Applied Energy 184 (2016) 840–852

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Reasonable potential for GHG savings by anaerobic biomethane in Germany and UK derived from economic and ecological analyses

Thomas Horschig [a,*], Paul W.R. Adams [b], Mirjam Röder [c], Patricia Thornley [c], Daniela Thrän [a,d]

[a] DBFZ - Deutsches BiomasseForschungszentrum gGmbH, Leipzig, Germany
[b] Sustainable Energy Research Team, Dept. Mechanical Engineering, University of Bath, UK
[c] Tyndall Centre for Climate Change Research, The University of Manchester, UK
[d] Helmholtz Centre for Environmental Research, UFZ, Leipzig, Germany

HIGHLIGHTS

- Biomethane market potential estimation through biogas market analyses.
- Country comparison of Germany and the UK in terms of bioenergy.
- Assessment of possible greenhouse gas emission savings by biomethane.
- Role of biomethane to achieve greenhouse gas reduction goals in Germany and the UK was investigated.

ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form 19 July 2016
Accepted 25 July 2016
Available online 11 August 2016

Keywords:
Biomethane markets
Greenhouse gas emissions
Fossil fuel substitute
Bioenergy
Potential estimation

ABSTRACT

This study introduces a new approach to estimate biomethane market potential by analysing biogas markets and their relative environmental and economic advantages. This potential is then combined with greenhouse gas emission values for different feedstock shares (farm-fed and waste-fed systems) and different application share to determine the possible contribution of biomethane to national greenhouse gas emission saving goals. Markets that are considered are Germany and the UK being the biggest emitters of CO_{2eq} in the European Union. The current use was compared with the scenarios (i) market projection, derived from literature study and (ii) reasonable potential, derived from environmental and economic calculations. The current market status is presented to show the past market development until the present date and associated greenhouse gas savings. Additionally the potential of biomethane to contribute to greenhouse gas emission savings is extensively described. Results indicate that the share of application in Germany is more environmental beneficial than the one in the UK achieving higher greenhouse gas savings at comparable feed-in level. In contrast, the UK has a higher share of waste-fed systems to produce biomethane. The use of biomethane in CHP plants achieves the highest GHG emission savings and if organic waste is used as feedstock the possible savings are even higher. With an increase of biomethane used in CHP plants and a decrease of biomethane used for direct heating the savings in the UK could increase up to 52%. Current savings of 2446 kt CO_{2eq} (Germany) and 606 kt CO_{2eq} (UK) can be extended to 4483 kt CO_{2eq} (Germany) and 1443 kt CO_{2eq} (UK) respectively. Scenario results were determined based on the environmental and economic advantageousness development of the existing biogas market. In this way positive future market development as well as improved shares of feedstock and application can contribute to further greenhouse gas emission savings of Germany and the UK.

1. Introduction

At the EU-summit in Brussels in October 2014, heads of state of the EU member states reached the agreement to reduce the mitigation of Greenhouse Gases (GHG) till 2030 by at least 40% compared to 1990, whilst the share of renewables at the energy consumption shall reach at least 27% [1]. This will be achieved by improvements in energy efficiency and energy system transformation according to Kyoto Protocol, the Copenhagen Accord and Paris agreement [2,3]. GHG is a collective term for chemical compounds that are responsible for the effect of global warming, including CO_2, CH_4 and N_2O. Because of the huge amounts of CO_2 that are released into

* Corresponding author at: DBFZ - Deutsches BiomasseForschungszentrum gGmbH, Torgauer Straße 116, 04347 Leipzig, Germany.
E-mail address: thomas.horschig@dbfz.de (T. Horschig).

http://dx.doi.org/10.1016/j.apenergy.2016.07.098
0306-2619/© 2016 The Authors. Published by Elsevier Ltd.

Nomenclature

Abbreviations

CO_{2eq}	carbon dioxide equivalents
EU	European Union
GHG	greenhouse gas
RE	renewable energy
GWP	global warming potential
NG	natural gas
CHP	combined heat and power
bio-SNG	biogenic synthetic/substitute natural gas
R&D	Research and Development
NNFCC	The National Non-Food Crops Centre
CNG	compressed natural gas
EnWG	German Energy Industry Act
GasNZV	Gas Network Access Regulation
EEG	Renewable Energy Source Act
RHI	Renewable Heat Incentive
BImSchG	Federal Immission Control Act
FIT	Feed-In-Tariff
AD	Anaerobic Digestion
RTFO	Renewable Transport Fuel Obligation
NRMM	non-road mobile machinery

Symbols

£	pound Sterling
€	euro
kW h	kilowatt hours
MW_{el}	megawatt electrical power
TW hpa	terawatt hours per year
kt	kilo tons
m	million
t	tons
bn	billion
PJ	Petajoule
MT	megatons
N m^3	standardized cubic meter

the atmosphere, both from natural and human sources, most efforts to reduce global warming concentrate in the reduction of CO_2 emissions [4], and reduction targets are expressed as CO_{2eq}, taking into account the different global warming potentials of the contributing gases. In the EU-28 the biggest emitters of CO_{2eq} are Germany and the UK with 940 m t CO_{2eq} and 581 m t CO_{2eq} respectively which is about one third of EU-28 [5]. Realizing the 40% mitigation reduction goal compared to 1990 would mean to reduce the GHG emissions of 1990 by about 749 m t CO_{2eq} for Germany and 465 m t CO_{2eq} for the UK.

To reach this goal large investment in renewable energy (RE) and energy saving has been made because energy provision is the main source for GHG emissions (Section 1.1). In 2014, Germany spent 18.8 bn € on renewable energy, mainly for the installation of wind power plants whilst the UK invested about 10.7 bn £ [15 bn €] in RE in 2014 [6,7]. The UK installed four carbon budgets to control the achievement of its legislated target of 80% GHG emission reduction till 2050. Currently the UK is on track to keep within its first three carbon budgets [8]. Nevertheless, to achieve the goals of the 4th carbon budget (<400 m t CO_{2eq} until 2027) the speed of emission reduction should increase because the fourth carbon budget is much more challenging due to a non-linear emission trajectory. Germany's self-imposed target of a 40% reduction in GHG emissions till 2020 will most likely not be accomplished (27% emission reduction until 2015) whereas it has more than fulfilled GHG reduction targets under the Kyoto Protocol [9]. Still, a lot of effort has to be done to fulfill self-imposed emission reduction targets.

1.1. Sources of GHG emissions in the UK and Germany

A combination of the above mentioned investments in RE, displacement of coal-fired plants by gas plants and further progress in energy saving and energy system transmission, Germany and the UK were able to reduce GHG emissions, measured in $CO_{2eq,}$ by 27% between 1990 and 2013. Since 1990 the emission of GHG was reduced mainly each year in both countries. It was not reduced in Germany in 1996, 2001, 2006, 2008, 2010 and 2013 and in 1996, 1998, 2000, 2001, 2003–2006, 2010 and 2012 in the UK, respectively [10,11]. CO_2 is the most significant GHG in Germany and the UK contributing more than 80% of calculated global warming potential (GWP) [11,12]. Whilst the share of methane and nitrous oxide were heavily reduced, the share of CO_2 decreased by 4% in comparison to 1990. Reasons for the overall reduction are besides the decarbonisation of the energy system and improvements in energy efficiency outsourcing of industry, changes in some industrial sectors (waste management) and processes [13].

The composition of the energy system (shares of energy industry, manufacturing, mobility sector, etc.) and the composition of fuels used to meet the energy demand of a country is responsible for emission balances. A use of cleaner technologies for energy production like natural gas (NG) fired combined heat and power (CHP) plants or RE technologies like wind power, solar power and bioenergy can contribute saving GHG emissions without even saving energy [15–17]. Between Germany and UK there are some differences in primary energy mix. Whereas both rely heavily on oil, NG and coal, renewables play a bigger role in Germany. In addition UK decided to continue with nuclear power whilst Germany decided to close all nuclear plants by 2022 [18,19]. An overview on Germany's and the UK's primary energy supply divided by fuel and sector is shown by Figs. 1 and 2, respectively.

To meet the EU's renewable target both countries will have to increase their renewable capacity and outputs significantly. There are different ways to reduce national GHG emissions. The focus of this work will be laid on energy, being the main reason for the production of GHG, illustrated in Fig. 3. The two main options to reduce GHG emissions are on the one hand the reduction of the required amount of energy via energy saving and efficiency improving and on the other hand the substitution of fuels for energy production (power, heat and mobility sector) that are cleaner than the fossil ones mostly used. In the scope of this work the focus is on fuel substitution. The fossil energy carriers coal and oil as well as nuclear power cannot be substituted directly. The installed plants cannot be used by a renewable and cleaner technology. Indeed, solar hybrid systems as well as co-firing are technologies that allow a part-wise substitution of fossil fuels and an associated GHG emission reduction. Several studies investigated a combination of solar systems with diesel engines [21], coal-plants [22] and biomass [23]. Co-firing is another possibility to reduce at least a certain amount of GHG emissions in coal plants. This has been deployed extensively in the UK with most of the remaining operating stations incorporating some level of biomass

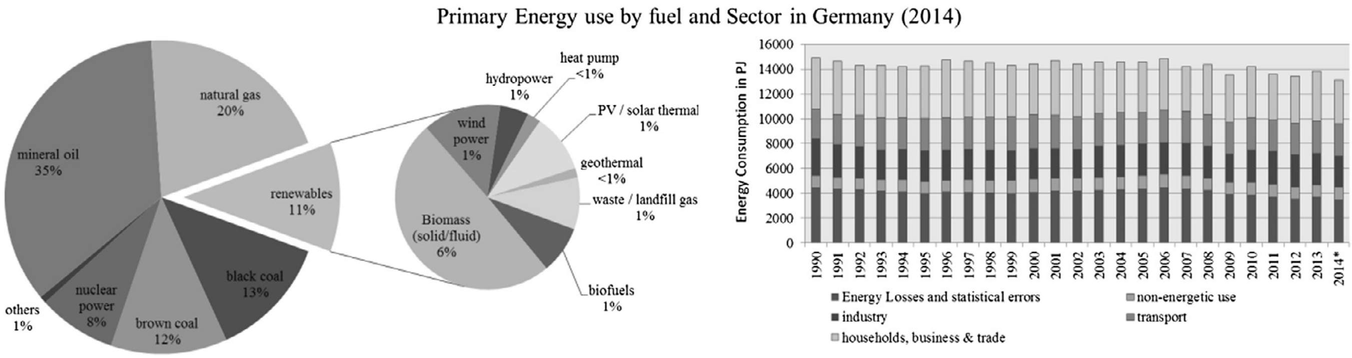

Fig. 1. Primary energy use in Germany by fuel and sector, in PJ [14].

