energies

MDPI

Review

Biogas Upgrading: A Review of National Biomethane Strategies and Support Policies in Selected Countries

Christopher Schmid [1], Thomas Horschig [1,*], Alexandra Pfeiffer [1], Nora Szarka [1] and Daniela Thrän [1,2,3]

1 DBFZ—Deutsches Biomasseforschungszentrum gGmbH, Torgauer Straße 116, 04347 Leipzig, Germany; christopher.schmid@dbfz.de (C.S.); alexandra.pfeiffer@dbfz.de (A.P.); nora.szarka@dbfz.de (N.S.); daniela.thraen@dbfz.de (D.T.)
2 Helmholtz Centre for Environmental Research, UFZ, Permoserstraße 15, 04318 Leipzig, Germany
3 University of Leipzig, Chair of Bioenergysystems, Grimmaische Straße 12, 04109 Leipzig, Germany
* Correspondence: thomas.horschig@dbfz.de

Received: 4 September 2019; Accepted: 30 September 2019; Published: 8 October 2019

check for updates

Abstract: Bioenergy contributes significantly towards the share of renewable energies, in Europe and worldwide. Besides solid and liquid biofuels, gaseous biofuels, such as biogas or upgraded biogas (biomethane), are an established renewable fuel in Europe. Although many studies consider biomethane technologies, feedstock potentials, or sustainability issues, the literature on the required legislative framework for market introduction is limited. Therefore, this research aims at identifying the market and legislative framework conditions in the three leading biomethane markets in Europe and compare them to the framework conditions of the top six non-European biomethane markets. This study shows the global status and national differences in promoting this renewable energy carrier. For the cross-country comparison, a systematic and iterative literature review is conducted. The results show the top three European biomethane markets (Germany, United Kingdom, Sweden) and the six non-European biomethane markets (Brazil, Canada, China, Japan, South Korea, and the United States of America), pursuing different promotion approaches and framework conditions. Noteworthy cross-national findings are the role of state-level incentives, the tendency to utilise biomethane as vehicular fuel and the focus on residues and waste as feedstock for biomethane production. Presenting a cross-country comparison, this study supports cross-country learning for the promotion of renewable energies like biomethane and gives a pertinent overview of the work.

Keywords: cross-country comparison; biomethane policies; renewable natural gas; biogas upgrading; biomethane market

1. Introduction

With the Paris Agreement of 2015, the international community agreed on pursuing efforts for the limitation of global average temperature increase to below two degrees compared to the pre-industrial temperature level to address the threats of climate change. One crucial pillar of this agreement is the reduction of greenhouse gas (GHG) emissions [1,2]. This target of the Paris Agreement was transferred to supranational or national targets and strategies for GHG emission reduction. Consequently, the European Union (EU) and its member countries set increasingly ambitious GHG-emission reduction targets for 2020, 2030, and 2050. One pathway to reach GHG-emission reductions is the increase and further deployment of renewable energy (RE) technologies. These technologies can potentially contribute to an emission reduction compared to fossil energy carriers, with the exact amount being dependent on the specific technology and its associated value chain [3–7]. Currently, bioenergy has the largest share of RE carriers at the global scale [8]. Bioenergy is provided via solid, liquid, and gaseous energy carriers [9]. Although gaseous bioenergy carriers (biogas) play a minor role (2%) compared to solid bioenergy carriers (89%), global biogas production increased with annual average growth rates of 11.2% between 2000 and 2014 [10]. About half of the global biogas production capacity is located in Europe [10].

Biogas can be upgraded to biomethane, which is considered a mature technology [11]. Biomethane, also called renewable natural gas (RNG), especially in North American countries, is produced via upgrading of biogas produced via anaerobic digestion to conditions necessary for feed-in into the natural gas grid [12]. Biomethane can also be produced through thermo-chemical conversion [13]. In this case, it is called bio-synthetic natural gas (bio-SNG). Bio-SNG is not further considered in this study since bio-SNG plants are still subject to research (Technology Readiness Level of 4–7 [14]) and show no market penetration yet [13]. Hence, only biochemical conversion to biogas and its upgrading to biomethane is considered in this study.

Upgrading of biogas to biomethane is done by removing components like water, hydrogen sulphide, ammonia, oxygen, nitrogen, carbon monoxide, halogenated hydrocarbons, siloxanes, and particles in the first stage. In the second stage, carbon dioxide (CO_2) is removed for the increment of the methane (CH_4) content [15]. Currently, biogas upgrading to biomethane is done via water scrubbing, chemical scrubbing, physical scrubbing, pressure swing adsorption, and membrane separation [16]. Water scrubbing represents the highest share in Europe, with about 40% [17]. Recent advantages have been made in the field of biochemical biogas upgrading using microbial-based systems in particular [18]. Those encompass biological methanation approaches where H_2 is coupled with CO_2 from the biogas production process to form CH_4. This can be done either by direct injection of H_2 into the anaerobic digester or by injection of H_2 into a separate bioreactor. Both approaches can also be combined. More detailed information on the technological advances of biochemical biogas upgrading can be found in the literature [18–20]. Another promising approach is currently seen in cryogenic upgrading technologies, which can also support further business options for biogas upgrading plants [21]. Cryogenic approaches can simultaneously obtain high-purity biomethane and food-grade CO_2 [22].

Compared to biogas, biomethane offers additional application possibilities like (1) the use as vehicle fuel or (2) grid injection and additional advantages like (3) enhanced RE storage capabilities through higher energy density of biomethane, (4) increment of external heat use, and, thus, higher efficiencies, as well as (5) an extended timely and spatially decoupling of production and utilisation [15,23]. However, upgrading biogas to biomethane is not always advantageous, since the upgrading process increases costs, energy demand, and material use and, thus, can trigger environmental effects [24]. Furthermore, the methane slip within the biomethane production value chain can negatively impact the ecological balance [4,25].

Analogous to biogas production, possible feedstock for biomethane production through biochemical conversion is primarily lignin-poor substrates, such as sugar and starch or oil or fat, containing biomass [13,26]. Its composition is determined by the place of injection and the onsite requirements for gas properties. Compared to natural gas, biomethane saves GHG emissions in each utilisation pathway; using waste or residues such as residues from livestock production even increases the possible emission savings further [4]. In any known case, the production of energy (power, heat, or fuel) from biomethane is costlier than the production of energy from its fossil counterpart natural gas. Purchasing costs of biomethane are currently two to three times higher than those for natural gas [4]. Usually, energy production from fossil fuels is cheaper because negative externalities of energy technologies like GHG emission remain unpriced [27]. If biomethane shall be a cost-effective option for the production of renewable power, and as a result, renewable heat, or within the transport sector, it needs clear political support [28]. However, the design of such political measures can be diverse. It should include several aspects, such as desired feedstock composition, sustainability issues within the value chains, and the desired end-use sector. Consequently, the implementation of biomethane as an option within an energy system striving for a higher share of renewables (as present in many European countries) has been done in many different ways and thus had different success. A similar situation, as described above, can be witnessed in international publications on this topic. Whereas literature about technologies employed [29,30], feedstock potentials [31–33], or sustainability issues [34,35] associated with biomethane use are broadly available, literature on how to successfully implement biomethane as a technology option in an energy system transforming to a RE based energy system, is limited [36–39]. Indeed, such literature is mainly available for other technological options like photovoltaic [40] or wind power [41]. Lewis and Wiser (2007) investigated wind industry policy support mechanisms in 12 countries with the result that a mixture of policies supporting a sizeable and stable market in conjunction with policies supporting local manufacturing of wind power plants are favourable [42]. A review of global solar power supporting policies has been done by Solangi et al. (2011). Their research points out that feed-in tariffs (FiT), renewable portfolio standards (RPS), and incentives are the most supportive policies [43]. In most cases, analysis of the successful implementation of renewable technology options in a transforming energy system is done on a case study level for one country [40,44].

Cross-country comparison can highlight measures on why a policy is effectively promoting a RE carrier (such as biomethane). In addition to the comparison of specific technologies, the cross-country comparison of a set of policies has also been subject to research, i.e., FiT evaluation in Spain and Germany [45] or the comparison of renewable obligation system in the UK and feed-in tariffs in Germany [46]. In terms of biogas promotion in Africa, a comprehensive review comparing promotion policies from different countries in Europe, Asia, and America was conducted by Kemausuor et al. in 2018 [39]. Regarding biomethane, the only publication utilising a cross-country comparison investigates the difference between Germany and the UK in terms of reasonable potential for biomethane production and how to exploit it [4]. Hence, it highly depends on local conditions, requirements, and the purpose of the planned bioenergy plant, and whether biogas should be upgraded or used directly onsite.

2. Materials and Methods

To reach the set goals, first, a systematic literature review, according to [47], was performed to obtain data and information on biomethane of individual countries, e.g., production, markets, and legislation. Collected data were analysed and compared through a set of criteria.

The process of the literature review was threefold. In the first step, the criteria were defined to later compare the different biomethane markets. Secondly, the relevant countries were determined based on data availability and relevance to the study. In the last step, keywords were utilised to obtain country-specific data to feed into the selected criteria. The following words (including different spellings such as biomethane and bio-methane) were selected as a baseline: bioenergy, biomethane, biogas, gaseous bioenergy, and renewable natural gas. When combined with topic-specific keywords, such as production, plants, infrastructure, strategy, policy, incentive, programme, market, goals, and quality standard and/or selected country names, the keyword-based search provided a holistic data set. The keyword search applied to the title and abstract. The selection of papers and articles for the literature review then followed a three-step procedure: (1) relevance of title, (2) relevance of abstract, and (3) relevance of the article as a whole based on skim-reading. After this selection process, all remaining articles were analysed for the literature review. When conducting the literature review, only publications in English were considered, as the majority of scientific literature is published in the English language. The authors acknowledge that publications, especially non-scientific literature, in the native language of each country may enrich the data set; however, that was not the scope of this study.

The results are presented in a cross-country comparison table using the obtained data and a set of assessment criteria. The assessment criteria and their selection are as follows.

The stakeholder and resource criteria emphasise the relevance of biomethane with regard to national resource assessment and the interest of private market actors:

- Resource assessment (identification of biomethane potentials): this criterion examines if a stand-alone assessment of the national biomethane production potential exists, based on local biomass resource availability and studies thereon by scientific or public institutions. The purpose of this criterion is to ascertain if a national effort is taken to generate knowledge about resources explicitly for biomethane production. Knowledge of resource potential is considered important for evaluating available options and developing strategic approaches for establishing a certain renewable energy product [48–51].
- Biomethane associations/organisations: here, it is examined if associations or organisations exist that aim to promote the development of biogas and/or biomethane through networking, lobbying, consulting, educational work, or further services. The purpose is to detect the interest of private market actors. The motivation for selecting these criteria is showing whether market actors in a country are interested in the development of a biomethane market.

