

# GREEN GAS

Facilitating a future green gas grid  
through the production of renewable gas



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# 1. Executive summary

To mitigate climate change, it is essential to develop integrated and sustainable decarbonised renewable energy systems. Heat and transport together, account for about 80% of final energy consumption. Significant progress has been made in renewable electricity but decarbonisation of transport fuel is problematic. Gaseous renewable energy carriers, such as renewable ‘green gas’ can have a considerable impact in future energy systems and play a key role in decarbonising heat and transport. Green gas at present is dominated by biomethane, which can be generated from the anaerobic digestion of organic biomass and residues produced in agriculture, food production and waste processing.

## Biomethane present and future

In 2015, there were 459 biogas-upgrading plants in operation producing 1,230 M Nm<sup>3</sup> of biomethane (European Biogas Association, 2016). The market for biomethane is still growing. Sweden, the UK, Switzerland, France and the Netherlands have all increased their biomethane production significantly in the last five years. In the short term, the development of green gas projects, including the injection of biomethane to gas networks will be the primary focus of this developing industry. Future renewable gas technologies such as gasification-methanation and power to gas systems have been identified as methods that could contribute substantially to greening natural gas grids of the future. Recent EU policy measures facilitate the development of such pathways with progressively increasing obligations on decarbonisation. The share in renewable and low-carbon transport fuels (excluding first generation bio-fuels and including for electrification) is required to increase from 1.5% in 2021 to 6.8% in 2030, with advanced biofuels to make up at least 3.6% by that time (EC, 2016).

## Country roadmaps and technology deployment

Many countries are currently dependent on fossil fuels (including natural gas) to meet their national energy demand. The concept of renewable electricity is well understood. However a number of countries are now in the process of generating roadmaps for the deployment of renewable green gas; these roadmaps highlight the potential availability of biomass and technological innovation. This report outlines the various substrates and technologies for green gas production and examines how much natural gas can be replaced by green gas in specific countries. The logistics of injecting green gas in to existing gas grid infrastructure are also examined. The roadmaps developed for accelerating the use of green gas thus far in specific countries are analysed. Utilising all of the available deployment pathways, future production of green gas may account for 41PJ in Ireland, 77PJ in the Netherlands, 280PJ in the UK, 1260PJ in Italy and over 100PJ in Denmark. This represents approximately 26%, 24%, 8%, 44% and 75% of current

natural gas demand in these countries respectively and thus indicates a significant source of clean renewable energy and the role that gas energy and infrastructure can play in the future. It is suggested that in 2050 the same gas demand will be needed in Europe as today, however potentially 76% of the gas could be green (EURATIV, 2017).

## Cascading bioenergy

Cascading renewable gas systems will become a very important tool in maximising the quantities of green gas production and ensuring sufficient sustainability. An example of cascading bioenergy could include integration of green gas technologies, to maximise sustainable renewable gaseous fuel production whilst minimising greenhouse gas emissions. The technologies investigated in this report (anaerobic digestion, gasification-methanation, power to gas, micro-algae biogas upgrading) and feedstocks (energy crops, agricultural residues and wastes, food waste, micro-algae, seaweed, woody crops) when integrated can optimise a system producing decarbonised indigenous renewable energy. By-products of the different technologies may be further amalgamated to ensure the use of the full supply chain and circular economy concepts. Examples of this include CO<sub>2</sub> from biogas used in a power to gas system to produce more green gas; solid digestate from a biogas plant used as a feedstock for gasification; oxygen produced from electrolysis used for the gasification process; and micro-algae biogas upgrading as a method of offsetting the costs of traditional upgrading methods.

## The biomethane economy

As indicated in this report, an indigenous biomethane resource can potentially replace significant amounts of natural gas. Particularly in countries with well-established and closely linked gas grids, there are good opportunities for cross-border trade and to create a market for biomethane, thus lowering dependency on fossil fuels. Biomethane is very flexible in its application. It may be injected directly into the existing natural gas grid allowing for energy-efficient and cost-effective transportation. Gas grid operators can switch to a renewable gas source in a straightforward manner and provide energy for an array of applications including electricity generation, heat and transport. The production of biomethane from regional resources creates jobs, especially in agriculture, supply logistics, engineering, plant construction and maintenance. Farmers can profit in “non-food” related sectors with an alternative source of revenue through biomethane.