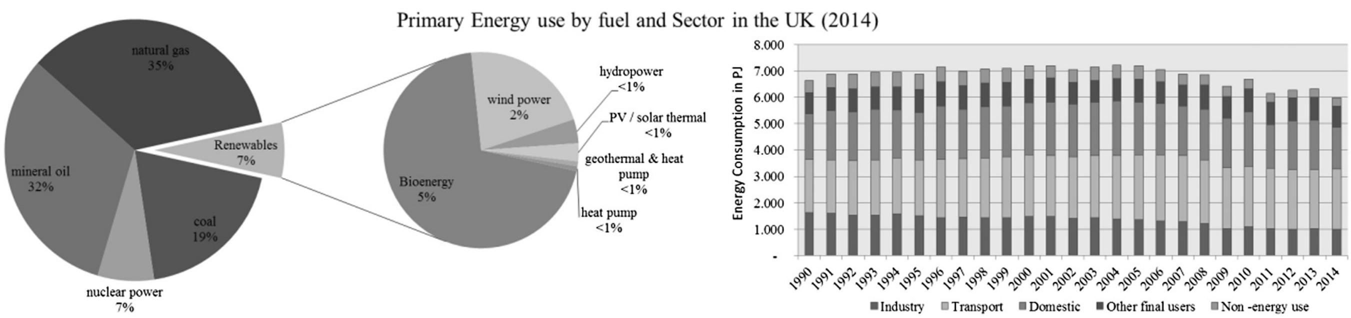

Fig. 2. Primary energy use in UK by fuel and sector, in UK [20].

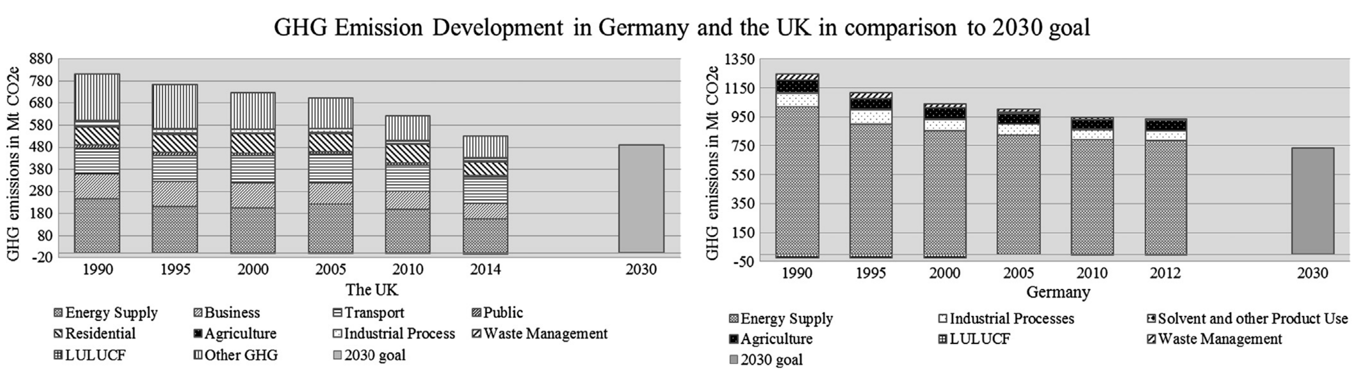

Fig. 3. GHG emission development between 1990 and 2012 in Germany and the UK by sector [10,11].

co-firing and the largest power station in the country, Drax Power, having completely converted one of its 4 units to 100% biomass, with plans for further bioenergy expansion. NG plants, including CHP units, can be run with a renewable biogenic alternative, biomethane.

1.2. Role of bioenergy and biomethane

Climate change is caused by the accumulation of greenhouse gases in the atmosphere and anthropogenic climate change is caused by a net transfer of long term fossil carbon stocks from the ecosphere to the atmosphere. Biogenic energy carriers (including biomass) are fuels which embody carbon which has been relatively recently absorbed from the atmosphere and so returning that CO_2 to the atmosphere does not contribute to an increase in the net long term concentration of atmospheric GHG's. Therefore biogenic fuels can contribute to the decarbonisation and CO_2 emission reduction in all sectors. In addition bioenergy is not dependent on short-term weather events, it can be used to flexibly follow demand and can be stored. Furthermore bioenergy can contribute significantly to rural development. One highly valuable form of bioenergy is biomethane. It is a biogenic and renewable gas that can be produced either via biological processing (anaerobic digestion and upgrading) of organic matter such as energy crops, manure, sewage, and organic waste (biomethane) or via thermo-chemical processing (gasification and methanation) of cellulosic material such as forestry residues or energy crops like straw (Bio-SNG) [24–26]. Whilst biomethane from fermentation is implemented in the market, bio-SNG is still on R&D level and therefore out of the scope of this paper. Being chemically identical to NG, biomethane can use the already existing grid infrastructure and serve as a replacement in all NG applications. Furthermore it can be fed-in and buffered in the existing gas grid and thus be an option for the upcoming task of energy plants that can operate responsively. Besides their advantages, bioenergy is often associated with landscape change and fostering food competition [27]. It should also be mentioned that bioenergy is generally more cost-intensive than fossil energy if only the pure energy price without external costs is considered. This fact relates to market failures and further work on this topic has been performed by Wood and Dow [28], Brown [29], and von Rosenstiel et al. [30]. Besides the application in power generation and CHPs biomethane is a promising option for the fuel market, the heat market and the chemical industry [31]. A study by Cucchiella and D'Adamo [32] highlights the environmental effects of biomethane in the transport sector using a rough estimate only. The here presented approach brings insights to environmental advantageousness depending on factors like feedstock, heat usage and utilization pathway. With the possibility of grid feed-in biomethane could be traded within the EU, being liquefied it could be traded global, whereby the addition of biomethane to NG would be the more promising option. In this way a large-scale emission reduction could be achieved. The huge potential of biomethane in the heavy transport sector is stated by Alamia et al. [33]. It is therefore important to analyze the most important markets in Europe to assess a market potential for future emission friendly fuel alternatives. An economic analyses on biogas utilization pathways was performed by Wu et al. [34]. They point out the importance for decision makers to choose proper biogas utilization modes. In addition to economic considerations this paper focuses on environmental aspects in terms of GHG emission reduction and heat usage and provides insights for policy makers.

Renewable resources are not always environmental sustainable, as it is often assumed. The wide variability of renewable energy providing pathways need clear indicators for sustainability assessment [35]. In this study it is shown that when applying economic and environmental indicators at the anaerobic biomethane supply pathway the potential varies significantly from literature. A recently published analysis that determines the optimal location for a biomethane production system doesn't consider economic and environmental sustainability indicators [36]. It can be assumed that the potentials calculated will never be realized. Another study introduces several scenarios with economic calculations on biogas to biomethane pathways but without considering one of the most important factor for sustainability, the heat utilization [37]. Most studies screened for this paper estimate biomethane potential without considering the possibility of a biogas pathway with a meaningful heat usage [38,39]. This would significantly reduce calculated potentials for biomethane if used for CHP. The here presented study combines economic and environmental sustainability indicators with a novel method resulting in a most reasonable potential for biomethane production in the mid-term in Germany and the UK. Recent literature compares renewable energy policies and their effects between countries [40], biomass/energy potential for different types of feedstock [41], greenhouse gas emission of different bioenergy pathways [42] and different renewable energy technologies focusing on different sustainability indicators [43] (environmental, economic, social). To our knowledge an approach that combines market comparison, policy framework analysis as well as economic and environmental aspects of energy provision from biomass does not exist. To close this research gap the scope of this manuscript was to show which roles of importance biomethane can play for achieving national GHG emission savings in Germany and the UK under varying scenarios. We wanted to highlight market development, drivers and barriers and introduced the innovative concept of deriving the market potential for biomethane from the biogas market (using actual operating facility data) and not as usual from agricultural area or feedstock.

1.2.1. Status of bioenergy in Germany

With a share of 10.7% in the fuels sector, 41.8% in the heat sector and 13% in the power sector, bioenergy is the most important RE in Germany [44]. In 2013 Bioenergy substituted 48 bn kW h fossil power, 117 bn kW h fossil heat and provided 3.8 m tons renewable fuel [45]. In Germany biomethane is primarily used for CHP (combined heat and power) and therefore can be produced and consumed spatially separated, i.e. electricity is fed-into the grid and heat tends to be used locally or via district heating systems. Furthermore biomethane can be buffered when fed in the natural gas grid, a rare property of RE's [46,47].