The inventory framework criteria comprise criteria which consider the existence of incentive or subsidy programmes in a country on the national and state level. A state is an organised political community or area that forms a part of an organised federal country [52]. Political efforts explicitly promoting biomethane production and/or utilisation in the sectors of power, heat, and transport can be recognised through this. The inventory framework criteria are incorporated into the criteria set since promotion schemes are considered as fundamental for the market diffusion of novel energy technologies [53].

The regulatory framework criteria primarily consider the existence of consistent national quality requirements. In addition, the existence of further explicit regulations for biomethane is considered. The purpose of examining national quality requirements is to identify trade barriers within the country's national market. The motivation of criteria selection is that missing consistent national quality requirements are considered as one fundamental barrier in expanding the domestic trade of biomethane since the properties of gas are not the same within one market. The criterion of further national regulations is additionally incorporated to investigate the existence of further explicit biomethane regulations, showing the relevance of biomethane in terms of market regulation.

The market development criteria examine the development of the market through the number of deployed and operating biomethane projects, representing the supply side of the respective market. The purpose is to show the difference in the quantity of operating biomethane plants. Other criteria, like total biomethane production, demand, or traded volumes of biomethane, were considered for this study, but not enough reliable data were available.

The utilisation pathway criteria investigate the major distribution and utilisations pathways. The purpose of these criteria is to highlight in which energetic sector most of the produced biomethane is utilised and is motivated by the different options for utilisation, as described before.

The sustainability criterion examines whether residues and waste are used as feedstock for biomethane production primarily or if energy crops are dominant. The reason for the selection of this criterion as the sustainability criterion is that exploitation of residues and waste adds value creation. Moreover, residual material is a by-product of other processes, while energy crops are purpose-grown and hence require additional land, water, and nutrition.

3. Status Quo and Policy Analysis of Biogas Upgrading

The results are structured in the following order: first, the European biomethane market is described, focusing on its three largest biomethane markets. Secondly, a short description of the status quo of the top six countries outside Europe with noteworthy biomethane production is given. Thirdly, the described top six countries are analysed and compared with the three European biomethane markets.

3.1. European Status Quo of Biomethane

The EU established the Renewable Energy Directive (RED) 2009/28/EC, amongst other measures, to reach its envisaged emission reduction goals. This policy encompasses the target of reaching at least a share of 20% of Europe's overall energy consumption through RE by 2020. The RED is shaping national RE policy programmes by framing national targets for RE shares, ranging between 10% and 49%. The EU members individually devise how they plan to meet these targets in national RE action plans [54]. Consequently, the share of REs grew to about 13.2% of EU-28 gross inland energy consumption, which amounted to about 1641 Mtoe, in 2016 [55]. Amongst the renewables, the largest share is represented by bioenergy with a share of about 8.6%, similar to the global scale of 10%. Compared to global figures, biogas plays a significant role in Europe, although solid biofuels still represent the largest amount. In 2016, the European gross final inland consumption of solid biofuels amounted to about 98.3 Mtoe (primary production: 94.1 Mtoe). Biogas and liquid biofuel consumption amounted to about 16.6 Mtoe and 15.1 Mtoe (primary production: 16.6 Mtoe and 13.8 Mtoe) in 2016 [56]. However, not only biogas itself is an established RE option in Europe. Europe is also the frontrunner in upgrading biogas to biomethane [57]. The number of biogas-upgrading plants increased from 187 in 2011 to 497 in the first quarter of 2017 [58].

3.2. European Biomethane Market and Legislation

Prior to comparing international markets to markets in the EU, the European biomethane market is considered. Currently, it is the largest market in the world with almost 500 upgrading units in 2017, of which 194 are in Germany [58]. The number of biomethane plants in each country within Europe varies heavily (Table 1).

Table 1. Total number of operational biomethane plants and biomethane feed-in capacity in the EU-28 and European Economic Area (EEA) members in 2017 [58].

Country	Number of Upgrading Plants 2017	Total Biomethane Feed-In Capacity in 2017 [m^3/h]
Germany	194	>165,074
United Kingdom	85	>60,770
Sweden	63	>14,620
Switzerland [1]	31	>3333
France	30	>4387
Netherlands	26	14,212
Denmark	22	>7109
Austria	15	>2685
Finland	12	>1507
Norway	4	>1275
Italy	7	No Information
Luxembourg	3	680
Hungary	2	800
Iceland	2	550
Spain	1	6500

[1] = Switzerland is an EFTA member country and signatory of the EEA agreement that has not ratified.

Although there are similarities regarding national biomethane policies, such as supranational EU legislations or supranational EU quality requirements, differences between the national markets do exist. Supranational EU legislations and quality requirements that shape the national biomethane strategies are:

- RED requires each member to implement a nationally individual RE target through national RE action plans. It was introduced together with the Fuel Quality Directive (FQD) implementing sustainability criteria for liquid and gaseous biofuels for the transport sector [54,57,59].
- FQD 2009/30/EC pursues a reduction of GHG-emissions in transport fuels by 2020 [59].
- Indirect Land Use Change (ILUC) Directive 2015/1513 focuses on a reduction of the share of energetic biomass feedstock produced on agricultural land [60].

- EN 16723–1:2016—"Part 1: Specifications for biomethane for injection in the natural gas network" and EN 16723–2:2017—"Part 2: Automotive fuels specification" specify the requirements for biomethane used as automotive fuel and gas grid injection [61,62].

Whereas supranational EU legislation applies for each national legislation-making process, differences in feedstock processing, distribution pathways, quality requirements, and biomethane certification through national registers can be observed. EU regulations are binding as well as generally and directly applied in all member countries, whereas EU directives are binding for the objective to be achieved, without defining the exact measures [63]. The observed differences investigated in [4,58,64–67] can be summarized as follows:

- While energy crops currently dominate the German biomethane market, the other European biomethane markets primarily use residues and wastes like agricultural residues, bio- and municipal waste, industrial organic waste, landfill wastes, or sewage sludge.
- Regarding the connection to the natural gas grid, the following can be observed: in Italy and Iceland, no upgrading plant is connected to the grid. In Sweden, more than 75%, in Norway and Hungary 50%, and in Finland about 42% of the upgrading plants are not connected to the grid. There against, in Germany, the United Kingdom, Switzerland, France, Denmark, the Netherlands, or the other markets more than 90% of the biomethane plants inject into the grid.
- Utilisation of biomethane in Europe varies, too. For example, in Germany, biomethane is primarily used in the power sector, whereas the primary utilisation pathway in the UK is heat production and in Sweden, the provision as an automotive fuel.
- Regarding quality requirements, it can be stated that countries like Austria, Denmark, France, Germany, and Italy have standards for both the injection of biomethane into the grid and utilisation as vehicle fuel. Other countries like the UK, the Netherlands, and Italy have a standard only for grid injection. Sweden only has a standard for the utilisation as vehicle fuel.
- National biomethane registers exist in Germany, Austria, Denmark, France, the Netherlands, and the United Kingdom. In Sweden, Italy, or Spain, there are no biomethane registers yet.
- National incentives address different utilisations. In Germany, the Renewable Energy Source Act fosters power generation from biomethane with a Feed-in-Tariff and a market premium for renewable power generation. In the UK, heat production is promoted by the Renewable Heat Incentive, and in Sweden, the incentives address the utilisation as vehicle fuel. Another approach is the promotion of grid injection, like in France or Denmark.

Consequently, the three largest biomethane producers have been chosen as a case study for further cross-country comparison. Furthermore, these represent the three different utilisation pathways of biomethane (Germany—mainly power production, UK—mainly heat production, Sweden—mainly transport fuel).

The differences in the European biomethane markets underpin the complexity of policymaking for bioenergy promotion. It is considered highly challenging and difficult to prepare a sound bioenergy policy, since bioenergy is a diverse and complex issue represented by the following aspects: it (1) competes with other utilisation pathways like the food, feed, or material usage sector and (2) interacts with further sectors like forestry or waste management, (3) involves many diverse stakeholders, (4) has diverse ecological impacts, (5) comprises a large variety of usable feedstock, various conversion pathways, energy carriers, and value-added chains, and (6) is able to influence regional development. [68–74]. Hence, analysis of biomethane policies and framework conditions outside the EU-28 and EEA is required to understand the biomethane market on a global scale and the presumed variety of promotion strategies.

3.3. Status Quo of Biomethane in Selected Countries Outside the EU

For the comprehension of the status of the biomethane market on a global scale and the demonstration of the presumed variety in national promotion strategies, six noteworthy biomethane markets outside the EU-28 and EEA members are identified and compared with the three leading markets in the EU. The comparison is based on a set of criteria of market framework. Thus, the differences between the national markets are emphasised clearly in a comprehensive way. Hence, an overview of the global status quo of biomethane market development is prepared, allowing further studies that are more detailed and the possibility to learn from other countries in terms of biomethane promotion.

Based on the number of biomethane facilities, the following countries are identified as the top six countries with noteworthy biomethane production: Brazil, Canada, China, Japan, South Korea, and the United States of America. The development of the number and the total capacity of upgrading plants in these countries in the last five years is shown in Table 2.

Table 2. Total number of operational biomethane plants and the total upgrading capacity in the top 6 biomethane markets outside the EU [75–78].

Country	Number and Total Capacity of Upgrading Plants in 2014		Number and Total Capacity of Upgrading Plants (Most Recent Data)		
	Number	Upgrading Capacity (Nm^3 Raw Gas/h)	Number	Upgrading Capacity (Nm^3 Raw Gas/h)	Year
United States of America	50	>90,000	77	No Information	2018
China	2	~2000	73	No Information	2017
South Korea	6	~4000	10	~6000	2017
Canada	4	>1200	9	No Information	2018
Japan	6	~2400	6	~2400	2014
Brazil	4	>700	5	<1000	2017

Brazil: In Brazil, RE plays a significant role with a share of about 43% of the TPES (284.5 Mtoe) in 2016. Within the total RE supply, nearly two-thirds are covered by energy from biomass, which is dominated by solid and liquid biofuels [79]. The biogas and especially the biomethane market are in the early stages of market infiltration and therefore play a minor role compared to solid biomass combustion. Nevertheless, this market offers a large potential, based on the technical biomethane potential (~6.8 billion m^3/year), which could cover 37% to 46% of the total natural gas demand in 2013 and a comprehensive policy framework, which is currently being established [80]. Although a national financial incentive programme is currently not in place, national regulations regarding biomethane treatment and state-level promotion programmes exist accompanied by private incentives driven by several gas utilities [67,81]. According to the most recent data, five biomethane plants were in operation in 2017 [75].