*This report was produced by IEA Bioenergy Task 37, which addresses the challenges related to the economic and environmental sustainability of green gas production and utilisation.*

## 2. Introduction

### 2.1 What is green gas?

Green gas refers to renewable gas, which can be generated from the anaerobic digestion of organic biomass and residues produced in agriculture, food production and waste processing. The digestion process involves a series of biological processes in which microorganisms break down the biodegradable material in the absence of oxygen. Typically the biogas produced is approximately 60% methane (CH<sub>4</sub>) and 40% carbon dioxide (CO<sub>2</sub>). The biogas can be combusted directly in a combined heat and power (CHP) plant or upgraded to biomethane through the removal of CO<sub>2</sub> to leave a product similar to natural gas (with greater than 95% CH<sub>4</sub> content).

Renewable gas can also be produced from high-temperature gasification of woody crops with methanation of the syngas. Renewable gas may also be produced through power to gas technologies using electricity; preferably (but not always) this electricity would be both renewable to ensure sustainability and surplus electricity which may otherwise be curtailed or constrained to ensure financial sustainability. Algae are also a proposed source of biomethane; this includes for both seaweed and micro-algae.

Gas of biomethane standard is considered a very flexible energy vector as it can be injected directly in to existing gas grid infrastructure. It is an important fuel in terms of contributing to future renewable energy strategies in electricity, transport and heat whilst abating greenhouse gas (GHG) emissions in these sectors.

This report outlines the potential for biomethane (and renewable gas) as a multifaceted solution in “greening” future gas grids.

### 2.2 Coupling biomass availability with technology application

Biomass is a finite but wide ranging resource. It can come in the form of specifically grown crops, or by-products generated in agriculture (slurries/manures) or from industrial applications such as paper, wood, and furniture manufacturing. Biomass will play an important role in the future realisation of a sustainable energy system and considering its finite nature, it is important to maximise the available resource. One of the most auspicious applications of available biomass is the generation of biogas or biomethane. Wet biomass (with dry solids content in the range of 5-30%) can be used as input feed to produce biogas in an anaerobic digester. As indicated, the biogas

generated can be used directly in CHP units to produce electricity and heat or upgraded to biomethane and used in the same manner as natural gas. The supply of biogas or biomethane can be maintained year-round by ensuring a constant supply of feedstock. Slurries, manures (Figure 2.1a) and organic wastes from food processing can be accumulated and stored. Similarly, harvested crop-biomass can be preserved in silos and designed with sufficient scale to supply the required quantity of feedstock annually. Thus, the production of biogas and biomethane can be considered a stable and reliable energy source.

The biological process for producing biogas reflects a natural process present in ruminant animals (Figure 2.1b). Naturally occurring bacteria breakdown the biomass in the digester (similar to the way crops are digested in the stomach of a cow) producing biogas consisting of CH<sub>4</sub> and CO<sub>2</sub>. Minimal amounts of other trace gases such as ammonia and hydrogen sulphide (H<sub>2</sub>S) can also be produced in digestion.

Of late, there has been an academic focus on algal bio-fuels. Algae are an additional biomass source with significant growth rates, which may be cultivated in the form of seaweed (macro-algae) in a marine environment or as a means of capture of CO<sub>2</sub> through cultivation of micro-algae typically in raceway type ponds situated on marginal land. The production of biomethane is suggested as a beneficial route to sustainable energy for algae and is described in detail in the IEA Bioenergy report entitled “A perspective on algal biogas” (Murphy et al., 2015).

An additional technology pathway for renewable gas production is gasification-methanation. Gasification is a low-carbon pathway to produce energy, fuels, chemicals, and fertilisers. A large variety of biomass, typically with higher dry solids content greater than 40%, such as agri-forestry residues, black bin waste, indigenous energy crops grown on marginal land, and sewage sludge can be used in this process. Gasification involves the partial combustion of carbonaceous feeds to produce a synthetic gas (known as syngas). For biomethane, a methanation step is used to create synthetic natural gas (bio-SNG) with a CH<sub>4</sub> content greater than 95%.