1.2.2. Status of bioenergy in the UK

Bioenergy is also the most important RE in the UK. Of the total RE in the UK bioenergy contributes 9% in the fuels sector, 19% in the heat sector and 44% in the power sector [48]. In 2015 bioenergy substituted 22 bn kW h fossil power, 23 bn kW h fossil heat and provided 1671 m litres renewable fuel in the UK [49,50]. The UK's RE capacity is some way behind Germany but developing rapidly. Biomethane production is all gas-to-grid due principally to the Renewable Heat Incentive (RHI). The tariff received by biomethane producers does not currently differ between the different possible scopes of application or feedstock/technology mix. There are now over 400 CE plants in the UK, of which 40 are biomethane facilities [51]. The capacity of biomethane electricity/CHP plants is ~400 MW_{el} and biomethane is ~30,000 m^3/h (2,31 TW hpa). Biomethane production therefore displaces approximately 0.3% of fossil-derived NG in the UK. The numbers mentioned above show the important contribution of bioenergy to GHG emission reduction in Germany and the UK. To reach the self-imposed goals further effort has to be done to increase bioenergy share in an economic and sustainable way. Biomethane is an already market-implemented biogenic energy carrier that can significantly contribute to GHG reduction when used as natural gas substitute. It should be noted when using this highly valuable energy carrier to produce and consume it in the most beneficial supply chain.

1.3. Aims and objectives

As mentioned above large efforts have to be made for further fostering RE deployment and fossil fuel substitution. An opportunity to do this is the part-wise substitution of NG with biomethane [52]. This paper introduces a combined quantitative and qualitative approach to answer the question how much CO_{2eq} can be saved in the UK and Germany when the economic and environmental useful potential for biomethane is used to substitute NG. Within the environmental potential only CO_{2eq} was considered, as this is the strongest driver of policy and provides a strong indicator of environmental impact. There is an analysis with different scenarios for biomethane market development and scopes of application substitution like heat, power and fuel market. This is done for an estimation of possible CO_{2eq} reduction scenarios for NG substitution by biomethane.

Overall aim:

- Assess the reasonable potential of the market share and associated GHG emission savings of biomethane in the German and UK energy supply.

Specific objectives to address the aim:

i. Assess the current biomethane supply based upon existing operational biomethane plants via literature and database study.
ii. Calculate the future reasonable potential for increased biomethane supply.
iii. Analysis of the GHG savings of different biomethane use scenarios of substituting existing fossil fuel use in the CHP, district heating, and in transport.

2. Methodology

The outline of the approach is illustrated in Fig. 4. To compare the present GHG savings by the substitution of NG with biomethane and possible future savings it is important to assess the current biomethane supply (Sections 3.1 and 3.3). At first the number of biomethane plants and the feed-in capacity for Germany was determined by using an extensive database of the DBFZ - Deutsches BiomasseForschungszentrum gGmbH [53]. To determine these numbers for the UK industry data was obtained in addition to publically available databases [54,55]. Results of these analyses are described in Section 3. This part of the presented methodology follows a similar approach to recent bioenergy and other industry assessments with associated GHG emission savings [56,57].

Then the future biogas production was determined through literature and study review (see Section 3.5) [58]. For a realistic assessment of a possible future of biogas and thus biomethane (i.e. the amount of biogas deployed in the natural gas grid), associated with possible shifts in use it is important to know the current way biogas and biomethane is incentivized. This is described in Sections 3.2 and 3.4

The next step was using indicators and principles from [59] to calculate the reasonable biomethane potential from the biogas potential for Germany and the UK (see Section 2.1) [59]. For the calculation of the GHG savings specific values of GHG emissions of different biomethane pathways, value chains, and the fossil alternatives were required. Values were taken from a previous published study [60]. This is described in more detail in Section 4. To show possibilities of different futures, three scenarios were defined. This is also part in a study assessing potential future energy systems in Germany unitl 2050 [61]. Numeric assumptions of the scenarios are shown in Table 1. Further assumptions of the scenarios are shown in Table 2. Concluding we draw policy implications from our findings. This study uses a methodological and theoretical strong approach for further insights that may lead to model development as well as policy implications that is also used for an analysis of the New Energy Strategy of Europe 2011–2020 [62], biomass generation in the UK [63], biomass penetration in centralized energy systems [64] or critiquing policy frameworks and using expert input to consider cross-country and wider policy implications [65].

Scenario 1 (CS – current status) displays the current (2015) situation of biomethane production, use and the associated avoided GHG emissions. Second is the market projection scenario (MPS) that describes a literature and study driven situation for biomethane production and use. The third scenario displays a reasonable potential (PRS) that is economic and environmentally beneficial as fossil fuel substitute. Table 2 outlines the rational basis underpinning the assumptions in Table 1 to ensure they provide a realistic and internally cohesive indication of possible future bioenergy implementation.

Table 1
Assumptions of the used scenarios for Germany/the UK [59,48,58].

Scenario	Biomethane plants	% Farm-fed	% Waste-fed	Output in 1000 N m^3/a	Output in TW hpa
CS	170/40	86/50	14/50	100/30	8.56/2.56
MPS	190/80	86/50	14/50	115/60	9.84/5.14
RPS	300/95	86/50	14/50	176/71	15.14/6.12

Table 2
Time horizon and references of the scenarios.

Scenario	Assumptions[a]	Reference
CS	Mid 2015 situation	Derived from literature and database review of operational biomethane facilities
MPS	Predicted market development until 2025	Derived from literature review and published industry and planning information but based on known facilities either operation, in planning, construction or commissioning
RPS	Potential for substantial conversion of biogas (mainly FIT) to biomethane, as currently no use for heat and less efficient Incentives for sustainable biomethane upgrade conversion	Concept derived from literature review

[a] Consideration given to estimated useful economic life of facilities, duration of support scheme, availability of biomass resources, competition for feedstock, land and resource availability, etc.

The distinction between farm-fed systems and waste-fed systems is that farm-fed systems are capable of using crop residues, energy crops and animal manures and slurries as feedstock whereas waste-fed systems are capable of using municipal waste, food waste, including separation/sorting plant to remove plastic, metal and glass packaging materials [58]. Share of waste-fed and farm-fed systems was calculated driven by the annual output of both feedstock systems and not by number of plants.

2.1. Concept of reasonable potential

The third scenario focuses on the reasonable potential. This incorporates factors like availability of land, but also economic and environmental constraints. Common potential estimations for biomass estimate the contribution to energy provision that can be made by biomass [66,67]. The most encompassing potential is called theoretical potential including the total available potential of renewable resources being an upper limit for a specific area at a specific time. The next smaller stage is the technical potential. The

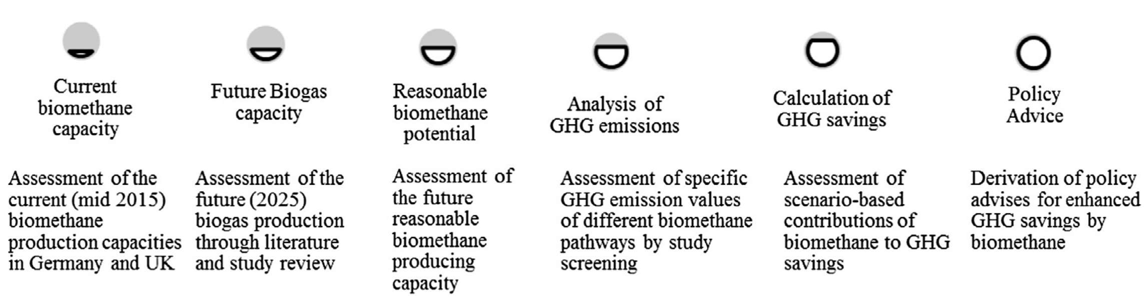

Fig. 4. Summary of methodology approach.

technical potential is the part of the theoretical potential that can be derived sustainably from a specific area in a specific time. The term sustainable, when defining the technical potential, encompasses the availability of natural resources, preservation of natural cycles, technical limitations, etc. Only a proportion of the environmentally sustainable potential will be economically viable in prevailing market conditions and so the next smaller stage is the economic potential which is used to compare the specific energy supply costs for energy out of biomass in comparison to fossil energy. Because only some value chains for biomass energy can compete with their fossil references at current fossil prices and limited carbon prices, the economic potential depends highly on external financial support. The final and smallest stage in the common potential estimation concept is the expectation potential. This potential is mostly smaller than the economic due to further barriers besides economic ones like social factors or financing difficulties, adaption periods and the fact that economic models project resources associated with economically rational decision-making. Many of them not always prevail, particularly where there are conflicting priorities or where the economic benefit associated with pursuing the low-carbon or renewable option is marginal [68] (see Fig. 5).

It is important to constrain the resource potential to that which is genuinely sustainable [69]. To determine the reasonable potential for the pathway of energy out of biomethane this paper adds the constraint of environmental effects focusing on GHG emissions and sustainability criteria to the smallest stage of potential estimation to get a more realistic and sustainable potential. This is highly important for biomethane pathways because they are not only in a competitive situation with NG but also with biogas pathways. Furthermore this specific situation results from the fact that the production of biomethane always needs a biogas supply chain. If the upgrading of a biogas supply chain to a biomethane supply chain did not come along with a higher amount of GHG savings, there is no sustainability rationale to upgrade biogas to biomethane, despite the possibility to buffer biomethane in the gas grid. Another possibility is the decentralized use of biomethane at fuel stations. Currently this use is limited in Germany as well as in the UK due to inappropriate support schemes. Besides that there are further factors influencing the competition between the decentralized use of biogas and the option of upgrading to biomethane. The economic considerations of the competition are further influenced by the distance to the gas grid connection or insufficient infrastructure.

Considering the above mentioned economic and environmental aspects there is a reasonable potential of 10% for the installation of biogas upgrading extensions at existing biogas plant locations in Germany which is about 300 MW_{el} [59]. This is based on the assumption that the upgrading of on-site conversion of biogas to electricity units to biomethane and thus feed-in units if the heat usage is smaller than 50% and system performance is higher than 800 kW_{el}. On-site combustion of biogas in CHP plants has environmental advantages compared to an upgrading of biogas which comes along with negative effects like methane slip if more than 50% of the process heat from the CHP plant can be meaningfully utilised. This assumption results from GHG saving calculations whereas the minimum system performance of 800 kW_{el} (≈200 N m^3/h) results from economic calculations [59]. Applying the above mentioned parameters to the UK biogas market derives a reasonable biomethane potential of 162 MW. Basing on expert interviews it is assumed that three percent of the biogas plants with attached CHP plant meet the above mentioned heat threshold of 50%.