Canada: Compared to Brazil, the Canadian TPES amounting to 280.1 Mtoe in 2016 is of a similar scale. However, the share of RE in the TPES is lower with a percentage of about 17.4% in 2016 with hydropower dominating. Furthermore, in the bioenergy sector, biogas is also of minor relevance compared to liquid and especially solid biofuels [79]. Nevertheless, there is a technical biomethane potential of 3.9 Mtoe methane produced by anaerobic digestion per year [82]. Currently, the Canadian biomethane market has nine upgrading facilities in operation and more in the planning stage. The plants in operation are located in British Columbia and Quebec, whereas plants are in the planning stage are in Ontario [77]. This is mirrored in the legal promotion framework since there is no federal programme and the states of British Columbia and Quebec have implemented supporting schemes exclusively [83–86]. Ontario's government programme is still being established, but the gas utilities themselves are starting to promote biomethane [87]. The same applies for the whole of Canada where the natural gas utilities, not government policy, develop the biomethane market [88], but a national Low Carbon Fuel Standard is in development [83].

China: China is the country with the highest TPES worldwide amounting to 2972.5 in 2016, largely covered by fossil fuels (share of ~91%). To decrease fossil fuel and import dependency, China is promoting RE, as part of that bioenergy, which covers about 40% of the RE supply. Within final bioenergy consumption, the solid biofuels are dominating [79]. Nevertheless, biogas plays a significant role. More than 110,000 biogas plants—most of them are household digesters—are in operation and producing more than 2.5 billion m^3 of biogas annually, as well as organic fertilizer for agriculture [78,89]. However, not only is biogas relevant for the Chinese RE development, but biomethane is also a pursued option. The 13th 5-Year Plan (2016–2020) aims to promote a biomethane market with the target to deploy 172 new biomethane projects by 2020 [89]. Between 2015 and 2017, investments were made towards the construction of 73 large scale biomethane plants [78]. Thereby, the number of plants increased from less than 10 plants in 2014 to more than 70 plants in 2018. This is the first step to exploit the total biomethane potential of 150–170 billion m^3/year from residues and wastes based on the current technical state of the art [90,91].

Japan: Japan set the target to reach a share of RE of 13% to 14% in the TPES and 22% to 24% in the electricity sector by 2030 [92]. Bioenergy covers nearly half of the RE supply which amounted to 972.1 PJ in 2014, representing about 5% of the national TPES [93,94]. More than 90% of consumed bioenergy comes from solid biofuels, whereas liquid and gaseous biofuels play no significant role [93]. Nevertheless, electricity production from biogas became attractive with the FiT, established in 2012 [95,96]. Besides the FiT, subsidies for the construction of biogas plants are available [97]. In 2017, the registered electricity generation capacity of biogas plants was 103 MW [98]. Biomethane had its outset in 2004; since then, the number increased to six known biomethane plants by 2012. These plants all upgrade biogas to biomethane as compressed natural gas (CNG) for vehicular applications, but other forms of utilisation also exist [75,99]. It is assumed that the 2012 FiT is responsible for the stop in biomethane capacity development: (1) the tariffs for electricity by direct biogas conversion are on an economically attractive level [95,96,100] and (2) the upgrading of biogas causes additional costs [24]. However, the fossil substitute of natural gas covers about a quarter of the national TPES and most of it is currently imported [94,101]. Hence, the potential demand for biomethane does exist.

South Korea: Korea is focusing on RE capacity expansion. There is a national binding target of 11% for RE in the gross final energy consumption by 2030 and the target to cover 8% of the electricity with RE by 2020. In 2016, RE covered a share of about 4.8% of the TPES with a production of 14.2 Mtoe. A TPES of 2.8 Mtoe is covered by bioenergy, which is dominated by solid biofuels, followed by liquid biofuels and biogas [67,93]. There were 110 biogas plants in operation producing 2798 GWh in 2016, supplemented by the downstream biomethane sector with ten upgrading facilities in operation and one under construction. The upgrading facilities produce biomethane for grid injection or as CNG, which is mainly used in public or municipal vehicles [67,75,102]. Nevertheless, the biomethane potential remains untapped. There are estimations that biomethane could cover up to 25% of the natural gas supply for transportation, with a market potential of 331×106 Nm^3/year [103]. To tap into this potential, a Renewable Fuel Standard (RFS)-programme applicable to biomethane is currently being discussed. Currently, an RPS for electricity producers is applicable to biomethane, and public construction loans for RE plants are available [67,102].

United States of America: After China, the United States of America has the highest TPES on a global scale with more than 90% covered by fossil fuels. Bioenergy is the most relevant source among the renewables and equally proportioned in energy from solid and liquid biofuels. Biogas is of minor relevance [79]. Nevertheless, biogas and biomethane have a long history in the country. Starting with its first biomethane plant in 1982, the U.S. biomethane market grew to a total number of 77 upgrading plants in operation plus 22 under construction and 35 in substantial development in 27 U.S. states in 2018. A total of 59 of the facilities in operation are injecting biomethane into the grid [77,104]. Between 1982 and 2011, nearly all of the biomethane produced was utilised in electricity production driven by state-level RPS-programmes. Currently, about 87% of the upgraded biogas is used as CNG or LNG transportation fuel and 13% as an energy carrier for power production [104]. The reason for this is the national RFS-programme and the state-level Low Carbon Fuel Standard (LCFS)-programmes (some are in development), which promise higher revenues for sale as vehicular fuel [104,105]. A barrier for the development of a biomethane market is the lack of a consistent biomethane quality specification for grid injection and use as CNG since the existing specifications for natural gas vary across the USA.

Moreover, newly set biomethane specifications are often far more stringent than those for natural gas. The same applies to regulations: there is no nationwide consistent regulative framework, but there are state-level regulations [106,107].

3.4. Cross-Country Comparison of Biomethane Markets

For a clear illustration of the differences between the national biomethane markets, the three leading European countries are compared with the presented top six countries regarding their biomethane market development status in Table 3, with more detailed information given in Appendix A.

At the beginning of this review, Japan was expected to be a large and promising biomethane market. However, it quickly became apparent that, currently, little interest and development in biogas upgrading or biomethane utilisation can be noted. Although commercial biomethane plants do exist, this lack of interest is based on the absence of progressive deployment of plants between 2012 and 2019. The national FiT, introduced in 2012, is considered to be responsible for this stop in biomethane capacity expansion. Furthermore, the literature review did not reveal any data on the assessments of biomethane potentials, associations, or organisations dedicated to biomethane and specific regulations. The other investigated markets, especially in Europe, fulfil the interest and regulatory framework criteria. Hence, Japan is a prime example for illustrating how not having a clear regulatory and inventory framework, as well as established association work combined with other strategic objectives (namely power production), can slow down or hinder market development of certain RE. Although there is no specific interest for biomethane detected in Japan, there is development in the bioenergy market like the expansion of the biogas production or the energetic utilisation of wood, agricultural products, and residues [95]. Consequently, even though a biomethane market still needs to be established, the country provides technical and resource basis for it.

The European countries show a comprehensive framework supporting biomethane market development, especially regarding regulations and incentives on country-level. This comprehensive support is mirrored by the large number of commercial upgrading projects. Germany has by far the largest amount of biomethane facilities. There are only two countries outside the EU-28 and EEA, which have project numbers as high as the leading European countries, namely China and the United States of America. However, rather than having an as comprehensive framework as the European countries, these two countries provide very attractive national incentives resulting in a fast increase of project numbers. Therefore, Europe is still in the lead regarding biomethane projects and demonstrates well that a comprehensive and attractive regulatory and inventory framework on country-level with a clear strategic objective on biomethane production and use supports the increase of biomethane projects. Opposing this observation, the absence of national incentives (Brazil, Canada) or incentives with other strategic objectives and unattractive conditions (Japan, South Korea) lead to slow growth in project numbers.

Outside the EU-28 and EEA, in countries such as Brazil, Canada, and the United States of America, the establishment of state-level incentives is particularly noteworthy in addition to the national framework. Such state-level incentives are considered as an effective tool to introduce a biomethane market with first projects in countries with a federal structure. Here, certain federal states can serve as pioneer or exemplary markets to then support market development in the whole country. Nevertheless, a certain degree of federal autonomy is required.

Table 3. Market comparison checklist [4,15,58,64,66,67,75,77,78,81,83,86,89,95,97,100,102–104,106–133].

Criteria		Germany	United Kingdom	Sweden	Brazil	Canada	China	Japan	South Korea	United States
Stakeholder and Resource Criteria										
Resource Assessment (Identification of Biomethane Potentials)		✓	✓	✓	✓	✓	✓		✓	✓
Biomethane Associations/Organisations		✓	✓	✓	✓	✓	✓			✓
Inventory Framework Criteria										
National Incentive or Subsidy Programmes for	Electricity Production with Biomethane	✓	✓	✓				✓	✓	
	Heat Production with Biomethane	✓	✓	✓						
	Utilisation of Biomethane as Transport Fuel	✓	✓	✓						✓
	Construction and/or Operation of Biomethane Plants (Investment Grants/Loans, Tax Reductions)	✓		✓			✓	✓	✓	
Other Support programmes National Level		✓	✓	✓			✓			
State-Level Incentive or Subsidy Programmes for	Electricity Production with Biomethane						✓			✓
	Heat Production with Biomethane	✓					✓			
	Utilisation of Biomethane as Transport Fuel					✓				✓
Other Support programmes State-Level					✓	✓				
Regulatory Framework Criteria										
Consistent National Quality Standard for	Grid Injection	✓	✓		✓		✓		✓	
	Use as vehicle fuel	✓		✓	✓		✓		✓	
Further National Regulations for a Biomethane Market Framework		✓	✓	✓	✓		✓			
Market Development Criteria										
Pilot/Demonstration Projects		✓	✓	✓	✓	✓	✓	✓	✓	✓
Commercial Projects		✓	✓	✓	✓	✓	✓	✓	✓	✓
More than 10 Commercial Projects		✓	✓	✓			✓			✓
Increasing Number of Commercial Projects in the last 5 Years		✓	✓	✓	✓	✓	✓		✓	✓
Utilisation Pathway Criteria										
Major Distribution Pathway	Gas Grid	✓	✓		n.d.	✓	n.d.	n.d.	n.d.	✓
	Road, Rail, Shipping			✓						
Major Utilisation	Electricity	✓								✓
	Heat	✓	✓	✓	✓	✓				
	Mobility		✓	✓	✓	✓	✓	✓	✓	✓
Sustainability Criterion										
Primary Type of Feedstock	Energy Crops	✓								
	Residues & Wastes		✓	✓	✓	✓	✓	✓	✓	✓
Key	✓ = Available; n.d. = No data found									

The United States of America and China are the two countries with the fastest market development when measured by the expansion of projects. The United States and its federal states have created very attractive promotion schemes, such as the mandatory addition of biomethane, which creates a sustainable demand and is therefore considered beneficial for long-term biomethane market development. The increase in China, based on the investment programme in the 13th Five Year Plan, is considered remarkable. However, it remains to be seen whether the increase will continue to grow rapidly, or whether a redirection of the investment programme will lead to a slowdown. Moreover, European examples of investment subsidies showed low effectiveness in developing bioenergy and even more in sustaining it [134].