Furthermore, power to gas is a technology that converts electricity to hydrogen gas (through electrolysis of water), which can be subsequently converted to CH<sub>4</sub> in a methanation step. The theoretical advantage in this technology is the use of surplus electricity associated with



Figure 2.1 (a) Slurries and manures generated in agriculture can be used as feedstocks for anaerobic digestion; (b) Ruminants stomach digests crops similar to biological digestion process

(From DEN EELDER FARM: Small farm scale mono-digestion of dairy slurry, March 2017 available in <http://task37.ieabioenergy.com/case-studies.html>)

intermittent renewable electricity sources such as from wind turbines and solar energy devices. Electricity, which would otherwise be curtailed and/or constrained, may be available at a cheaper rate. This advantage of cheap excess electricity may also be associated with transmission grid constraints. In practice the power to gas system would be oversized or under capacity in terms of equipment if the only source of electricity were surplus electricity. It is expected that such systems will be sized for long term operation and as such will bid for electricity alongside other users (Ahern et al., 2015). However power to gas offers a storage solution for electricity in the form of renewable gas whilst changing the energy vector to one available to transport fuel. This fuel is termed gaseous fuel from non-biological origin in the EU Renewable Energy Directive (RED) and is seen as an advanced biofuel (EC, 2017).

### 2.3 Benefits of a biomethane economy

Biomethane generated from biological processes substitute fossil-natural gas as a source of electricity, heat or transport fuel. It can abate GHG emissions through for example reduction of fugitive methane emissions from open slurry holding tanks and from displacement of fossil fuels. Biomethane can promote a sustainable, circular economy. CO<sub>2</sub> emissions resulting from the burning of fossil-fuels and CH<sub>4</sub> from slurry management and waste facilities are primary causes of global warming. Biomethane produced from crops release CO<sub>2</sub>, which was absorbed from the atmosphere by the crops as they mature; this is known as short term carbon. Therefore, the provision of low carbon energy is conceivable through crop

biomass derived energy. The utilisation of agricultural wastes for biomethane production can make a further contribution to climate protection and contributes to the overall ideology of greening agriculture and diversifying the rural economy. For instance, the digestion of freshly collected manure can potentially reduce methane emissions from manure storage on farms. The European Commission's Joint Research Centre (JRC) methodology assumes a 17% methane emissions savings through replacing open slurry storage with digestion as described in the 2017 IEA Bioenergy report on methane emissions from biogas plants (Liebetrau et al., 2017). In essence slurry biomethane systems (or indeed other combined waste management biogas systems) can be carbon negative. It is recommended by the authors that crop digestion systems include for co-digestion with slurries to ensure the maximum possible decarbonisation. This positive attribute is unique to biomethane production technologies. As such biomethane systems are an effective measure in contributing to key European renewable energy supply (RES) targets and also alleviating GHG emissions in problematic sectors such as transport and agriculture.

Many countries are dependent on the importation of fossil fuels to meet their national energy demand. Biomethane can be an indigenous resource, derived from localised organic wastes and residues. Previous literature studies and developed roadmaps in member countries have shown that biomethane can replace significant amounts of natural gas. For example, utility company Engie estimates that biogas from agricultural and other waste (excluding crops) can provide for 100% of

gas consumption in France by 2050 (Reuters, 2017). In countries with a well-established and closely linked gas grid, there are good opportunities for cross-border trade and to create a market for biomethane, thus lowering the import dependency of fossil fuels. The production of biomethane from regional resources creates jobs, especially in agriculture, supply logistics, engineering, plant construction and maintenance. Farmers can profit in “non-food” related sectors with an alternative source of revenue through biomethane.

Anaerobic digestion plants are typically located in close proximity to areas where biomass is cultivated or sourced. This circumvents the need for energy-intensive transportation of biomass to the plant location. It also minimises the cost of redistributing the digestate, a commercial biofertiliser by-product, to the surrounding cropland. The digestate can reduce the farmers’ costs associated with the purchase of manufactured chemical fertilisers. The use of all by-products generated in biomethane production systems can ensure the optimisation of the full value-added chain.