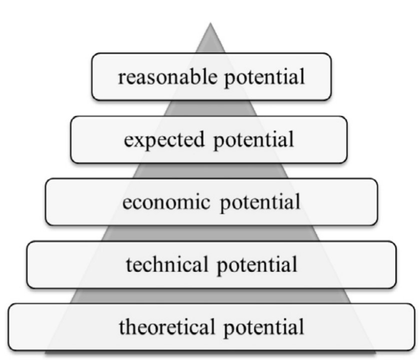

Fig. 5. Biomass potential concept with reasonable potential.

To sum up this paper derives the reasonable potential for Germany and the UK's biomethane supply to 2025, pathway-specific GHG emission values for biomethane and scenario-based assumptions. In doing so it was possible to assess scenario-based contributions of biomethane to GHG savings. Finally policy advises for an enhanced contribution of biomethane to GHG savings are derived from the results.

3. The development and present situation of biomethane in Germany and the UK

This section uses background to the current and estimated future market to notify the assessment of future biogas capacity described in Fig. 1 to inform the reasonable potential scenario and provides contextual information for classification of the results in Section 5. Germany and the UK invested effort and money to create a sustainable biomethane market in each case. This section provides an overview on the different developments and approaches both countries chose. However, both countries have different approaches on how to use biomethane most efficiently. Whereas Germany incited the market development for biomethane in the (CHP) power, heat and transport sector through different incentive schemes, the UK compensates the pure feed-in of biomethane.

3.1. Market development from 2006 to 2015 in Germany

Referring to Fig. 6 between 2006 and 2015, 165 biomethane plants were connected to the grid injecting 106,800 N m^3/h biomethane in 2015 [70]. About 24 projects are in line [31]. The overwhelming part of biomethane in Germany is used in CHP plants (87%), as fuel (4%) and for direct heat provision and export (9%) producing 1,5 TW hpa power and 1,6 TW hpa heat in 2014 [31,59,71].

Besides the mentioned laws, regulations and support schemes, described in Section 3.2, it is also important to consider competition with NG which is crucial for investment decisions influencing the market development. Additional factors influencing biomethane market development are production potential, technology and economic issues [72]. The economic situation is determined by the price for biomethane and NG and the profit that can be extracted. Biomethane produced by energy crops usually costs 7–8 €-ct/kW h and thus is 1–3 €-ct/kW h more expensive than biomethane produced by waste and residual products [71]. The price for biomethane is about 2–3 times higher than for NG depending on the supply chain; whereas the fixed costs, i.e. for the CHP unit, the staff or market effort can be assumed equal. Otherwise the achievable incentives are mostly higher, strongly depending on the support schemes. Another possibility to make biomethane projects profitable is customers that are willing to pay a certain amount more for RE. This can be done via specific green power or green gas contracts with the power and gas supplier. Currently only a small fraction of potential customers are

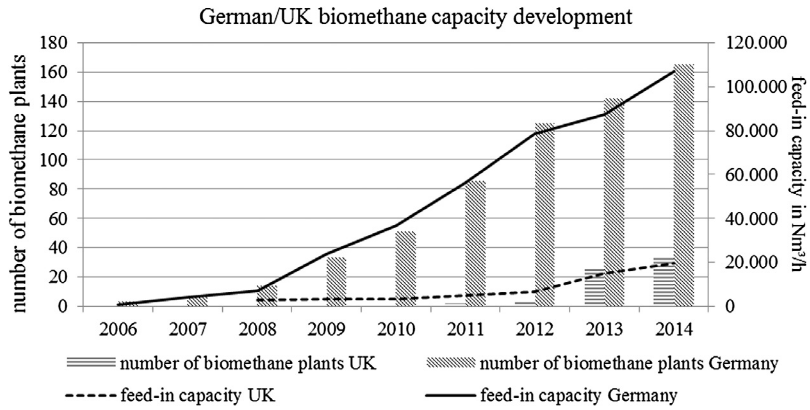

Fig. 6. Biomethane plant and capacity installation in Germany and the UK 2006–2014 [70,54].

willing to pay a higher price for sustainable and climate-friendly energy. For CNG cars (compressed natural gas) biomethane is available as a mixture with NG with a range from 5% to 100%. Nevertheless this is only a niche market. When used as fuel biomethane can achieve a price of 5–8 €-ct/kW h [73]. Besides the compensation schemes and the direct marketing of the produced electricity the sale of the arising process heat make a biomethane CHP project profitable. In the heat sector biomethane as an additive product substitute for NG has average prices of 13 €-ct/kW h and is more expensive then heat supply by pure NG [73]. Therefore sales in this market are highly dependent on customers paying a higher price for renewable heat.

3.2. Laws and regulations Germany

This section provides summarized data on the laws and regulations that fostered and still foster market development of biomethane in Germany. Extended data of the laws and regulations can be found in the supplementary data file. Since 2004 the implementation of a biomethane market in Germany was promoted by a plurality of laws and regulations leading to a continuous expand of biogas upgrading plants and thus biomethane feed-in capacities. The feed-in and compensation for biomethane production is managed by many laws and regulations. In comparison to electricity out of biogas there is no fundamental right for compensation for the injected biomethane amounts. Biomethane producers have to put their biomethane on the market on their own whereas the governmental policy mix helps to create the necessary markets. The right to compensation is reserved for the direct users of biomethane like CHP plant operators and this has encouraged growth of self-supply CHP installations. Biomethane has to be bought on the market with mostly long-term supply contracts to produce power and heat. In the following the main important support schemes for a market creation for biomethane are presented.

The superior scheme introducing the regulated network access model is the German Energy Industry Act (EnWG). The access to the national network is regulated by cooperation agreements between German gas suppliers and transmission system operators. In relation to biomethane, the GasNZV regulates terms and conditions for grid operators for the gas network access of biogas upgrading plants. The costs for the connection and access to the gas grid are split between the biomethane supplier (25%) and the grid operator (75%), but in general does not exceed 250,000 € for the upgrading plant operator.

The main support scheme that fostered a predominant use of biomethane in the power and heat sector is the Renewable Energy Source Act (EEG). It is in force since 2000 with regular adaptions in 2004, 2009 and 2014. The EEG provides compensation for the use of biomethane in CHP's for the simultaneous production of heat and power from the version of 2004 onwards. In the version of 2000 the EEG did not provide sufficient compensation and therefore the first biomethane plant went on grid in 2006 (delay between support scheme and construction). To get full compensation, 100% of the arising heat must be used. Because of the recent version (2014) of the Renewable Energy Source Act support for further biomethane capacity expansion is no longer sufficient. This comes along with a nearly total cessation of plant installations and capacity expansion. Details on this development are described in the supplementary data file. The Renewable Energy Heat Act fosters an increased share of RE within the heat sector. Essential elements of this law are the obligation to use RE's in new buildings and existing public buildings that can be fulfilled with biogas and biomethane when used in a CHP. The Federal Immission Control Act (BImSchG) influences the market development via the so-called biofuel quota. Biomethane can be used to fulfill the quota as direct substitute of NG in the transport sector.

3.3. Market development in UK from 2010 to 2015

In contrast to the German biomethane market the British market is continuing to develop with a significant amount of plants being connected to the grid. Nevertheless both markets share the dependence on support schemes. This usually comes along with a high degree of uncertainty for future investments. Biogas CHP plants increased with the introduction of the Feed-In-Tariff (FIT) from 2010. The first biomethane-to-grid plant in UK was commissioned under the Renewable Heat Incentive (RHI) in 2012. These support schemes spurred the agricultural and food waste sector in the UK equally. Because of time-delay between incentives and the construction of plants, the first year with a significant biomethane-to-grid plant installation was 2014. Biomethane plants built in 2015 are expected to be smaller than the ones built before due to changes in tariffs. Further effects on the market were uncertainties around the implementation of sustainability criteria for the RHI scheme, although since October 2015 this is now clearly defined. Further adjustments to economy of scale effects within the RHI scheme have occurred with a tariff degression mechanism in place.

Fig. 6 shows that there were 33 biomethane plants connected to the grid in UK by the end of 2014, producing around 23,000 N m^3/h for the heating demand of more than 100,000 homes [51]. By the end of 2015, 40 biomethane facilities are operational with a combined capacity of over 30,000 N m^3/h. Further projects are in development [74] and with the continuation of the RHI an additional 140 biomethane projects could be constructed by 2021 [75]. Over 50% of the plants use agricultural feedstocks, the remainder use sewage sludge, food waste and residues. In contrast to Germany, more than half of the upgrading plants use the membrane technology whereas in Germany only a small percentage of plants use this upgrading technology. With the forecast plants for 2016 nearly 3 TW hpa of renewable heat could be injected into the grid [75]. Production costs for biomethane in the UK can be assumed equal to those in Germany described in Section 3.1

3.4. Laws and regulations UK

There are 4 main financial support schemes in the UK that are relevant for AD plants, each of these are described as follows:

The UK has targeted premium payments for electricity in its energy sector since 1990, but these originally only focused on large scale electricity developments and had limited success in incentivizing bioenergy because of its higher market cost than onshore wind [63]. FITs were introduced in April 2010 to specifically encourage the "higher cost"/"under-represented" renewable categories and the scheme makes guaranteed payments to all eligible installations for all the electricity generated and an additional payment for any electricity exported to the grid, for a period of 20 years. FITs support AD installations of up to 5 MW in producing electricity from biogas.