Besides the inventory framework, the regulatory framework is deemed crucial for sustainable market development, which provides a consistent framework for the actors of a market. The focus of this study is consistent with national quality requirements for biomethane, ensuring uniform properties in the respective market and facilitating domestic trading. As shown in Table 3, nearly half of the compared countries show consistent national quality requirements for both grid injection and use as vehicular fuel. In Canada, Japan, and the United States, no consistent quality requirements are found; however, gas utility or federal state-specific requirements do apply. Different quality requirements within one national market are considered to hinder domestic trade since the properties of gas have to be adjusted according to the respective quality requirement. The United Kingdom and Sweden stand out since there is consistency in quality requirements for either grid injection or use as vehicular fuel. This reflects the respective focus of each country regarding the utilisation of biomethane. Additionally, with the European quality requirements for grid injection and use as automotive fuel, a consistent frame is available for both countries. In terms of further specific national regulatory market conditions, hardly any information was available for the markets outside the EU-28 and EEA. Hence, it is considered (as far as known) that (1) there are no specific biomethane regulations, (2) the regulations which affect biomethane are not available in context of biomethane literature, or (3) regulations are exclusively established on the federal-state-level. The latter applies particularly to Canada and the United States, where the inventory framework and the quality requirements are embedded in the federal-state level.

Biomethane utilisation and application varies from country to country; however, a tendency towards use as vehicular fuel is apparent in all these countries, where the share of biomethane used in the transport sector has different proportions respective to the country. In Germany, for example, the share of biomethane as vehicular fuel by itself is quite distinct but rather small compared to utilisation in the electricity sector where most biomethane is currently used. In Sweden, Brazil, China, South Korea, Japan, and the United States of America, biomethane utilisation in the transport sector is dominant. The following may provide reasons for these preferred utilisation pathways: (1) the incentives and regulations, based on the RE strategy of the respective country, promote the vehicular use and/or (2) different revenues in the respective biomethane utilisation sector stimulate a certain utilisation. The sectoral difference in revenues may be associated directly with an inventory or regulatory framework. Thus, a country is able to stipulate the utilisation pathway or is at least able to influence the way of utilisation. It is assumed that the transport sector is the preferred utilisation since biogas (without further upgrading) is adequate for the production of heat and/or electricity. Furthermore, many alternatives like solid biomass or solar and wind power are available for these sectors; whereas the transport sector does not have as many attractive renewable alternatives.

Furthermore, the analysis shows that in all considered markets apart from Germany, the feedstock focus is on residues and wastes. Agricultural residues, municipal and industrial waste, sewage sludge, or landfill waste are the primary feedstock in the top six countries outside the EU-28 and EEA as well as in Sweden and the United Kingdom, whereas in Germany, energy crops are currently the major feedstock. Nevertheless, there is an increase in waste and residue utilisation in Germany. Overall, it is assumed that at present, energy production is not the only main objective for biomethane production in the compared countries, but also the recycling of residues.

3.5. Observations on Market Stability

Considering the stability of the markets, the following issues have to be discussed. (1) The investigated markets are in different phases of market diffusion. (2) The design of the inventory framework in the form of support schemes plays a significant role [134]. (3) Further factors like price and competitive situation of substitutes like natural gas, the revenue of biomethane, public acceptance, environmental issues as well as the existence of financing mechanisms, professional stuff, infrastructure, corporate networks, approval, and legislative procedures and a lot more are influencing sustainable market penetration [70,72,135]. One example showing that market penetration of bioenergy depends on a variety of factors, as well as the design of the inventory and regulatory framework, is commercial biogas in Africa [39].

It can be derived from the comparison that Brazil, Canada, Japan, and South Korea are in an introductive phase of biomethane market development. This is underpinned by the low number of biomethane production plants and by the poor national support schemes in comparison to the leading European, United States, and Chinese markets. Hence, under current conditions, biomethane can be considered as one renewable option under test in these markets. It is unclear if a comprehensive national support scheme, which is deemed as a crucial factor for further market penetration [53], will be implemented in the next years or if the previous work will be reduced. This also depends on the development of the political orientation of the country and the other further influencing factors mentioned before. Therefore, the stability of these biomethane markets is considered low.

The example of Japan shows that despite initial capacity expansion, a stop in plant deployment is possible if no adequate support scheme is in place. China is assumed to be in an early growth phase of market penetration compared to the other markets since the number of installed plants rose strongly from 2014 to 2018. Since the increase of plants depends on the support scheme, the stability of the market is strongly connected to the existence of this support. However, the long-term stability of the biomethane market will depend on long-term favouring conditions and again, the price and competitive situation of substitutes. Investment subsidies, which are the main promotion instrument in China, are considered as suitable for building up first-generation plants, but not for a sustainable market penetration [134,136]. Moreover, it is not possible to draw conclusions on the effective operation of the market using the expansion rate of the plants. As a consequence, the long-term stability of the Chinese biomethane market is uncertain as long as no other support programme with sustainable impact is implemented or the price of the substitute natural gas is lower than the biomethane price.

In contrast to the other markets, the biomethane market in the United States of America is assumed to be in a late growth phase, since there is already a high number of plants but still progress in the expansion of plant numbers. Furthermore, biomethane has been produced and utilised in the United States since the 1980s. Hence, a certain degree of long-term stability in the past can be derived. Regarding market stability in the future, the mandatory addition of biomethane as a promotion instrument is considered as beneficial. Nevertheless, the stability is bound to the existence of a support scheme. The three leading European biomethane markets are also considered to be in a later growth phase of market penetration. Similarly, the long-term stability of the biomethane markets depends on the existence of comprehensive support schemes with sustainable impact.

3.6. Limitations and Opportunities for Future Research

The results presented here are based on a systematic literature review of the relevant scientific, governmental, and industry/associative literature in the English language. Hence, the results are valid and comprehensive and based on sound data, which are sufficient to outline and compare the examined markets. However, further investigations with expert interviews and a literature review in the respective national language could enable a more comprehensive market overview. Especially with regard to non-scientific literature, e.g., policy documents and considering documents in the native language will enrich the data set. Nevertheless, markets are in constant alteration, and hence, this study is a snapshot of the current global biomethane status quo. The study is limited to a qualitative analysis without quantitative analyses, like a comparative analysis of the development of the biomethane production, installed capacity, or plant size, since hardly any valid quantitative data was found for markets outside EU-28 and EEA. Already, the identification of the current number of upgrading plants proved to be challenging. Hence, a collection of quantitative data is recommended to conduct a quantitative assessment of biomethane on a global level.

A further limitation of this study is the exclusive focus on three EU-28 and the current top six markets outside the EU-28 and EEA. Although further countries with efforts in biomethane market development outside the EU-28 & EEA are identified during the preparation (namely Chile, Colombia, India, Indonesia, Malaysia, Philippines, South Africa, and Thailand), these are excluded. The motive of exclusion is the initial status of these markets as measured by the existence of inventory and regulatory framework, number of commercial projects, and production capacities. The excluded countries are sorted regarding their capacity and their regulatory/inventory framework:

- Countries with no or small production capacity and no regulatory/inventory framework are Chile, Indonesia, and the Philippines [137,138]
- Countries with small production capacity and a more comprehensive but still incomplete regulatory/inventory framework are Colombia, India, Malaysia, South Africa, and Thailand [39, 137,139–144].

Nevertheless, these markets could be considered in future studies, as the market constantly alters. Regarding further markets within the EU-28 and EEA, a limitation on the three leading countries is considered adequate, since these three are already quite diverse and also the leading markets on a global level. Further suggestions for future studies are country-specific investigations providing deeper insights into the respective framework, market development, infrastructure, or applied technologies and their cost structures. Moreover, a comparison of the here identified markets regarding specific biomethane topics like infrastructure, cost and price development, or biomethane potentials is considered as interesting.

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

4. Conclusions

This study shows insights into a selection of biomethane markets around the world while comparing them to the leading markets in Europe, namely the United Kingdom, Sweden, and Germany. Biomethane plants are numerous in Europe, followed by North America and China; showing an overall increasing trend; the application of biomethane in the transport sector is particularly apparent. Also noteworthy is that almost all countries focus on the utilisation of residues and wastes for the biomethane process. This shows that apart from becoming of growing importance as a fuel, biomethane can positively contribute to waste reduction and resource management. In the country comparison, the following observations are noteworthy: although a common European framework is given through RED and RED II, the national energy policies and action plans differ in terms of the biomethane application, e.g., vehicular fuel. Finally, this study also supports cross-country learning, as it can be utilised to study how other countries supported their energy or climate goals and the market development of biomethane and consider similar actions for their own nations.

A further aspect continuously re-appearing in this study is the inhomogeneity of framework conditions between the national markets and especially within national markets of certain countries. According to the results of this study, associated literature, and industry and research trends, market harmonisation needs to consider the following three aspects:

1. The necessity of an economic level playing field There are heterogeneous incentives and regulations on the state level or even within a state, resulting in different costs, prices, and product properties.

This leads to significant trade barriers. A renewable gas register is seen as one option that could be implemented in diverse ways [53].

2. Technical uniformity Uniformity regarding technical requirements for biomethane feed-in and transport as well as gas quality are seen as the core prerequisites for market development and trade. In Europe, this is realised via CEN standards such as CEN/TC 408 (Natural gas and biomethane for use in transport and biomethane for injection in the natural gas grid) and CEN/TR 17238:2018 (Proposed limit values for contaminants in biomethane based on health assessment criteria). On an international basis, ISO standards apply, e.g., for terms and classifications (ISO 20675:2018 Biogas production, conditioning, upgrading, and utilisation—Terms, definitions, and classification scheme). This shows that initial progress towards technical uniformity supporting international trade of biomethane is made, but further progress is necessary.
3. Requirements for a sustainable feedstock basis A sustainable feedstock basis in combination with cross-border trade of biomethane is probably realisable via certification schemes after market-build up [65]. Activities regarding this issue are part of the upcoming RED II. Experiences from the wood pellet market can help to install a sound scheme [145].