Biomethane is very flexible in its application, more so than other renewable sources of energy. Its ability to be injected directly into the existing natural gas grid allows for energy-efficient and cost-effective transportation. This allows gas grid operators to enable consumers to make an easy transition to a renewable source of gas. The diverse, flexible spectrum of applications in the areas of electricity generation, heat provision, and mobility creates a broad base of potential customers. Biomethane can be used to generate electricity and heating from within smaller decentralised or large centrally-located CHP

plants. It can be used by heating systems with highly efficient conversion efficiencies, and employed as a regenerative power source in gas-powered vehicles. The utilisation of biomethane as a source of energy is a crucial step towards a sustainable energy economy. A further pathway for biomethane can be found in large industry energy users. A growing demand for green gas has been evident from multinational companies who want to fulfil their corporate social responsibilities. These industries would typically include breweries, distilleries, milk processing facilities and data centres. The substitution of natural gas with biomethane can lower the use of fossil materials and support the intended change from a fossil to a bio-based society without the need for expensive new infrastructure.

## 2.4 Biogas and biomethane deployment

Anaerobic digestion can now be considered a mature technology that is widespread particularly throughout Europe. If biomethane is produced, the preferred end-use typically varies by country and the extent of their gas grid infrastructure. For instance, Sweden has a gas grid restricted to one region in the country and so biomethane is used primarily as a vehicle fuel with set financial incentives (IEA Bioenergy Task 40 and Task 37, 2014). At the end of 2015 there was a total of 17,376 biogas plants and 459 biomethane plants in operation in Europe (European Biogas Association, 2016). Figure 2.2 gives an insight into the quantity of biogas plants in a number of countries and the different types of facility (WWTP, agricultural/industrial or landfill). The estimated energy output (TWh) from the facilities in the same countries is indicated in Figure 2.3.

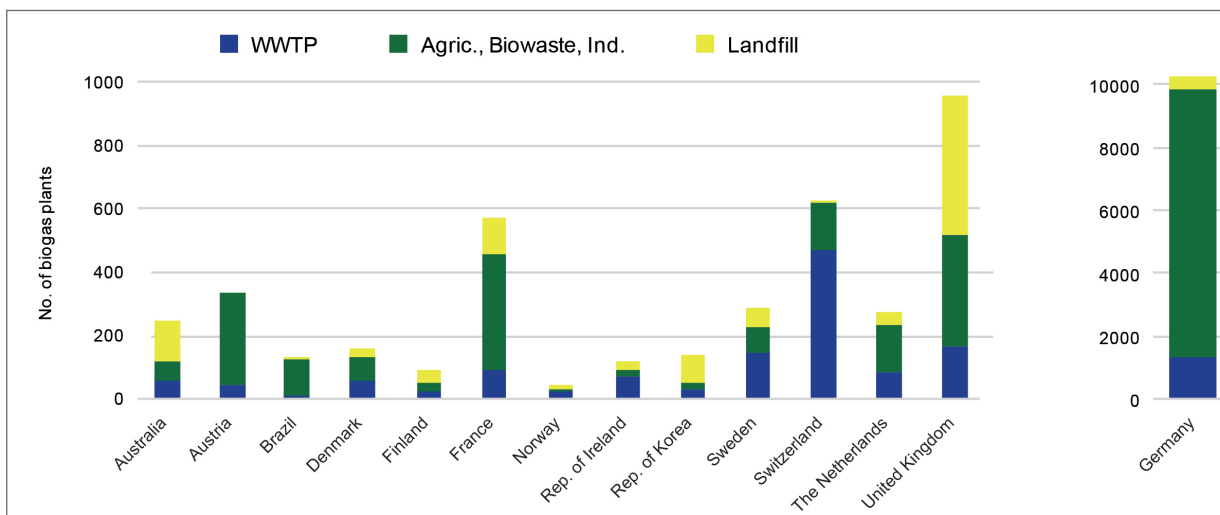


Figure 2.2 Number and type of biogas plants in selected countries (Source: IEA Bioenergy Task 37 Country Report summaries 2016, <http://task37.ieabioenergy.com/country-reports.html>)