The first phase of the RHI was introduced much more recently in November 2011, as part of UK efforts to expand energy sector RE targets and GHG reductions. It is an environmental programme designed to increase the uptake of renewable heat technologies by providing incentive payments to eligible generators of renewable heat for commercial, industrial, not-for-profit and public sector purposes and to producers of biomethane. It provides a subsidy, payable for 20 years, to eligible, non-domestic renewable heat generators (e.g. biogas CHP) and biomethane to grid projects.

The RTFO supports the UK government's policy on reducing greenhouse gas emissions from vehicles by encouraging the production of biofuels that don't damage the environment. Under the RTFO suppliers of transport and non-road mobile machinery (NRMM) fuel in the UK must be able to show that 4.75% of the fuel they supply comes from renewable and sustainable sources [76]. The UK market is dominated by biodiesel (834 m litres in 2014/15) and bioethanol (808 m litres in 2014/15), whereas biomethane accounts for under 2 m litres [76]. To ensure biomass sustainability, criteria were introduced in the UK following the EU Renewable Energy Directive and are now applicable to all biogas and biomethane facilities receiving Government support [77]. Operators must comply with GHG emission limits and land criteria which limits the use of some feedstocks and operating practices [78].

3.5. Biomethane future and potential

Although the current market situation in Germany can be considered a challenge, future regularities or policy changes can promote an ongoing market implementation of biomethane, especially in the heat and fuel sector where biomethane is a niche market. Biomethane can be beneficial because it can be easily stored and transported via the existing infrastructure, which is likely to be more valuable in future with a higher share of fluctuating renewables.

3.5.1. Future and potential of biomethane in Germany

The potential to substitute fossil energy is tremendous with an annual gas demand of around 683 TW hpa (70 bn N m^3) (2014) [66]. Currently roughly 876 m N m^3 biomethane are injected into the grid per year. The predicted amount of biomethane used in the energy system until 2030 ranges from 140 m N m^3 biomethane [67] about 6.9 bn N m^3 biomethane [68] to 12.3 bn N m^3 biomethane in 2050 [79]. However, each assumption depends on the future development of support schemes.

3.5.2. Future and potential of biomethane in UK

The UK has an annual gas demand of around 800 TW hpa [81.8 bn N m^3/h] [80] with a share of 50% in domestic heating, 25% in power generation and 25% in industry. The high share in domestic heating can be explained by the absence of many practical and economic alternatives. With a share of 1.8 TW hpa in 2015 biomethane already contributes to emission reduction in heating districts. A further development of biomethane use in CHP plants is limited to the restricted district heating infrastructure in UK, that faces several challenges [81]. Green Gas Grids [82] state a potential of 20 TW hpa by 2030. Realization of this potential depends mainly on support schemes like the RHI. Anaerobic Digestion & Bioresources Association [83] estimate a biogas potential in the UK of 40.4 TW hpa. In contrast [84] estimates a biogas potential of 14 TW hpa out of food waste (5 TW hpa), agricultural waste (8 TW hpa) and sewage sludge (1 TW hpa). Whereas these are the potentials for biogas production, a potential for biomethane cannot be derived directly from these numbers.

4. GHG reduction potential of biomethane

The input data, assumptions and the used methodology for the presented GHG emission values can be looked up in [60]. The amounts of GHG that can be saved when substituting NG differ from each other depending on the biomethane supply chain. GHG mitigation is determined by the choice of biomass/feedstock, the biogas technology and operating conditions of the plant, including the upgrading process to biomethane. Furthermore the fossil reference is crucial for the amount of GHG emissions that can be saved. Comparing the different biomethane applications in the power, heat and fuel sector this paper differences between GHG reduction with state of the art technologies and emission optimized technologies. Those future technologies and emission reduction values can be reached by ongoing R&D investment. Fossil references are illustrated in Fig. 7.

Fig. 7 shows GHG emission values for different biomethane supply chains. Significant GHG savings can only be made with internal energy supply. Internal energy supply means that energy being produced within the pathway of the biomethane production is used. Using organic waste as feedstock will result in the highest possible GHG savings in comparison to the fossil references because offsets are included for the methane releases which would otherwise have been incurred with the waste disposal. However, the use of renewable resources including energy crops as feedstock will result in a GHG saving, too. State of the art technology is capable of an approximately GHG emission reduction of 30% when renewable resources were used as feedstock (Fig. 7). With organic waste as feedstock there can be an overall reduction of about 200%.

5. Results and discussion

Fig. 8 displays the GHG emission savings against the fossil reference from the use of biomethane for the UK and Germany with current savings compared to the defined scenarios. In the scenarios RSC and MPS further emission savings of CO_{2eq} are possible. In Germany, where most of the biomethane is used in CHP plants (87%), high emission savings come from the combined production of power and heat out of biomethane. In Germany direct heating is only a niche market (9%) and not as efficient as the combined production of power and heat. Furthermore, the fossil reference system, NG in gas boilers, is a comparatively clean fossil fuel system that is why only small savings are made by the use of biomethane

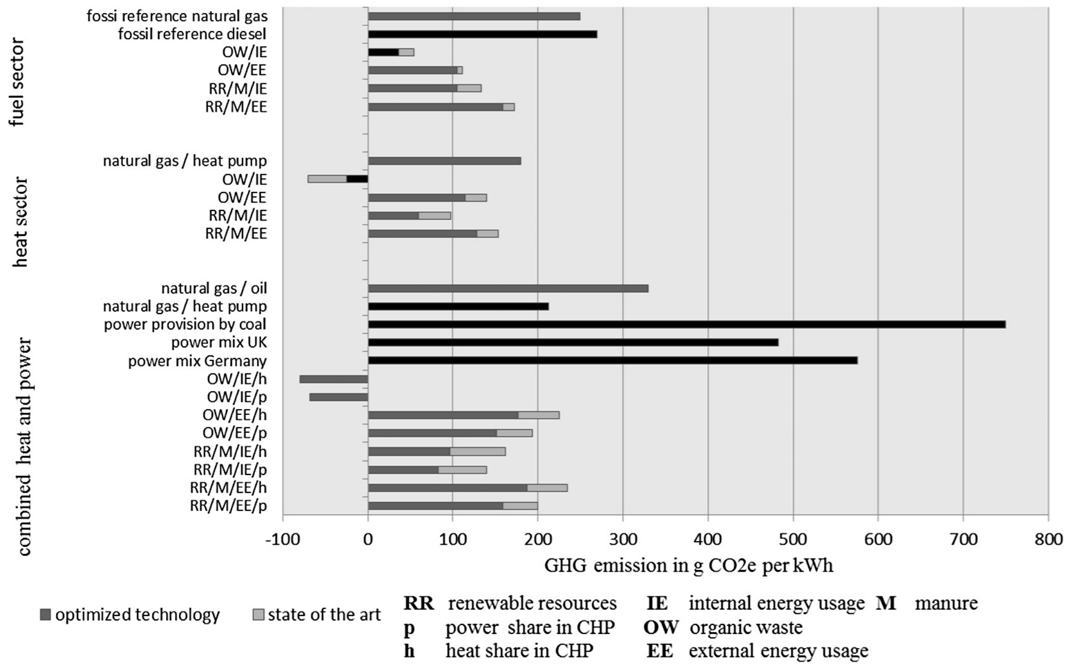

Fig. 7. GHG emissions for biomethane applications and fossil references in power system [60].

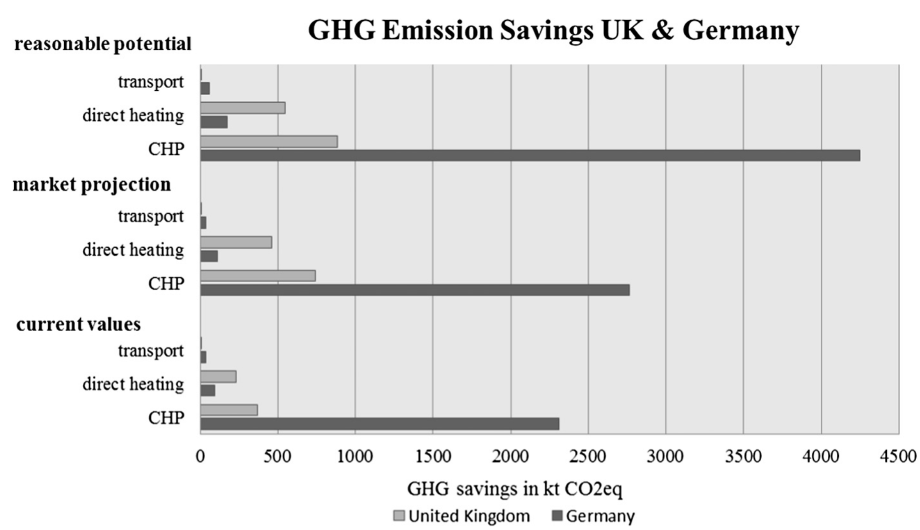

Fig. 8. Application-dependent GHG emission savings by biomethane in Germany and the UK using reasonable potential.

in direct heating. The use of biomethane as fuel is a niche market (4%) and is predominantly limited by incentive schemes and the amount of gas vehicles in Germany which is comparatively low [85]. The UK uses NG and biomethane, respectively in CHP (43%), direct heating (56%) and as fuel (1%) since 2009 [80]. The incentive schemes applied in the UK do not incite local uses of biomethane but only the direct feed-in. In contrast, German incentive schemes incite the local use.