Furthermore, cross-country learning (e.g., in the form of this study) can support decisionmakers in all phases of market build-up and consolidation. For example, sustainability issues in the German biogas sector have been taken into account in Danish support programmes. Technological advances regarding biogas upgrading is another example of the advantages of cross-country learning. The most recent technologies, such as cryogenic upgrading or the use of biochemical approaches, can positively affect overall process efficiency and possibilities for further business options.

This study can also serve as a baseline for more detailed studies, which are longitudinal and in-depth, country-specific analyses, i.e., by additionally considering data in the national language. Furthermore, as only the legislative framework is considered here, a comparison of financial support or financing options for biomethane upgrading facilities should be considered for further work. It needs to be noted that the role of biomethane in all considered countries has large expansion potential.

Author Contributions: Conceptualisation, C.S. and T.H.; methodology, C.S and A.P.; investigation, C.S.; writing—original draft preparation, C.S, T.H. and A.P.; writing—review and editing, C.S., T.H., A.P., N.S., D.T..; supervision, D.T.

Funding: The project was supported by funds of the Federal Ministry of Food and Agriculture (BMEL) based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office of Agriculture and Food (BLE) under the innovation support. Furthermore, this work was funded by the Helmholtz Association of German Research Centers.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A Market Background Information

Table A1. Market background information [4,15,58,64,66,67,75,77,78,81,83,86,89,95,97,100,102–104,106–133].

Market Criteria	Germany	United Kingdom	Sweden	Brazil	Canada	China	Japan	South Korea	United States
Number of Upgrading Plants [1]	194 (2017)	85 (2017)	63 (2017)	5 (2017)	9 (2018)	73 (2017)	6 (2014)	10 (2017)	77 (2018)
Primary Type of Feedstock	Energy crops	Residues & waste	Residues & waste	Residues & waste	Residues & waste	Residues & waste	Residues & waste	Residues & waste	Residues & waste
Consistent National Quality Standard for Grid Injection	DVGW e.V. worksheets 260 & 262	Gas Safety Regulations 1996 &1998	- (Locally specific quality requirements)	Resolution 08/2015 & 685/2017	- (Gas utility specific quality requirements)	Natural gas standards: GB 17820-200x & GB17820-1999	- (Gas utility specific quality requirements)	Based on Swedish SS 155438:1999	- (State/gas utility specific quality requirements)
Consistent National Quality Standard for Vehicle Fuel	DIN 51624:2008-02: Automotive fuels—Compressed natural gas—Requirements and test methods	-	SS 155438:1999	Resolution 08/2015 & 685/2017	-	Derived from standard for CNG: GB 18047-2000	n.d.	Based on Swedish SS 155438:1999	- (American SAE J1616_201703 as recommended practice for CNG quality)
Noteworthy National Regulation(s) specific to Biomethane	Biomass Regulation; Gas Network Access Regulation; Biofuel Sustainability Regulation	Biomass Sustainability RHI Regulations; Microgeneration Certification Scheme	n.d.	Resolution 08/2015 & 685/2017	- (Different regulations in each federal State)	Regulation on Scaled Husbandry Pollution Control (2014); Law about Environmental Protection Tax (2018): Tax for untreated waste disposal	n.d.	n.d.	- (Regulations on state-level)
Major National Incentive(s)	Renewable Energy Source Act; Combined Heat and Power Generation Act; Renewable Energy Heat Law; Biofuel Quota Act + Federal Emission Control Act	Biomethane injection tariffs (Renewable Heat Incentive Scheme); Renewable Transport Fuels Obligation; Tax exemptions for CHP generation with biomethane (Climate Change Levy); FiT for electricity production (Closed)	Tax exemption for biomethane as automotive fuel + high taxes for fossil fuels (Law 1994:1776); Electricity certificate market (Regulation 2005/06:154); Support of heat production from biomethane (District Heat Law 2008:263)	-	- (Under development: Low Carbon Fuel Standard (LCFS))	Investment grants for large scale biomethane projects (2015–2017); 2018: Investment grant for Fermenter construction; Tax reliefs & exemptions for biogas sector, since 2008;	FiT for electricity production; Subsidies for biogas plant construction	RPS for electricity producers; Under discussion: RFS for biomethane; National RE plant construction loans	Mandatory Renewable Fuel Standard (RFS2)

Table A1. *Cont.*

Market Criteria	Germany	United Kingdom	Sweden	Brazil	Canada	China	Japan	South Korea	United States
Main Federal State Level Incentives	Renewable Heat Law (Baden-Württemberg)	n.d.	n.d.	Obligatory percentage addition of biomethane to natural gas mix in São Paulo (Decree 58.659) & Rio de Janerio (Law 6.361); Rio Grande do Sul: Provision of various tools like sales contracts or tax and credit reliefs	Obligatory percentage addition of biomethane to natural gas mix in British Columbia & Quebec; Under Development: RFS in Ontario	Subsidy for power generation; Guidance for coal replacement through electricity and gas in coal-forbidden-areas of Baoding and Langfang City	n.d.	n.d.	Established LCFS in California & Oregon; Under development LCFS in some Northeast/Mid-Atlantic states & Washington; Mandatory RPS for electricity provision in 29 States
Major Distribution Pathway	Gas grid	Gas grid	Road transport	n.d.	Gas grid	n.d.	n.d.	n.d.	Gas grid
Major Utilisation Pathway	>60% electricity production in CHP-units	Heat	~60% automotive fuel ~20% Heat	~75% automotive fuel; ~17% Heat	Heat & automotive fuel	automotive fuel	automotive fuel	automotive fuel	automotive fuel & electricity

Key: - = not available; n.d. = no data found; [1] = most recent data.

References

1. United Nations (UN). Adoption of the Paris Agreement—Paris Agreement: Text English. Available online: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf (accessed on 21 November 2018).
2. Rogelj, J.; den Elzen, M.; Höhne, N.; Fransen, T.; Fekete, H.; Winkler, H.; Schaeffer, R.; Sha, F.; Riahi, K.; Meinshausen, M. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **2016**, *534*, 631–639. [CrossRef] [PubMed]
3. Jin, T.; Kim, J. What is better for mitigating carbon emissions—Renewable energy or nuclear energy? A panel data analysis. *Renew. Sustain. Energy Rev.* **2018**, *91*, 464–471. [CrossRef]
4. Horschig, T.; Adams, P.W.R.; Röder, M.; Thornley, P.; Thrän, D. Reasonable potential for GHG savings by anaerobic biomethane in Germany and UK derived from economic and ecological analyses. *Appl. Energy* **2016**, *184*, 840–852. [CrossRef]
5. Moutinho, V.; Madaleno, M.; Inglesi-Lotz, R.; Dogan, E. Factors affecting CO_2 emissions in top countries on renewable energies: A LMDI decomposition application. *Renew. Sustain. Energy Rev.* **2018**, *90*, 605–622. [CrossRef]
6. Mohlin, K.; Camuzeaux, J.R.; Muller, A.; Schneider, M.; Wagner, G. Factoring in the forgotten role of renewables in CO_2 emission trends using decomposition analysis. *Energy Policy* **2018**, *116*, 290–296. [CrossRef]
7. Mandova, H.; Leduc, S.; Wang, C.; Wetterlund, E.; Patrizio, P.; Gale, W.; Kraxner, F. Possibilities for CO_2 emission reduction using biomass in European integrated steel plants. *Biomass Bioenergy* **2018**, *115*, 231–243. [CrossRef]
8. IEA. *World Energy Balances 2018*; IEA: Paris, France, 2018.
9. Bloche-Daub, K.; Hartmann, H.; Hofbauer, H.; Kaltschmitt, M.; Pfeiffer, D.; Thormann, L.; Thrän, D. Einleitung und Zielsetzung. In *Energie aus Biomasse*; Kaltschmitt, M., Hartmann, H., Hofbauer, H., Eds.; Springer: Berlin/Heidelberg, Germany, 2016; pp. 1–76. ISBN 978-3-662-47437-2.
10. Kummamuru, B. *Wba Global Bioenergy Statistics 2017*; World Bioenergy Association (WBA): Stockholm, Sweden, 2017.
11. Verotti, M.; Servadio, P.; Bergonzoli, S. Biogas upgrading and utilization from ICEs towards stationary molten carbonate fuel cell systems. *Int. J. Green Energy* **2016**, *13*, 655–664. [CrossRef]
12. FNR. *Biomethan*; Fachagentur Nachwachsende Rohstoffe e. V. (FNR): Gülzow-Prüzen, Germany, 2012.
13. Billig, E. DBFZ Report Nr. 26. Ph.D. Thesis, Universität Leipzig and Helmholtz-Zentrum für Umweltforschung, Leipzig, Germany, 2016.
14. Fendt, S.; Buttler, A.; Gaderer, M.; Spliethoff, H. Comparison of synthetic natural gas production pathways for the storage of renewable energy. *Wires Energy Environ.* **2016**, *5*, 327–350. [CrossRef]
15. Adler, P.; Billig, E.; Brosowski, A.; Daniel-Gromke, J.; Falke, I.; Fischer, E. (Eds.) *Leitfaden Biogasaufbereitung Und-Einspeisung*; 5., vollständig überarbeitete Auflage; Fachagentur Nachwachsende Rohstoffe e. V. (FNR): Gülzow-Prüzen, Germany, 2014; ISBN 3-00-018346-9.
16. Miltner, M.; Makaruk, A.; Harasek, M. Review on available biogas upgrading technologies and innovations towards advanced solutions. *J. Clean. Prod.* **2017**, *161*, 1329–1337. [CrossRef]
17. Jecha, D.; Niesner, J.; Stehlík, P. Biogas Upgrading Technologies: State of Art Review in Biogas Upgrading Technologies: State of Art Review in Biogas Biogas Upgrading Techniques: State of Art Review in European Region. *Chem. Eng. Trans.* **2013**, *35*, 517–522. [CrossRef]
18. Aryal, N.; Kvist, T.; Ammam, F.; Pant, D.; Ottosen, L.D.M. An overview of microbial biogas enrichment. *Bioresour. Technol.* **2018**, *264*, 359–369. [CrossRef] [PubMed]
19. Sarker, S.; Lamb, J.J.; Hjelme, D.R.; Lien, K.M. Overview of recent progress towards in-situ biogas upgradation techniques. *Fuel* **2018**, *226*, 686–697. [CrossRef]
20. Kougias, P.G.; Treu, L.; Benavente, D.P.; Boe, K.; Campanaro, S.; Angelidaki, I. Ex-situ biogas upgrading and enhancement in different reactor systems. *Bioresour. Technol.* **2017**, *225*, 429–437. [CrossRef] [PubMed]
21. Horschig, T.; Welfle, A.; Billig, E.; Thrän, D. From Paris agreement to business cases for upgraded biogas: Analysis of potential market uptake for biomethane plants in Germany using biogenic carbon capture and utilization technologies. *Biomass Bioenergy* **2019**, *120*, 313–323. [CrossRef]
22. Song, C.; Fan, Z.; Li, R.; Liu, Q.; Kitamura, Y. Efficient biogas upgrading by a novel membrane-cryogenic hybrid process: Experiment and simulation study. *J. Membr. Sci.* **2018**, *565*, 194–202. [CrossRef]

