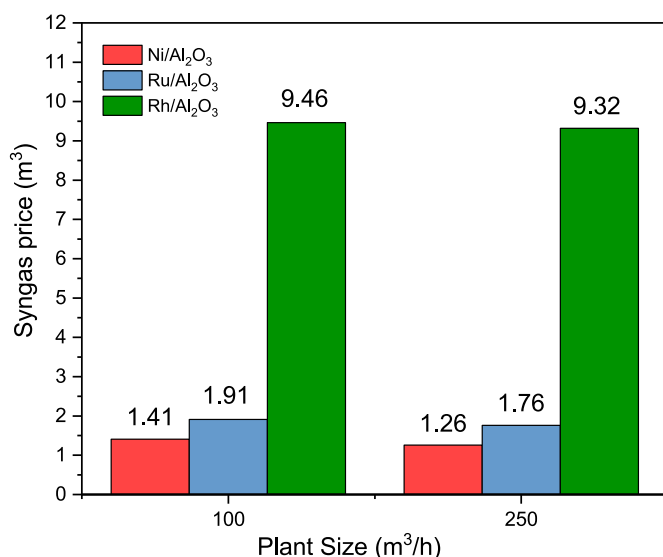

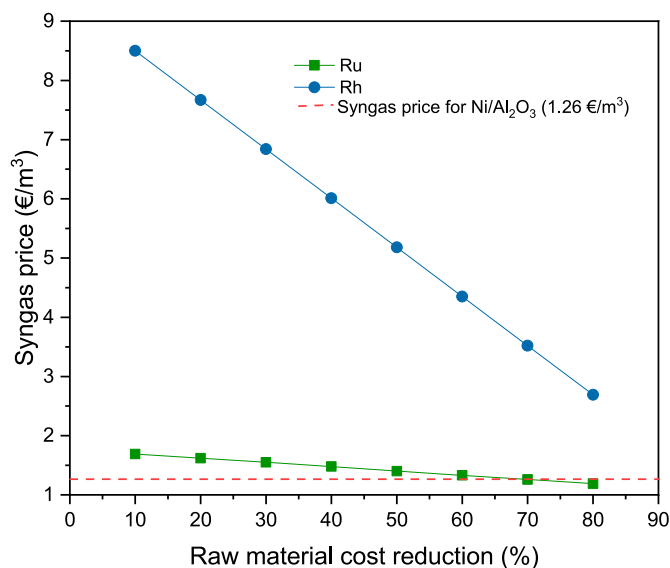**Fig. 10.** Syngas prices vs raw material cost reduction (250 m^3/h).

variation of these parameters affects considerably to Rh-based catalyst. This could be expected from the previous results as Rh catalyst needs the highest syngas prices. As shown in Fig. 11A, increasing WHSV can be a partial solution to improve the profitability of DRM with Rh catalyst. Nonetheless, the prices needed to reach an NPV equal to zero are still far from being competitive vs other alternatives discussed above. Regarding the adequacy of the six-tenths rule to estimate the investment costs, Fig. 11C reveals that the results obtained in our estimation will have an assumable error from 0.4 to 0.9 (0.6 was chosen for the initial estimation). Overall, it seems rather unlikely to use values below 0.4 and therefore, one can conclude that our estimation is valid.

3.4. Alternative utilisation routes for syngas: potential production and comparison

Fig. 12 gathers the results obtained for electricity, biofuel and methanol production from syngas. According to the potential electricity production from syngas, this path may not be a worthy alternative. The electricity consumption in the UK is greater than the electricity that could be produced by syngas utilisation in a SOFC. Table 5 includes a comparison of the potential electricity production from syngas and the actual electricity consumption in the UK. As shown, electricity production from syngas cannot meet the electricity needs in the UK, but it can contribute to the share of renewable electricity. Even in the most productive region, the percentage of electricity consumed from syngas would be 0.14%, i.e. Northern Ireland (NI). Based on these results, the production of green electricity may be better carried out by means of other renewable energy alternatives. Nonetheless, it could contribute to increase the local electricity production – consumption, hence boosting the independence from big electricity producers.

Interesting results were obtained regarding the green diesel production from syngas. Green diesel is commonly used to cover the needs for public transport. Indeed, a third of London's 9500 buses are already running on 20% blends of green diesel [133]. Fig. 13 compares the potential for green diesel from syngas with the consumption of diesel of public transport buses in UK. The data for buses fuel consumption were obtained from the UK Government [134]. In some regions such as East of England (EE) or the East Midlands (EM), the replacement of fossil fuels by green diesel could attain around 15%. This value reaches 37% of the diesel production in Northern Ireland (NI). The production of green diesel from syngas could be, along with other routes to produce green diesel, a partial solution for the fuel demand of public transport.