The different GHG emission savings for Germany and the UK are mainly influenced by the different share of application for biomethane, the different share of feedstock and the share of the different applications transport, direct heating and CHP. The use of biomethane in CHP plants achieves the highest GHG emission savings. If organic waste is used as feedstock the possible savings are even higher. This is due to the negative emissions that are derived from the emissions that are saved when organic waste is used for energetic purposes instead of being landfilled. Currently, Germany and the UK save 2446 kt CO_{2eq} and 606 kt CO_{2eq} respectively. The difference is due to the smaller amount of biomethane being injected into the grid, the different share of application and the different share of feedstock. Whilst the UK use biomethane in less efficient direct heating applications the share of biomethane produced out of waste is higher. If the UK produced the same amount of biomethane as Germany the savings would still be lower because of the different applications. But if the UK used biomethane in more efficient applications like CHP plants (with a share similar to Germany) the savings would increase, although a key barrier to this is identification of significant heat and power loads with an appropriately high capacity factor, since lower capacity factors significantly affect the economic viability of these applications [86]. This is displayed in Fig. 9 for different shares at 30,000 N m^3/h biomethane production. With an increase of

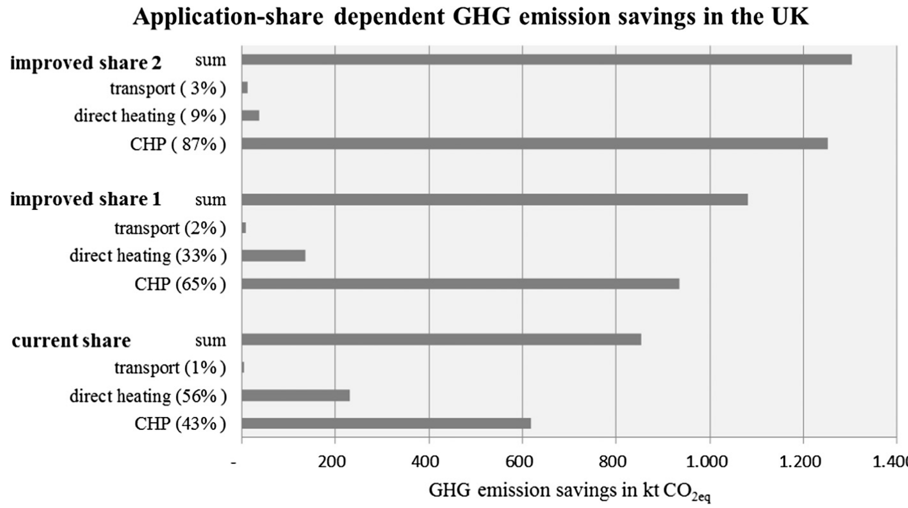

Fig. 9. Application-share dependent GHG emission savings in the UK.

biomethane used in CHP plants and a decrease of biomethane used for direct heating the savings could increase by 26% (improved share 1) and 52% (improved share 2).

Possible emission savings in the market projection scenario are limited by the predicted amount of biomethane being fed-in by 2025. Changes in feedstock share or application share are not assumed. The emission savings can achieve 2917 kt CO_{2eq} and 1212 kt CO_{2eq} respectively. Whereas Germany can increase its savings in the market projection scenario by 13% the UK can nearly double their GHG emission savings. This is due to the assumptions that the UK can double their produced biomethane capacity whilst the biomethane capacity in Germany will only slightly increase. Referring to the current values the use of biomethane in Germany is ecologically beneficial. Further savings are only possible by an increased use of biomethane in CHP plants and a higher share of organic waste as feedstock. The UK can increase its savings in the market projection scenario analogous to the current situation by either increasing efficiency (saving more GHG emissions) use of biomethane or via an increase of waste-fed biomethane.

From the calculations a reasonable potential of 4483 kt CO_{2eq} (+83%) for Germany and 1443 kt CO_{2eq} (+138%) for the UK respectively avoided GHG emissions through substituting fossil energy by biomethane was derived. Analogous to the current values and the market projection scenario the avoidable GHG emissions could be increased by a higher share of efficient CHP use and organic waste feedstock. Nevertheless the numbers presented here illustrate how much GHG emissions can be saved when the economic and ecological beneficial potential is completely exploited. Being a highly valuable energy carrier, biomethane should be used in the most beneficial, economic and ecological way. High shares of waste-fed biomethane will improve the overall GHG emission balance. Nevertheless, it has to be mentioned that feedstock potentials for waste-fed systems are lower than for farm-fed systems.

The more ecological beneficial use of biomethane in CHP plants in the UK is mainly limited by a lack of district heating opportunities, the absence of appropriate heat loads and a lack of gas vehicles. This and the fact that policy support has historically favoured electricity applications explain why there are so many electricity plants in operation. Only appropriate heat concepts will make a biomethane CHP plant ecologically and economically beneficial and feasible. Therefore the importance of finding appropriate heat loads has to be highlighted. Comparing the results of a reasonable potential with potentials from the literature shows how enormously these numbers vary from each other. Technological potentials mostly state capacities of biomethane that will never be injected into the grid due to economic and environmental restrictions. Furthermore it has to be mentioned that GHG emission values are highly dependent on the underlying assumptions. Variations in feedstock, plant size, plant type, etc. influence the GHG emission values.

To derive the reasonable potential of biomethane in the UK a mature biogas market till 2017 was assumed and a reasonable heat use of 3% for all biogas plants with an attached CHP unit. Future developments within the biogas market, such as a more efficient heat use will affect the development of the biomethane market, of course. This should be addressed in future research. The presented study addresses only biochemically produced biomethane. Thermochemically produced biomethane, so called bio-SNG (biogenic synthetic natural gas) out of lignin-rich feedstock, is not yet fully commercially mature [87]. Bio-SNG can influence a future biomethane market development depending on cost development and incentive schemes.

Biomethane as fuel is a promising alternative for the decarbonisation and GHG emission reduction in the mobility sector, especially vehicles for heavy duty traffic that cannot yet be powered by future fuels like electric or hydrogen fired engines. Because of its price advantage against biomethane from energy crops and missing incentives in the mobility sector in Germany, most biomethane as fuel is made out of organic waste. Nevertheless, the limited potential of gas vehicles is one factor restricting future market development. It has to be mentioned that the use of organic waste needs an increased effort in pre-processing of the feedstock. Economic feasibility of waste-fed systems relies heavily on the price or fees for waste. Savings of more than 100% are achievable for biomethane with a high share of waste feedstock (>85%) and use in CHP and direct heating.

The dimension of the annual savings of currently 2446 kt CO_{2eq} and 606 kt CO_{2eq} respectively become apparent when compared to the necessary savings to reach 2030 GHG emission reduction goals (Fig. 3). The UK needs to reduce its GHG emissions from currently 520 Mt CO_{2eq} to 485 Mt CO_{2eq} by 2030. This means an annual reduction of about 2.3 Mt CO_{2eq} (2300 kt CO_{2eq}). If the reasonable potential for biomethane in the UK is exploited savings of 1443 kt CO_{2eq} would be feasible. This is a plus of 837 kt CO_{2eq} and thus one third of UK's additional annual reduction till 2030. If biomethane is used in more environmental beneficial applications and more organic waste is used as feedstock savings would even increase. In contrast to savings of GHG emissions in the UK

Germany has to put more effort in GHG emission reduction. Further savings of about 200 Mt CO_{2eq} are needed to fulfill 2030 GHG emission goals. This means an annual reduction of about 13 Mt CO_{2eq} (13,000 kt CO_{2eq}). Exploiting the reasonable potential for biomethane in Germany could increase GHG emission savings to 4483 kt CO_{2eq} and thus a plus of about 50%. In this way biomethane could contribute to further GHG emission reduction with a share of 15%.

A further opportunity to foster a European-wide market development of biomethane and to take advantage of the reasonable potential to contribute to GHG emission savings would be cross-border trade of biomethane. Factors influencing a European-wide trade are presented in [25].

Another factor influencing a future biomethane development is governmental plans to design low carbon energy systems. Germany and the UK differ highly in the point of the future of nuclear power. These plans affect the development of other low carbon technologies. Whereas Germany decided to fade out nuclear power by 2022, the UK wants to increase nuclear power by 16 GW of new installed capacity [88]. In this way nuclear power will compete with renewable low carbon technologies, like biomethane. To calculate the reasonable biomethane potential for Germany and the UK we used biogas market forecasts, based on published mathematical models and market analyses. Being sound methods performed by renowned institutions and researchers, a drawback in modeling and market forecasting lies in dependency on assumptions. However, future research has to consider uncertainty in forecasting in more detail. In addition the presented approach assumes that 3% of UK's biogas plants use their heat meaningful. An increase of this number, i.e. by legislative action, would decrease the market potential for biomethane in the UK. Furthermore GHG emission values were taken from literature and depend mainly on assumptions, but can show the scale of GHG emission savings appropriately.

6. Conclusions

The results from this work show clearly the very significant potential for increased GHG savings from biomethane implementation, particularly in the UK. However, it also points clearly to the need to prioritize the pathways which will contribute the most significant GHG reductions, particularly in the context of constrained capital for economic investment. The high valorisation of biomethane makes burning biomethane for the production of heat exergetically inefficient. It would be more beneficial to use biomethane in the described high value pathways. Taking into account the combination of high levels of GHG reductions per unit of energy produced and availability of overall resource there is a clear indication that a focus on more efficient use of the waste resource would be appropriate. It should be noted that this represents a significant technical shift from the current agricultural feedstocks and care must be taken to ensure that appropriate technologies for the wide compositional variety of waste streams that may be used are implemented. In detail the results can be summarized as follows:

(a) Currently, Germany and the UK save approximately 2446 kt CO_{2eq} and 606 kt CO_{2eq} respectively substituting natural gas by biomethane.
(b) With an increase of biomethane used in CHP plants and a decrease of biomethane used for direct heating the savings could increase by 26% (improved share 1) and 52% (improved share 2) in the UK.
(c) Savings in the Market Projection Scenario can achieve 2917 kt CO_{2eq} and 1212 kt CO_{2eq} respectively. Whereas Germany can increase its savings in the market projection scenario by 13% the UK can nearly double their GHG emission savings.
(d) From the calculations a reasonable potential of 4483 kt CO_{2eq} (+83%) for Germany and 1443 kt CO_{2eq} (+138%) for the UK respectively avoided GHG emissions through substituting fossil energy by biomethane was derived.
(e) Analogous to the current values and the market projection scenario the avoidable GHG emissions could be increased by a higher share of efficient CHP use and organic waste feedstock.
(f) The numbers presented here illustrate how much GHG emissions can be saved when the economic and ecological beneficial potential is completely exploited.
(g) One third of UK's additional annual GHG emission reduction till 2030 can be achieved by biomethane, economic and environmental sustainable.
(h) Biomethane could contribute to further GHG emission reduction with a share of 15% in Germany till 2030.