23. Wellinger, A.; Petersson, A. *Biogas Upgrading Technologies—Developments and Innovations*; IEA Bioenergy: Paris, France, 2009.
24. Dunkelberg, E. *Biomethan im Energiesystem. Ökologische und ökonomische Bewertung von Aufbereitungsverfahren und Nutzungsoptionen*; IÖW: Berlin, Germany, 2015; ISBN 978-3-940920-10-2.
25. Kvist, T.; Aryal, N. Methane loss from commercially operating biogas upgrading plants. *Waste Manag.* **2019**, *87*, 295–300. [CrossRef] [PubMed]
26. Müller-Langer, F.; Klemm, M. Liquid and Gaseous Biofuels for the Transport Sector. In *Smart Bioenergy: Technologies and Concepts for a More Flexible Bioenergy Provision in Future Energy Systems*; Thrän, D., Ed.; Springer: Cham, Switzerland, 2015; pp. 107–120. ISBN 978-3-319-16192-1.
27. Brown, M.A. Market failures and barriers as a basis for clean energy policies. *Energy Policy* **2001**, *29*, 1197–1207. [CrossRef]
28. Horschig, T.; Adams, P.W.R.; Gawel, E.; Thrän, D. How to decarbonize the natural gas sector: A dynamic simulation approach for the market development estimation of renewable gas in Germany. *Appl. Energy* **2018**, *213*, 555–572. [CrossRef]
29. Prussi, M.; Padella, M.; Conton, M.; Postma, E.D.; Lonza, L. Review of technologies for biomethane production and assessment of Eu transport share in 2030. *J. Clean. Prod.* **2019**, *222*, 565–572. [CrossRef]
30. Nizami, A.-S.; Murphy, J.D. What type of digester configurations should be employed to produce biomethane from grass silage? *Renew. Sustain. Energy Rev.* **2010**, *14*, 1558–1568. [CrossRef]
31. Wang, S.; Jena, U.; Das, K.C. Biomethane production potential of slaughterhouse waste in the United States. *Energy Convers. Manag.* **2018**, *173*, 143–157. [CrossRef]
32. Singh, R.; Kumar, S. A review on biomethane potential of paddy straw and diverse prospects to enhance its biodigestibility. *J. Clean. Prod.* **2019**, *217*, 295–307. [CrossRef]
33. Chinnici, G.; Selvaggi, R.; D'Amico, M.; Pecorino, B. Assessment of the potential energy supply and biomethane from the anaerobic digestion of agro-food feedstocks in Sicily. *Renew. Sustain. Energy Rev.* **2018**, *82*, 6–13. [CrossRef]
34. Ardolino, F.; Arena, U. Biowaste-to-Biomethane: An LCA study on biogas and syngas roads. *Waste Manag.* **2019**, *87*, 441–453. [CrossRef] [PubMed]
35. Singlitico, A.; Goggins, J.; Monaghan, R.F.D. The role of life cycle assessment in the sustainable transition to a decarbonised gas network through green gas production. *Renew. Sustain. Energy Rev.* **2019**, *99*, 16–28. [CrossRef]
36. Rajendran, K.; O'Gallachoir, B.; Murphy, J.D. The combined role of policy and incentives in promoting cost efficient decarbonisation of energy: A case study for biomethane. *J. Clean. Prod.* **2019**, *219*, 278–290. [CrossRef]
37. Ferreira, M.; Marques, I.P.; Malico, I. Biogas in Portugal: Status and public policies in a European context. *Energy Policy* **2012**, *43*, 267–274. [CrossRef]
38. Eker, S.; van Daalen, E. A model-based analysis of biomethane production in the Netherlands and the effectiveness of the subsidization policy under uncertainty. *Energy Policy* **2015**, *82*, 178–196. [CrossRef]
39. Kemausuor, F.; Adaramola, M.; Morken, J. A Review of Commercial Biogas Systems and Lessons for Africa. *Energies* **2018**, *11*, 2984. [CrossRef]
40. Hafeznia, H.; Aslani, A.; Anwar, S.; Yousefjamali, M. Analysis of the effectiveness of national renewable energy policies: A case of photovoltaic policies. *Renew. Sustain. Energy Rev.* **2017**, *79*, 669–680. [CrossRef]
41. Li, S.-J.; Chang, T.-H.; Chang, S.-L. The policy effectiveness of economic instruments for the photovoltaic and wind power development in the European Union. *Renew. Energy* **2017**, *101*, 660–666. [CrossRef]
42. Lewis, J.; Wiser, R.H. Fostering a renewable energy technology industry: An international comparison of wind industry policy support mechanisms. *Energy Policy* **2007**, 1844–1857. [CrossRef]
43. Solangi, K.H.; Islam, M.R.; Saidur, R.; Rahim, N.A.; Fayaz, H. A review on global solar energy policy. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2149–2163. [CrossRef]
44. Shrimali, G.; Srinivasan, S.; Goel, S.; Nelson, D. The effectiveness of federal renewable policies in India. *Renew. Sustain. Energy Rev.* **2017**, *70*, 538–550. [CrossRef]
45. García-Alvarez, M.T.; Mariz-Pérez, R.M. Analysis of the Success of Feed-in Tariff for Renewable Energy Promotion Mechanism in the EU: Lessons from Germany and Spain. *Procedia Soc. Behav. Sci.* **2012**, *65*, 52–57. [CrossRef]

46. Mitchell, C.; Bauknecht, D.; Connor, P.M. Effectiveness through risk reduction: A comparison of the renewable obligation in England and Wales and the feed-in system in Germany. *Energy Policy* **2006**, *34*, 297–305. [CrossRef]
47. Fink, A. *Conducting Research Literature Reviews. From Paper to Internet*; SAGE Publications: Thousand Oaks, CA, USA, 1998.
48. Gonzalez-Salazar, M.A.; Venturini, M.; Poganietz, W.-R.; Finkenrath, M.; Spina, P.R. Methodology for improving the reliability of biomass energy potential estimation. *Biomass Bioenergy* **2016**, *88*, 43–58. [CrossRef]
49. Brosowski, A.; Thrän, D.; Mantau, U.; Mahro, B.; Erdmann, G.; Adler, P.; Stinner, W.; Reinhold, G.; Hering, T.; Blanke, C. A review of biomass potential and current utilisation—Status quo for 93 biogenic wastes and residues in Germany. *Biomass Bioenergy* **2016**, *95*, 257–272. [CrossRef]
50. Berndes, G.; Hoogwijk, M.; van den Broek, R. The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass Bioenergy* **2003**, *25*, 1–28. [CrossRef]
51. Brosowski, A.; Hauschild, S.; Naumann, K.; Hösel, J.; Thrän, D. *Review of Technical Glycerol Potential from Biodiesel Production and Availability for Improved Cascading in Europe*; DBFZ: Leipzig, Germany, 2017.
52. Oxford University Press. Definition of State in English. Available online: https://en.oxforddictionaries.com/definition/state (accessed on 15 June 2018).
53. Lehtovaara, M.; Karvonen, M.; Kässi, T. The Role of Energy Support Schemes in Renewable Energy Market Penetration. *IJRSE* **2013**, *2*, 30. [CrossRef]
54. European Parliament, Council of the European Union. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA Relevance): RED 2009/28/EC. *Off. J. Eur. Union* **2009**, *140*, 16–62.
55. European Commission. *EU Energy in Figures. Statistical Pocketbook 2018*; Publications Office of the European Union: Luxembourg, 2018; ISBN 978-92-79-88735-2.
56. Eurostat. Supply, Transformation and Consumption of Renewable Energies—Annual Data. Available online: http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do (accessed on 21 November 2018).
57. Scarlat, N.; Dallemand, J.-F.; Fahl, F. Biogas: Developments and perspectives in Europe. *Renew. Energy* **2018**, *129*, 457–472. [CrossRef]
58. Gas Infrastructure Europe (GIE); European Biogas Association (EBA). European Biomethane Map: Infrastructure for Biomethane Production 2018. Available online: http://european-biogas.eu/wp-content/uploads/2018/01/2018.01.09.GIE_BIO_2018_A0_1189x841_FULL_415_clean_final.pdf (accessed on 21 October 2018).
59. European Parliament, Council of the European Union. Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC: FQD 98/70/EC. *Off. J. Eur. Union* **2009**, *140*, 88–1132.
60. European Parliament, Council of the European Union. Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources: ILUC 2015/1513. *Off. J. Eur. Union* **2015**, *239*, 1–29.
61. European Committee for Standardization. EN 16723-1. 2016: Natural Gas and Biomethane for Use in Transport and Biomethane for Injection in the Natural Gas Network—Part 1: Specifications for Biomethane for Injection in the Natural Gas Network: Work Item Number: 00408006. 2016. Available online: https://standards.cen.eu/dyn/www/f?p=204:110:0::FSP_PROJECT:59781&cs=193AB741DC4F3AE4584E03DE130F55D78 (accessed on 27 June 2018).
62. European Committee for Standardization. EN 16723-2. 2017: Natural Gas and Biomethane for Use in Transport and Biomethane for Injection in the Natural Gas Network—Part 2: Automotive Fuels Specification: Work Item Number: 00408005. 2017. Available online: https://standards.cen.eu/dyn/www/f?p=204:110:0::FSP_PROJECT:41008&cs=1D7CD581175157FBF537040E3716A707E (accessed on 27 June 2018).
63. European Parliament. Sources and Scope of European Union Law. Fact Sheets on the European Union. Available online: http://www.europarl.europa.eu/ftu/pdf/en/FTU_1.2.1.pdf (accessed on 20 June 2018).