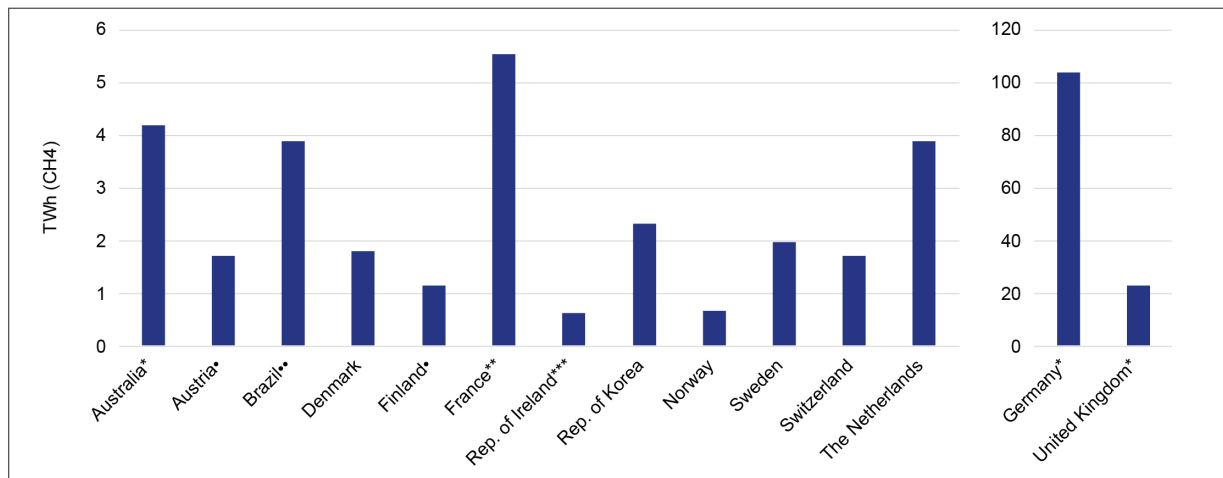


Figure 2.3 Current energy output (TWh) from anaerobic digestion in selected countries (Source: IEA Bioenergy Task 37 Country Report summaries 2016, <http://task37.ieabioenergy.com/country-reports.html>)

If biomethane, due to its flexibility as an energy carrier, is considered the future of renewable gas, the technology for upgrading biogas becomes a key consideration. Figure 2.4 gives the current breakdown of the number of upgrading plants in specific countries with Germany and the UK leading the way in Europe, and South Korea also demonstrating high uptake. The technology used

for biogas upgrading varies, however four main methods are currently most practiced: water scrubbing; chemical scrubbing; membrane separation; and pressure swing absorption (PSA). Figure 2.4 also illustrates the breakdown of CO<sub>2</sub> removal technologies used for the countries listed and highlights the growth of upgrading technologies since the turn of the century.