Furthermore it has to be pointed out that the achievements of the presented study will result in the creation of a simulation model that could significantly aid the analysis of future biomethane market shares, substituted natural gas pathways and associated GHG emission savings.

It is also interesting to reflect on the very different trajectories for UK and German implementation to date (with a centralized grid focus the UK echoing its previous centralized electricity policy) and a decentralized tariff approach in Germany prioritizing independent users and displacement of existing high carbon intensity loads. Each approach has been successful in its respective markets, with contributions in both countries increasing. However, climate change targets still require further development and so each country could now benefit significantly from exploring the approach of the other and expanding beyond their successes to date to increase future GHG reductions and meet RE targets. The presented approach shows how policy makers can learn from other countries, markets and paths to a decarbonized energy system and associated GHG emission reduction. In particular how UK policy makers can learn from Germany and vice versa. In the past several aspects of Germany's biomethane market development support either served as a blueprint (e.g. plant concepts, feedstock variety or support of rural development) or served as negative example (e.g. monocultural maize systems). Policy makers need to consider policies to promote biggest economic, social and environmental benefits to best possible use the highly valuable energy carrier biomethane. Furthermore policy makers also need to consider how easy it is to replace certain fuels, e.g. electricity has a lot of options, whereas less so for public and heavy duty transport where biomethane can be a valuable and already available substitute to fossil fuels. To prevent i.e. monocultural systems and to exploit the reasonable potential for biomethane feedstock aspects shall also be considered in more detail like promoting wastes and residues. Moreover industry should also be aware that feedstock and operational practices affect GHG saving potential. This would require new policy mechanisms in both countries, including some that go beyond the energy sector to increase the available waste resource and some that ensure that GHG savings are actually counted and maximized.

Acknowledgements

Bioenergy research at the University of Bath and the University of Manchester is supported by the EPSRC Supergen Bioenergy Hub [Grant Ref: EP/J017302/1]. This is a large interdisciplinary programme and the views expressed in this paper are those of the authors alone, and do not necessarily reflect the views of the collaborators or the policies of the funding bodies. Part of that research was funded by a SUPERGEN Bioenergy Hub small Grant fund.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2016.07.098.

References

[1] European Council. Conclusions on 2030 climate and energy policy framework; 2014.
[2] Lau LC, Lee KT, Mohamed AR. Global warming mitigation and renewable energy policy development from the Kyoto Protocol to the Copenhagen Accord—a comment. Renew Sustain Energy Rev 2012;16:5280–4. http://dx.doi.org/10.1016/j.rser.2012.04.006.
[3] Paris Agreement – European Commission. http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm [accessed 16 Feb 2016].
[4] Dhillon RS, von Wuehlisch G. Mitigation of global warming through renewable biomass. Biomass Bioenergy 2013;48:75–89. http://dx.doi.org/10.1016/j.biombioe.2012.11.005.
[5] European Environment Agency. Annual European Union greenhouse gas inventory 1990–2012 and inventory report 2014; 2014.
[6] Bundesministerium für Wirtschaft und Energie (BMWI). Erneuerbare Energien in Zahlen Nationale und internationale Entwicklung im Jahr 2014; 2014.
[7] Renewable Energy Association. Renewable energy view – the authoritative annual report on the UK renewable energy sector; 2015.
[8] Gambhir A, Vallejo L. The UK's progress towards its carbon budgets; 2011.
[9] The energy transition and climate change. In: Clean energy wire. https://www.cleanenergywire.org/dossiers/energy-transition-and-climate-change [accessed 17 Dec 2015].
[10] Umweltbundesamt. Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto- Protokoll 2014 Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990–2012; 2014.
[11] Department of Energy & Climate Change. 2013 UK greenhouse gas emissions. Provisional figures and 2012 UK greenhouse gas emissions. Final figures by fuel type and end-user; 2014.
[12] Icha P. Entwicklung der spezifischen Kohlendioxid- Emissionen des deutschen Strommix in den Jahren 1990 bis 2014; 2015.
[13] Davis SJ, Caldeira K. Consumption-based accounting of CO_2 emissions. Proc Natl Acad Sci 2010;107:5687–92. http://dx.doi.org/10.1073/pnas.0906974107.
[14] AG Energiebilanzen e.V. Auswertungstabellen zur Energiebilanz Deutschlands; 2015.
[15] Zhang Q, Li M, Shao S. Combustion process and emissions of a heavy-duty engine fueled with directly injected natural gas and pilot diesel. Appl Energy 2015;157:217–28. http://dx.doi.org/10.1016/j.apenergy.2015.08.021.
[16] Haro P, Aracil C, Vidal-Barrero F, Ollero P. Balance and saving of GHG emissions in thermochemical biorefineries. Appl Energy 2015;147:444–55. http://dx.doi.org/10.1016/j.apenergy.2015.02.083.
[17] Njakou Djomo S, Witters N, Van Dael M, et al. Impact of feedstock, land use change, and soil organic carbon on energy and greenhouse gas performance of biomass cogeneration technologies. Appl Energy 2015;154:122–30. http://dx.doi.org/10.1016/j.apenergy.2015.04.097.
[18] de Menezes LM, Houllier MA. Germany's nuclear power plant closures and the integration of electricity markets in Europe. Energy Policy 2015;85:357–68. http://dx.doi.org/10.1016/j.enpol.2015.05.023.
[19] Ngar-yin Mah D, Hills P. Participatory governance for energy policy-making: a case study of the UK nuclear consultation in 2007. Energy Policy 2014;74:340–51. http://dx.doi.org/10.1016/j.enpol.2014.08.002.
[20] Department of Energy & Climate Change. UK greenhouse gas emissions statistics; 2015.
[21] Lan H, Wen S, Hong Y-Y, et al. Optimal sizing of hybrid PV/diesel/battery in ship power system. Appl Energy 2015;158:26–34. http://dx.doi.org/10.1016/j.apenergy.2015.08.031.
[22] Peng S, Hong H, Wang Y, et al. Off-design thermodynamic performances on typical days of a 330 MW solar aided coal-fired power plant in China. Appl Energy 2014;130:500–9. http://dx.doi.org/10.1016/j.apenergy.2014.01.096.
[23] Tanaka Y, Mesfun S, Umeki K, et al. Thermodynamic performance of a hybrid power generation system using biomass gasification and concentrated solar thermal processes. Appl Energy 2015;160:664–72. http://dx.doi.org/10.1016/j.apenergy.2015.05.084.
[24] Petersson A, Wellinger A. Biogas upgrading technologies – developments and innovations; 2009.
[25] IEA Bioenergy. Biomethane – status and factors affecting market development and trade; 2014.
[26] Strauch S, Krassowski J, Singhal A. Biomethane guide for decision makers – policy guide on biogas injection into the natural gas grid; 2013.
[27] Popp J, Lakner Z, Harangi-Rákos M, Fári M. The effect of bioenergy expansion: food, energy, and environment. Renew Sustain Energy Rev 2014;32:559–78. http://dx.doi.org/10.1016/j.rser.2014.01.056.
[28] Wood G, Dow S. What lessons have been learned in reforming the renewables obligation? An analysis of internal and external failures in UK renewable energy policy. Energy Policy 2011;39:2228–44. http://dx.doi.org/10.1016/j.enpol.2010.11.012.
[29] Brown MA. Market failures and barriers as a basis for clean energy policies. Energy Policy 2001;29:1197–207. http://dx.doi.org/10.1016/S0301-4215(01)00067-2.
[30] von Rosenstiel DP, Heuermann DF, Hüsig S. Why has the introduction of natural gas vehicles failed in Germany?—lessons on the role of market failure in markets for alternative fuel vehicles. Energy Policy 2015;78:91–101. http://dx.doi.org/10.1016/j.enpol.2014.12.022.
[31] Deutsche Energie-Agentur GmbH. Branchenbarometer Biomethan. Daten: Fakten und Trends zur Biogaseinspeisung; 2014.
[32] Cucchiella F, D'Adamo I. Technical and economic analysis of biomethane: a focus on the role of subsidies. Energy Convers Manage 2016;119:338–51. http://dx.doi.org/10.1016/j.enconman.2016.04.058.
[33] Alamia A, Magnusson I, Johnsson F, Thunman H. Well-to-wheel analysis of biomethane via gasification, in heavy duty engines within the transport sector of the European Union. Appl Energy 2016;170:445–54. http://dx.doi.org/10.1016/j.apenergy.2016.02.001.
[34] Wu B, Zhang X, Shang D, et al. Energetic-environmental-economic assessment of the biogas system with three utilization pathways: combined heat and power, biomethane and fuel cell. Bioresour Technol 2016;214:722–8. http://dx.doi.org/10.1016/j.biortech.2016.05.026.
[35] Pierie F, Bekkering J, Benders RMJ, et al. A new approach for measuring the environmental sustainability of renewable energy production systems: focused on the modelling of green gas production pathways. Appl Energy 2016;162:131–8. http://dx.doi.org/10.1016/j.apenergy.2015.10.037.
[36] Wu B, Sarker BR, Paudel KP. Sustainable energy from biomass: biomethane manufacturing plant location and distribution problem. Appl Energy 2015;158:597–608. http://dx.doi.org/10.1016/j.apenergy.2015.08.080.
[37] Paturska A, Repele M, Bazbauers G. Economic assessment of biomethane supply system based on natural gas infrastructure. Energy Procedia 2015;72:71–8. http://dx.doi.org/10.1016/j.egypro.2015.06.011.
[38] Carlini M, Castellucci S, Moneti M. Anaerobic co-digestion of olive-mill solid waste with cattle manure and cattle slurry: analysis of bio-methane potential. Energy Procedia 2015;81:354–67. http://dx.doi.org/10.1016/j.egypro.2015.12.105.
[39] De Clercq D, Wen Z, Fan F, Caicedo L. Biomethane production potential from restaurant food waste in megacities and project level-bottlenecks: a case study in Beijing. Renew Sustain Energy Rev 2016;59:1676–85. http://dx.doi.org/10.1016/j.rser.2015.12.323.
[40] Li A, Du N, Wei Q. The cross-country implications of alternative climate policies. Energy Policy 2014;72:155–63. http://dx.doi.org/10.1016/j.enpol.2014.05.005.
[41] Corton J, Donnison IS, Patel M, et al. Expanding the biomass resource: sustainable oil production via fast pyrolysis of low input high diversity biomass and the potential integration of thermochemical and biological conversion routes. Appl Energy 2016;177:852–62. http://dx.doi.org/10.1016/j.apenergy.2016.05.088.
[42] Larsson M, Grönkvist S, Alvfors P. Synthetic fuels from electricity for the Swedish transport sector: comparison of well to wheel energy efficiencies and costs. Energy Procedia 2015;75:1875–80. http://dx.doi.org/10.1016/j.egypro.2015.07.169.
[43] Carnevale E, Lombardi L, Zanchi L. Life cycle assessment of solar energy systems: comparison of photovoltaic and water thermal heater at domestic scale. Energy 2014;77:434–46. http://dx.doi.org/10.1016/j.energy.2014.09.028.
[44] Fachagentur Nachwachsende Rohstoffe. Basisdaten Bioenergie Deutschland; 2014.
[45] Bioenergy in Germany: facts and figures; 2014.
[46] Chang MK, Eichman JD, Mueller F, Samuelsen S. Buffering intermittent renewable power with hydroelectric generation: a case study in California. Appl Energy 2013;112:1–11. http://dx.doi.org/10.1016/j.apenergy.2013.04.092.
[47] Bussar C, Stöcker P, Cai Z, et al. Large-scale integration of renewable energies and impact on storage demand in a European renewable power system of 2050—sensitivity study. J Energy Storage 2016;6:1–10. http://dx.doi.org/10.1016/j.est.2016.02.004.
[48] Department of Energy & Climate Change. Renewable sources of energy. Digest of United Kingdom Energy Statistics (DUKES); 2015 [chapter 6].
[49] Department of Energy & Climate Change. Bioenergy statistics – UK overview; 2013.
[50] Department of Energy & Climate Change. Renewable transport fuel obligation statistics: period 7, 2014/15, report 6; 2016.
[51] ADBA. Anaerobic digestion market report; 2015. Anaerobic Digestion & Bioresources Association (ADBA), London.