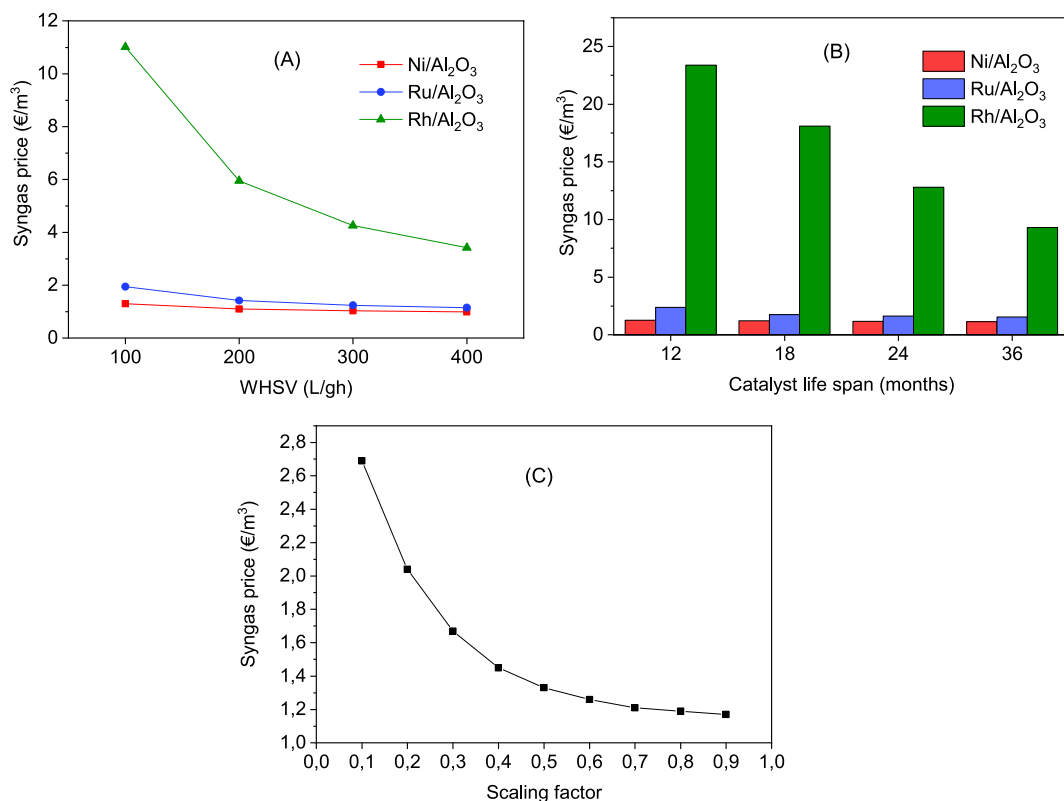Methanol production from syngas can be another interesting option

Fig. 9. Syngas prices for NPV equal to zero scenarios with different catalysts.

Fig. 11. Sensitivity analysis carried out for: (A) WHSV; (B) Catalyst life span; and (C) Scaling factor (for Ni/Al$_2$O$_3$ catalyst).
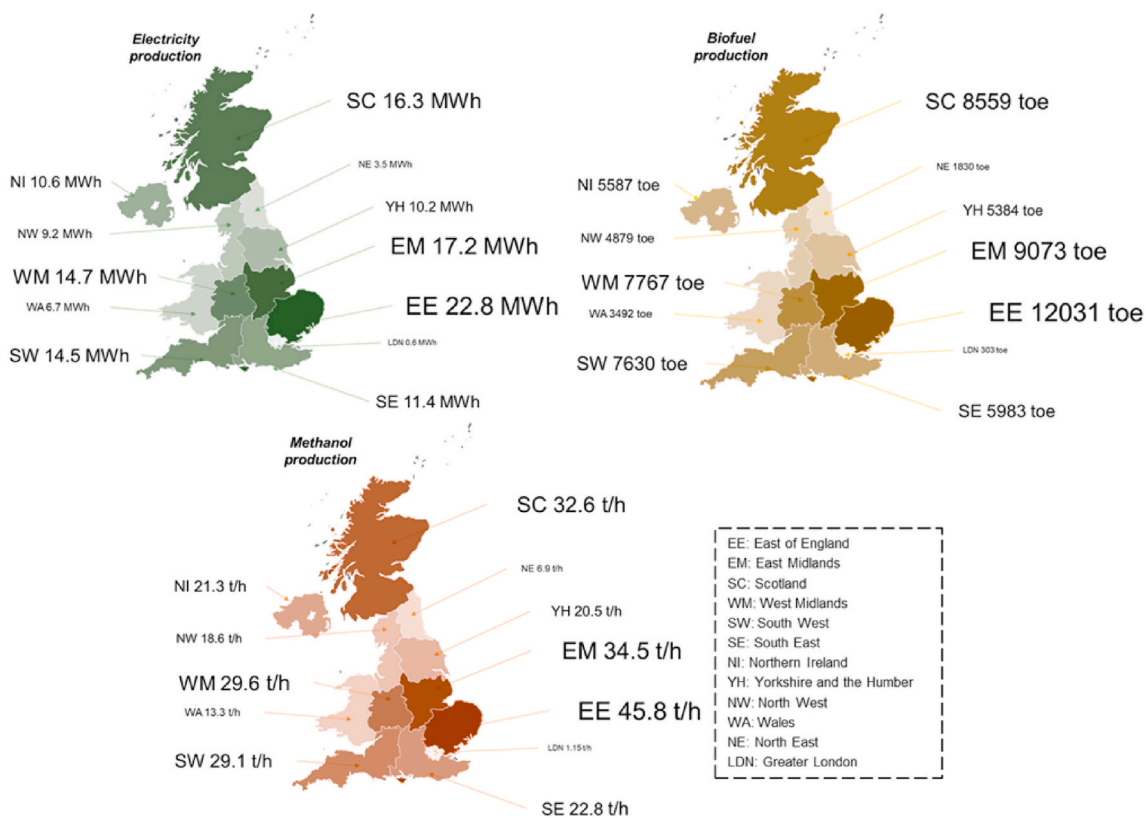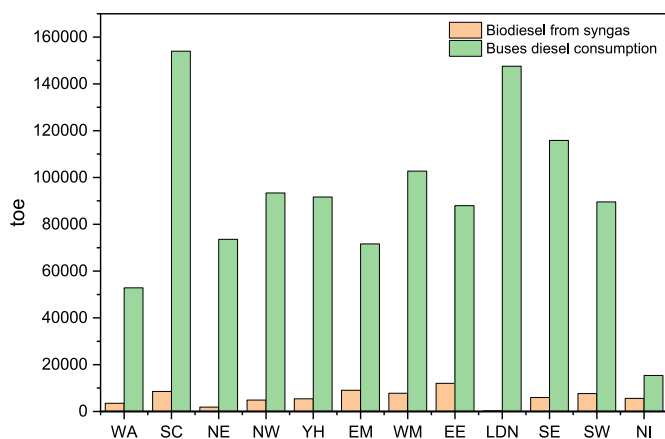