64. Rogstrand, G. Research Coordination for a Low-Cost Biomethane Production at Small and Medium Scale Applications. Overview on Administrative and Legal Conditions as Well as on Financial and Other Support Programs, for Small to Medium Scale Biomethane Production and Supply: Deliverable No. D2.1 + D2.2. 2017. Available online: https://biomethane-map.eu/regulatory-framework.82.0.html (accessed on 20 June 2018).
65. Horschig, T.; Billig, E.; Majer, S.; Thrän, D. Biomethane—local energy carrier or European commodity? In *The European Dimension of Germany's Energy Transition—Opportunities and Conflicts*; Gawel, E., Strunz, S., Lehmann, P., Purkus, A., Eds.; Springer International Publishing: Cham, Switzerland, 2018.
66. Thrän, D.; Billig, E.; Persson, T.; Svensson, M.; Daniel-Gromke, J.; Ponitka, J.; Seiffert, M. *Biomethane—Status and Factors Affecting Market Development and trade. IEA Task 40 and Task 37 Joint Study*; IEA Bioenergy: Paris, France, 2014; ISBN 978-1-910154-10-6.
67. Members of IEA Bioenergy Task 37. *IEA Bioenergy Task 37—Country Reports Summary 2017*; IEA Bioenergy: Paris, France, 2018; ISBN 978-1-910154-50-2.
68. Kaltschmitt, M.; Hartmann, H.; Hofbauer, H. (Eds.) *Energie aus Biomasse*; Springer: Berlin/Heidelberg, Germany, 2016; ISBN 978-3-662-47437-2.
69. Thrän, D. (Ed.) *Smart Bioenergy. Technologies and Concepts for a More Flexible Bioenergy Provision in Future Energy Systems*; Springer International Publishing: Cham, Switzerland, 2015; ISBN 978-3-319-16192-1.
70. Bauen, A.; Berndes, G.; Junginger, M.; Mozaffarian, H. *Bioenergy—A Sustainable and Reliable Energy Source. A Review of Status and Prospects*; Main Report; IEA Bioenergy: Paris, France, 2009; Available online: https://infoscience.epfl.ch/record/219072/files/MAIN-REPORT-Bioenergy-a-sustainable-and-reliable-energy-source.-A-review-of-status-and-prospects.pdf (accessed on 27 June 2018).
71. Clancy, J.M.; Curtis, J.; Ó'Gallachóir, B. Modelling national policy making to promote bioenergy in heat, transport and electricity to 2030—Interactions, impacts and conflicts. *Energy Policy* **2018**, *123*, 579–593. [CrossRef]
72. IEA. Technology Roadmap: Delivering Sustainable Bioenergy. Available online: https://www.ieabioenergy.com/wp-content/uploads/2017/11/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf (accessed on 14 June 2018).
73. IEA. HOWGUIDE 2forBioenergy: Roadmap Development and Implementation. Available online: https://www.iea.org/publications/freepublications/publication/How2GuideforBioenergyRoadmapDevelopmentandImplementation.pdf (accessed on 14 June 2018).
74. Domac, J.; Richards, K.; Risovic, S. Socio-economic drivers in implementing bioenergy projects. *Biomass Bioenergy* **2005**, *28*, 97–106. [CrossRef]
75. IEA Bioenergy Task 37. Upgrading Plant List 2017. 2017. Available online: http://task37.ieabioenergy.com/plant-list.html (accessed on 20 November 2018).
76. IEA Bioenergy Task 37. Upgrading Plant List 2014. 2014. Available online: http://task37.ieabioenergy.com/plant-list.html (accessed on 14 June 2018).
77. RNG Coalition. RNG Production Facilities in North America. Available online: https://docs.google.com/spreadsheets/d/1CpLTd1Yya4qQzUpWYtKMUGW1BlMmn-Jrj3uErd8lJ7A/edit#gid=0=0 (accessed on 21 November 2018).
78. Jing, F. 4.2 the Chinese Agricultural Biogas Sector—Current Challenges and Future Perspectives. In *Energetic Utilization of Agricultural Residues in China and Germany*, 1st ed.; How to foster the utilization of agricultural residues in the biogas sector in China; DBFZ: Leipzig, Germany, 2017; pp. 13–24.
79. OECD/IEA. Renewables Information. Available online: https://www.oecd-ilibrary.org/docserver/renew-2018-en.pdf?expires=1544969913&id=id&accname=oid018224&checksum=36CB587F810C790189921CFE25432680 (accessed on 16 December 2018).
80. German Chambers of Commerce Abroad: Brazil. Zielmarktanalyse Biogas Brasilien. Energetische Nutzung von Landwirtschaftsabfällen, mit Profilen der Marktakteure. 2016. Available online: https://www.erneuerbare-energien.de/EEE/Redaktion/DE/Downloads/Publikationen/AHK_Zielmarktanalysen/zma_brasilien_2016_bio.pdf?__blob=publicationFile&v=3 (accessed on 31 July 2018).
81. Gardemann, A. Brazilian Association of Biogas and Biomethane. Available online: http://www.iee.usp.br/gbio/sites/default/files/Alessandro%20Gardemann.pdf (accessed on 7 November 2018).

82. Abboud, S.; Aschim, K.; Bagdan, B.; Sarkar, P.; Yuan, H.; Scorfield, B.; Felske, C.; Rahbar, S.; Marmen, L. Potential Production of Methane from Canadian Wastes. 2010. Available online: https://www.researchgate.net/publication/268341359_Potential_Production_of_Methane_from_Canadian_Wastes (accessed on 21 November 2018).
83. Scott, W. Low Carbon Fuel Standards in Canada: Policy Brief. Available online: http://institute.smartprosperity.ca/sites/default/files/lowcarbonfuelstandards-web.pdf (accessed on 21 November 2018).
84. Ministry of Energy Mines Petroleum Resources British Columbia. Renewable and Low Carbon Fuel Requirements Regulation. Summary for 2010–2016: Information Bulletin RLCF-007-2016. 2017. Available online: https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf-007-2016.pdf (accessed on 30 July 2018).
85. Government of British Columbia. B.C.'s Climate Leadership Plan to Cut Emissions While Growing the Economy. B.C.'s Climate Leadership Plan at a Glance: Backgrounders. 2016. Available online: https://news.gov.bc.ca/releases/2016PREM0089-001501 (accessed on 30 July 2018).
86. Canadian Biogas Association. Renewable Natural Gas Developments in Ontario. An Evolving Outlook. 2017. Available online: https://biogasassociation.ca/resources/rng_outreach_and_market_development (accessed on 21 November 2018).
87. Enbridge Gas Distribution Inc.; Uniongas. Supporting Renewable Natural Gas in Ontario. Value of Biogas EAST. 2018. Available online: https://www.biogasassociation.ca/images/uploads/documents/2018/vob_east_presentations/2018VOB-Mar22-4-Evers-and-Welburn.pdf (accessed on 8 October 2019).
88. Canadian Biogas Association. Farm to Fuel. Developers' Guide to Biomethane. 2012. Available online: https://biogasassociation.ca/images/uploads/documents/2012/reports/Developers_Guide_to_Biomethane.pdf (accessed on 21 November 2018).
89. Jingming, L. 4.11 Manure management and biogas plantsLeipzig, Germany—The operational and technical challenge in China: Opportunity and Challenge of Biogas Sector in China. In *Energetic Utilization of Agricultural Residues in China and Germany*, 1st ed.; How to foster the utilization of agricultural residues in the biogas sector in China; DBFZ: Leipzig, Germany, 2017; pp. 87–98.
90. Liu, C.; Wang, J.; Ji, X.; Qian, H.; Huang, L.; Lu, X. The biomethane producing potential in China: A theoretical and practical estimation. *Chin. J. Chem. Eng.* **2016**, *24*, 920–928. [CrossRef]
91. Arteconi, A.; Spitoni, M.; Polonara, F.; Spigarelli, F. The feasibility of liquefied biomethane as alternative fuel: A comparison between European and Chinese markets. *Int. J. Ambient Energy* **2016**, *38*, 481–488. [CrossRef]
92. Ministry of Economy Trade and Industry Japan. Long-Term Energy Supply and Demand Outlook. Available online: http://www.meti.go.jp/english/press/2015/pdf/0716_01a.pdf (accessed on 21 November 2018).
93. Bacovsky, D.; Ludwiczek, N.; Christian, P.; Kumar Verma, V. IEA Bioenergy Countries' Report. Bioenergy Policies and Status of Implementation. 2016. Available online: http://www.ieabioenergy.com/publications/iea-bioenergy-countries-report-23-09-2016/ (accessed on 16 July 2018).
94. IEA. *Energy Balances of OECD Countries 2015*; OECD Publishing International Energy Agency: Paris, France, 2015; ISBN 978-92-64-23594-6.
95. German Industry & Commerce Chamber Japan. ZIELMARKTANALYSE JAPAN 2017. Biomasse und Biogas mit Profilen der Marktakteure. 2017. Available online: https://www.oav.de/fileadmin/user_upload/ZMA_Bioenergie_in_Japan_2017_FINAL.PDF (accessed on 21 November 2018).
96. Yokoyama, S.; Matsumura, Y. The Present Status and Future Scope of Bioenergy in Japan. *J. Jpn. Inst. Energy* **2015**, *94*, 1079–1086. [CrossRef]
97. Lybæk, R.; Asai, M. Future pathways for deploying agricultural based biogas plants in Denmark and Japan: A comparative analysis. *GMSARN Int. J.* **2017**, *11*, 126–138.
98. Aikawa, T. Restructuring Japan's Bioenergy Strategy: Towards Realizing Its True Potential. Available online: https://www.renewable-ei.org/en/activities/reports/img/pdf/20180628_01/REI_BioenergStrategy_EN_180628.pdf (accessed on 22 November 2018).
99. Hamdan, R.A. Tapping into the Transportation Fuel Market. 2013. Available online: https://www.globalmethane.org/expo-docs/canada13/biogas_03_Hamdan_CNG.pdf (accessed on 14 August 2018).
100. Du Plessis, L. Japan's Biomass Market Overview. Available online: https://www.jetro.go.jp/ext_images/_Events/ldn/Japan_biomass_market_overview.pdf (accessed on 21 November 2018).