[52] Patrizio P, Leduc S, Chinese D, et al. Biomethane as transport fuel – a comparison with other biogas utilization pathways in northern Italy. Appl Energy 2015;157:25–34. http://dx.doi.org/10.1016/j.apenergy.2015.07.074.
[53] DBFZ Deutsches Biomasseforschungszentrum. DBFZ-database; 2015.
[54] AD Biogas plant map from Anaerobic Digestion & Bioresources Association. http://adbioresources.org/about-ad/ad-map// [accessed 13 Jan 2016].
[55] The Bioeconomy Consultants — NNFCC. http://www.nnfcc.co.uk/ [accessed 13 Jan 2016].
[56] Jaber JO. Future energy consumption and greenhouse gas emissions in Jordanian industries. Appl Energy 2002;71:15–30.
[57] Energy Technologies Institute. Bioenergy – delivering greenhouse gas emission savings through UK bioenergy value chains; 2015.
[58] Department of Energy & Climate Change. Analysis of characteristics and growth assumptions regarding AD biogas combustion for heat, electricity and transport and biomethane production and injection to the grid; 2011.
[59] Scholwin F, Grope J, Schüch A, et al. Ist-Stand der Biomethannutzung Kosten – Klimawirkungen – Verwertungswege KWK aus Biogas. Biomethan und Erdgas im Vergleich; 2014.
[60] Majer S. Ergebnisse von Modellbiogasanlagen zur ökologischen Bewertung von Biogas/Biomethan, im Auftrag des Biogasrates e.V.; 2011.
[61] Lunz B, Stöcker P, Eckstein S, et al. Scenario-based comparative assessment of potential future electricity systems – a new methodological approach using Germany in 2050 as an example. Appl Energy 2016;171:555–80. http://dx.doi.org/10.1016/j.apenergy.2016.03.087.
[62] Nagy K, Körmendi K. Use of renewable energy sources in light of the "New Energy Strategy for Europe 2011–2020". Appl Energy 2012;96:393–9. http://dx.doi.org/10.1016/j.apenergy.2012.02.066.
[63] Thornley P. Increasing biomass based power generation in the UK. Energy Policy 2006;34:2087–99. http://dx.doi.org/10.1016/j.enpol.2005.02.006.
[64] Perry M, Rosillo-Calle F. Recent trends and future opportunities in UK bioenergy: maximising biomass penetration in a centralised energy system. Biomass Bioenergy 2008;32:688–701. http://dx.doi.org/10.1016/j.biombioe.2008.01.004.
[65] Thornley P, Cooper D. The effectiveness of policy instruments in promoting bioenergy. Biomass Bioenergy 2008;32:903–13. http://dx.doi.org/10.1016/j.biombioe.2008.01.011.
[66] Barisa A, Cimdina G, Romagnoli F, Blumberga D. Potential for bioenergy development in Latvia: future trend analysis. Agron Res 2013;11:275–82.
[67] DBFZ Deutsches Biomasseforschungszentrum gGmbH. Method Handbook 04 – Material flow-oriented assessment of greenhouse gas effects; 2015.
[68] Walsh C, Thornley P. Barriers to improving energy efficiency within the process industries with a focus on low grade heat utilisation. J Clean Prod 2012;23:138–46. http://dx.doi.org/10.1016/j.jclepro.2011.10.038.
[69] Thornley P, Upham P, Tomei J. Sustainability constraints on UK bioenergy development. Energy Policy 2009;37:5623–35. http://dx.doi.org/10.1016/j.enpol.2009.08.028.
[70] Einspeisekapazität der Biomethan-Anlagen in Deutschland bis 2014|Statistik. In: Statista. http://de.statista.com/statistik/daten/studie/198551/umfrage/aufbereitungskapazitaet-der-biogasanlagen-zur-biomethan-produktion/ [accessed 10 Dec 2015].
[71] Dunkelberg E, Salecki S, Weiß J, et al. Biomethan im Energiesystem – Ökologische und ökonomische Bewertung von Aufbereitungsverfahren und Nutzungsoptionen; 2015.
[72] Uusitalo V, Havukainen J, Soukka R, et al. Systematic approach for recognizing limiting factors for growth of biomethane use in transportation sector – a case study in Finland. Renew Energy 2015;80:479–88. http://dx.doi.org/10.1016/j.renene.2015.02.037.
[73] Daniel-Gromke J, Denysenko V, Barchmann T, et al. Aufbereitung von Biogas zu Biomethan und dessen Nutzung – Status quo und Perspektiven. In: Dezentrale Energieversorgung. TK Verlag; 2013. p. 468.
[74] Biomethane green gas is growing contender in UK renewable energy market – news – green gas certification scheme. https://www.greengas.org.uk/news/biomethane-green-gas-is-growing-contender-in-uk-renewable-energy-market [accessed 10 Dec 2015].
[75] Anaerobic Digestion & Bioresources Association. Anaerobic Digestion Market report; November 2015.
[76] Biofuel statistics: year 7 (2014–2015), report 5 – publications – GOV.UK. https://www.gov.uk/government/statistics/biofuel-statistics-year-7-2014-to-2015-report-5 [accessed 13 Jan 2016].
[77] Adams PWR, Mezzullo WG, McManus MC. Biomass sustainability criteria: greenhouse gas accounting issues for biogas and biomethane facilities. Energy Policy 2015;87:95–109. http://dx.doi.org/10.1016/j.enpol.2015.08.031.
[78] Sustainability Criteria|Anaerobic Digestion & Bioresources Association. In: ADBA Anaerob Dig Bioresour Assoc. http://adbioresources.org/members-area/sustainability-criteria/ [accessed 13 Jan 2016].
[79] Kirchner A, Matthes F. Modell Deutschland – Klimaschutz bis 2050: Vom Ziel her denken; 2009.
[80] Department of Energy & Climate Change. Natural gas. Digest of United Kingdom Energy Statistics (DUKES); 2015 [chapter 4].
[81] Hawkey DJC. District heating in the UK: a technological innovation systems analysis. Environ Innov Soc Trans 2012;5:19–32. http://dx.doi.org/10.1016/j.eist.2012.10.005.
[82] Green Gas Grids. UK roadmap development of the biomethane sector; 2014.
[83] Anaerobic Digestion & Bioresources Association. Biogas in the UK; 2012.
[84] Hopwood L. The UK biogas market; 2011.
[85] van Basshuysen R. Erdgas und erneuerbares Methan für den Fahrzeugantrieb. Wiesbaden: Springer Fachmedien Wiesbaden; 2015.
[86] Thornley P, Upham P, Huang Y, et al. Integrated assessment of bioelectricity technology options. Energy Policy 2009;37:890–903. http://dx.doi.org/10.1016/j.enpol.2008.10.032.
[87] Kopyscinski J, Schildhauer TJ, Biollaz SMA. Production of synthetic natural gas (SNG) from coal and dry biomass – a technology review from 1950 to 2009. Fuel 2010;89:1763–83. http://dx.doi.org/10.1016/j.fuel.2010.01.027.
[88] UK Government. Nuclear industrial strategy: the UK's nuclear future; 2013.