Fig. 12. Potential electricity generation, biofuel and methanol production from syngas by region (toe: tons of oil equivalent).

Table 5
Comparison electricity consumption vs potential electricity production in UK from syngas. All electricity consumption data were obtained from Ref. [131], except the data for NI [132].

Region	Electricity consumption in UK (2017) (MWh)	Potential electricity production from syngas in UK (MWh)
WA	14860	6.7
SC	24147	16.3
NE	11209	3.5
NW	30598	9.2
YH	22750	10.2
EM	20625	17.2
WM	23923	14.7
EE	26260	22.8
LDN	38100	0.6
SE	37718	11.4
SW	23570	14.5
NI	7950	10.6

Fig. 13. Comparison of green diesel production from syngas vs diesel consumed by buses in the UK.

for reducing the methanol imports. The present worldwide installed capacity for methanol production by traditional methods is 140 Mt, and is expected to reach 280 Mt in 2030 [135]. Based in the results herein, the UK could contribute significantly to achieve this target via syngas upgrading to methanol. According to our estimations, the global methanol production from syngas in the UK can be around 2.2 Mt per annum. Methanol production from syngas would inevitably compete with other routes both traditional (petro-methanol production) and renewable (i.e. power-to-methanol). This competition will depend on the cost performance of syngas to methanol path in comparison with these other routes.

4. Conclusions

In this work, the potential production of syngas from biogas via DRM in the UK has been analysed. The overview performed on DRM path for syngas production reveals a predominance of Ni based catalysts. The data analysed reveals that there are two potential biogas production areas of great potential in the UK: Scotland (12566 m^3/h) and the regions surrounding Greater London (EE, 17664 m^3/h; EM, 13321 m^3/h; WM, 11404 m^3/h, and SW, 11203 m^3/h). Syngas production from biogas follows similar trends to biogas production by region. An economic model was developed to estimate syngas production price from biogas. From an economic perspective, syngas prices ranging from 1.15 to 1.56 €/m^3 are needed to reach NPV equal to zero. Despite the economic model limitations, it can be drawn that the prices needed are not competitive with the current route to produce syngas (0.08 €/m^3). End uses of syngas were also studied, reaching the conclusion that electricity

production is not a worthy alternative, whereas the production of green diesel and methanol could be promising.

As these results evidence, syngas production from biogas can boost renewable energy production in the UK in terms of production capacity. The production of syngas from biogas should therefore be carefully weighed by the policies in those countries where the renewable energy production is considered an overriding need, particularly in the case of the UK, where international commitments have been signed to curb the emission of greenhouse gases by 2050.

Credit author statement

Francisco M. Baena-Moreno: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Daniel Sebastia-Saez: Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Laura Pastor-Pérez: Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Tomas Ramirez Reina: Supervision, Project administration, Funding acquisition.

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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