101. Elliot, J.; Bartos, J.; Lopez-Bassols, C.; Nishida, Y.; Robertson, A. Energy Supply Security. Emergency Response of IEA Countries 2014. 2014. Available online: https://www.oecd-ilibrary.org/docserver/9789264218420-en.pdf?expires=1533543434&id=id&accname=oid018224&checksum=460F67A9E33C9F29A1F9F358581FA9B2 (accessed on 3 August 2018).
102. German Chambers of Commerce Abroad: South Korea. Zielmarktanalyse Südkorea 2016. biogasanlagen und—Technologie Sowie Anlagen für Bio-Diesel. 2016. Available online: https://www.erneuerbare-energien.de/EEE/Redaktion/DE/Downloads/Publikationen/AHK_Zielmarktanalysen/zma_suedkorea_2016_bio.pdf?__blob=publicationFile&v=2 (accessed on 21 November 2018).
103. Jo, J.H.; Kim, W. Market potential of biomethane as alternative transportation fuel in South Korea. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 864–876. [CrossRef]
104. Escudero, J.D. Challenges & Opportunities for Increased Production of Renewable Natural Gas (RNG). Session 2: Policy & Market Overview. 2018. Available online: https://www.epa.gov/natural-gas-star-program/renewable-natural-gas-driving-value-natural-gas-and-biogas-sectors-workshop (accessed on 20 November 2018).
105. Williams, E. Commercial Landfill Gas Energy Projects. Opportunities & Barriers. 2017. Available online: https://www.epa.gov/lmop/2017-national-landfill-gas-energy-special-session (accessed on 28 July 2018).
106. American Biogas Council. ABC RNG Purity Recommendation. Available online: https://www.americanbiogascouncil.org/biogas_purityspecs.asp (accessed on 21 November 2018).
107. American Biogas Council. Biogas State Profiles. Available online: https://www.americanbiogascouncil.org/stateprofiles.asp (accessed on 21 November 2018).
108. Fraunhofer IWES; Fraunhofer UMSICHT; DBFZ. *BIOMON—Evaluierung der Biomethanbereitstellung, -Verteilung und -Nutzung in Deutschland durch ein Marktmonitoring*; Fraunhofer Umsicht: Oberhausen, Germany, 2012.
109. German Energy Agency (DENA). Branchenbarometer Biomethan. 2016. Available online: http://www.biogaspartner.de/fileadmin/biogas/documents/Branchenbarometer/Factsheet_Biomethan_2016.pdf (accessed on 19 June 2018).
110. German Energy Agency (DENA). *Biogaspartner—Gemeinsam Einspeisen. Biogaseinspeisung und -Nutzung in Deutschland und Europa Markt, Technik und Akteure*; German Energy Agency (DENA): Berlin, Germany, 2017.
111. State Parliament Baden-Württemberg. Renewable Heat Law: "Gesetz zur Nutzung erneuerbarer Wärmeenergie in Baden-Württemberg (Erneuerbare-Wärme-Gesetz)". EWärmeG. 2015. Available online: https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/5_Energie/Energieeffizienz/EWaermeG_BW/150317_Novelle_Erneuerbare_Waerme-Gesetz.pdf (accessed on 15 August 2018).
112. Lukehurst, C.; ADBA. IEA Bioenergy Task 37. UK Country Report. 2017. Available online: http://task37.ieabioenergy.com/country-reports.html (accessed on 13 July 2018).
113. Maggioni, L.; Pieroni, C. Report on the Biomethane Injection into National Gas Grid. Available online: http://www.isaac-project.it/wp-content/uploads/2017/07/D5.2-Report-on-the-biomethane-injection-into-national-gas-grid.pdf (accessed on 7 November 2018).
114. Department of Energy & Climate Change UK. Non-Domestic Renewable Heat Incentive (RHI) Biomass & Biomethane Sustainability. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/403106/Non-domestic_RHI_-_Biomass_and_Biomethane_Sustainability_Feb15_Final.pdf (accessed on 7 November 2018).
115. Record Biomap Project. Regulatory Framework for Biomethane Supply in UK. Available online: https://biomethane-map.eu/fileadmin/country_profile_regulatory_framework/Framework_mapping_-_UK_website.pdf (accessed on 7 November 18).
116. Record Biomap Project. Regulatory Framework for Biomethane Supply in Sweden. Available online: https://biomethane-map.eu/fileadmin/country_profile_regulatory_framework/Framework_mapping_-_Sweden_website.pdf (accessed on 7 November 2016).
117. Svensson, M. Challenges and Opportunities for the Future Biomethane Powered Automotive Market; Gent; 2016. Available online: www.european-biogas.eu (accessed on 2 May 2019).
118. Svensson, M. IEA Bioenergy Task 37. Country Report Sweden. 2016. Available online: http://task37.ieabioenergy.com/country-reports.html (accessed on 20 June 2018).

119. *Energetic Utilization of Agricultural Residues in China and Germany*, 1st ed.; How to foster the utilization of agricultural residues in the biogas sector in China; DBFZ Deutsches Biomasseforschungszentrum: Leipzig, Germany, 2017.
120. Turley, D. Sustainability Considerations. 2018. Available online: https://www.nnfcc.co.uk/ (accessed on 20 November 2018).
121. Canadian Gas Association. Renewable Natural Gas: Technology Roadmap for Canada. Available online: http://www.cga.ca/natural-gas-markets/renewable-natural-gas/ (accessed on 21 November 2018).
122. Raninger, B.; Zhou, H. Biogas from Landfills or Anaerobic Digestion Plants in China: Comparison for Biomass Wastes in China. Available online: http://www.vivis.de/phocadownload/Download/2012_wm/2012_WM_579_590_Raninger.pdf (accessed on 21 November 2018).
123. Qian, M. Biogas Policy and Technology. 2018. Available online: https://www.oav.de/fileadmin/user_upload/2_Termine/Allgemein/biogas_development_in_China.pdf (accessed on 21 November 2018).
124. Felizeter, B.; Schalit, V.; Peng, Q.; Chen, K. China—Effizienzsteigerung im Biogassektor in Nordchina. Zielmarktanalyse 2017 mit Profilen der Marktakteure. 2017. Available online: https://www.oav.de/fileadmin/user_upload/2_Termine/China_VR/cn_170707_ZMA_Biogas_2017_FINAL.pdf (accessed on 21 November 2018).
125. Okamura, T.; Furukawa, M.; Ishitani, H. Future forecast for life-cycle greenhouse gas emissions of LNG and city gas 13A. *Appl. Energy* **2007**, *84*, 1136–1149. [CrossRef]
126. Kang, H. *IEA Bioenergy Task 37. South Korea Country Report*; IEA Bioenergy: Paris, France, 2013.
127. Shen, Y.; Linville, J.L.; Urgun-Demirtas, M.; Mintz, M.M.; Snyder, S.W. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs. *Renew. Sustain. Energy Rev.* **2015**, *50*, 346–362. [CrossRef]
128. Fuels and Lubricants TC 7 Fuels Committee. *Recommended Practice for Compressed Natural Gas Vehicle Fuel*, 3rd ed.; SAE International: Warrendale, PA, USA, 2017; Available online: https://www.sae.org/standards/content/j1616_201703/ (accessed on 21 November 2018).
129. Serfass, P. A Snapshot of RNG and the Market. 2014. Available online: https://www.americanbiogascouncil.org/biogasProcessing/rngMarket_snapshot.pdf (accessed on 3 August 2018).
130. U.S. Environmental Protection Agency. Renewable Fuel Standard Program: Overview for Renewable Fuel Standard. Available online: https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard (accessed on 21 November 2018).
131. RNG Coalition. Low Carbon Fuel Standards. Federal & State Policies. 2018. Available online: http://www.rngcoalition.com/policies-legislation-1/ (accessed on 30 July 2018).
132. RNG Coalition. Renewable Portfolio Standard: Federal & State Policies. Available online: http://www.rngcoalition.com/policies-legislation-1-1/ (accessed on 21 November 2018).
133. Qian, M. Opportunity and Challange of Biogas Market in China. Available online: https://www.oav.de/fileadmin/user_upload/2_Termine/Allgemein/biogas_development_in_China.pdf (accessed on 20 November 2018).
134. Thornley, P.; Cooper, D. The effectiveness of policy instruments in promoting bioenergy. *Biomass Bioenergy* **2008**, *32*, 903–913. [CrossRef]
135. Fachagentur Nachwachsende Rohstoffe e. V. (FNR). Factors Influencing the Bioenergy Development. Available online: http://www.bio-prom.net/index.php?id=10369&L=2 (accessed on 1 July 2019).
136. Madlener, R. Innovation diffusion, public policy, and local initiative: The case of wood-fuelled district heating systems in Austria. *Energy Policy* **2007**, *35*, 1992–2008. [CrossRef]
137. Findeisen, C. Biomethane in Developing and Emerging Countries. 2017. Available online: http://www.biosurf.eu/wordpress/wp-content/uploads/2015/06/170322_Findeisen_-Biomethane-in-Developing-Countries.pdf (accessed on 6 August 2018).
138. Ansori Nasution, M. Bio-Methane Fuelled Palm Oil Operations Opportunities and Challenges Indonesia Perspective. 2015. Available online: https://www.researchgate.net/profile/Muhammad_Nasution/publication/285583078_BIO-METHANE_FUELED_PALM_OIL_OPERATIONS_OPPORTUNITIES_AND_CHALLENGES_Indonesia_perspective/links/56600dd108ae4988a7bf00d5/BIO-METHANE-FUELED-PALM-OIL-OPERATIONS-OPPORTUNITIES-AND-CHALLENGES-Indonesia-perspective.pdf (accessed on 27 June 2018).

139. Voigt, T.; Amado, G. Kolumbien Dezentrale Energieversorgung in Kolumbien (Bio-, Wind-, Solarenergie). Zielmarktanalyse 2018 mit Profilen der Marktakteure. 2018. Available online: https://www.german-energy-solutions.de/GES/Redaktion/DE/Publikationen/Marktanalysen/2018/zma_kolumbien_2018_dezentrale-energieversorgung.html (accessed on 13 August 2018).
140. Schaubach, K.; Brosowski, A.; Shah, A. *Assessment of the Status Quo of the Implementation and Potentials of Anaerobic Digestion in Indi. Final Report*; DeutschesBiomasseforschungszentrum: Leipzig, Germany, 2018.
141. Hoo, P.Y.; Patrizio, P.; Leduc, S.; Hashim, H.; Kraxner, F.; Tan, S.T.; Ho, W.S. Optimal Biomethane Injection into Natural Gas Grid—Biogas from Palm Oil Mill Effluent (POME) in Malaysia. *Energy Procedia* **2017**, *105*, 562–569. [CrossRef]
142. Pasupathy, R. The 3rd Annual Biogas Forum. In *Biogas Directory*, 2nd ed.; ICESN - International Clean Energy and Sustainability Network: Singapore, 2015; pp. 49–55. Available online: http://apacbiogas.org/publications/ (accessed on 27 June 2018).
143. Giok Seng, L. Official Launching of the First Commercial BioCNG (Biomethane) Plant in Malaysia. Available online: http://www.angva.org/wp-content/uploads/Report-BioCNG-Plant-Malaysia_281015.pdf (accessed on 13 August 2018).
144. German-Thai Chamber of Commerce. Thailand Biogas: Zielmarktanalyse 2019 mit Profilen der Marktakteure. Available online: https://german-energy-solutions.de/GES/Redaktion/DE/Publikationen/Marktanalysen/2019/zma_thailand-bioenergie-2019.pdf?__blob=publicationFile&v=2 (accessed on 10 February 2019).
145. Thrän, D.; Schaubach, K.; Peetz, D.; Junginger, M.; Mai-Moulin, T.; Schipfer, F.; Olsson, O.; Lamers, P. The dynamics of the global wood pellet markets and trade—key regions, developments and impact factors. *Biofuels Bioprod. Bioref.* **2019**, *13*, 267–280. [CrossRef]