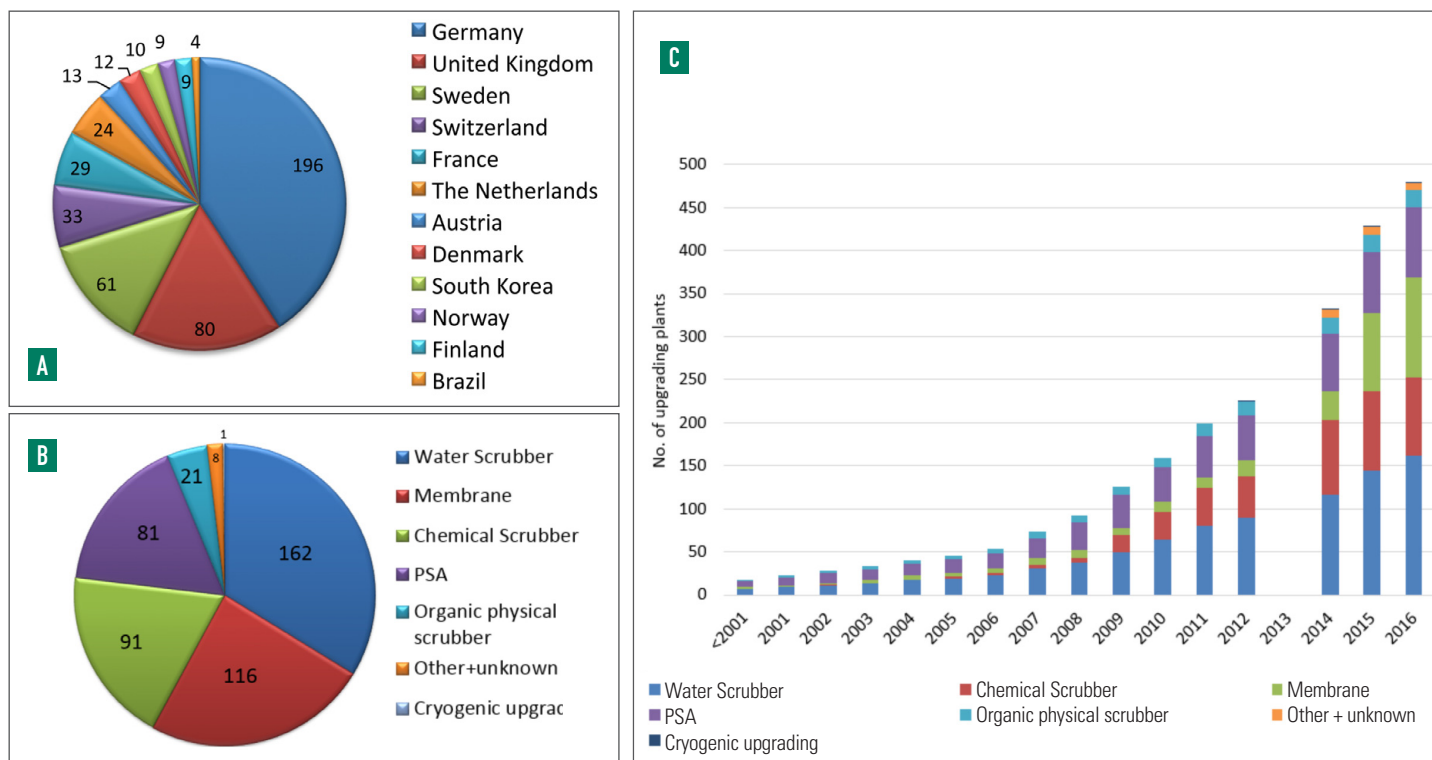


Figure 2.4 A: Number of biogas upgrading plants per country; B: Breakdown of biogas upgrading technologies used at biomethane plants; C: Biogas upgrading technologies uptake over time (IEA Task 37 Energy from Biogas, 2016)



## 3. Algal biofuels

### 2.5 Advanced technologies for biomethane production

First generation biofuels, such as rapeseed biodiesel and wheat ethanol, are now capped under the EU Renewable Energy Directive (RED) at 7% in terms of contributing to renewable energy supply targets for transport. This is to avoid a potential “food versus fuel” debate and alleviate concerns over the sustainability of first generation biofuels in achieving sufficient GHG emissions savings. It is proposed that the cap on first generation biofuels may be even further reduced to 3.8% by 2030 under the most recent EU legislation proposals in the Recast RED (EC, 2016). Consequently, second generation biofuel substrates, such as lignocellulosic crops (including perennial ryegrass), organic municipal wastes and agriculture residues, have become the main focus of renewable energy generation through anaerobic digestion. The digestion of second generation feedstocks is generally well understood. Typically, a form of pre-treatment is required for lignocellulosic materials to enhance their digestibility and improve biogas yields. However, providing a renewable and decarbonised energy system (for electricity, heat and transport) through second generation (land based) biofuels may put a significant constraint on both arable and agricultural land. As the world’s population increases, the total energy consumption and demand for food will increase. Use of large swathes of land for bioenergy may become questionable with potential rises in food production prices. Since the proportion of land that can be devoted to bioenergy is finite, future energy systems may need to shift to the sea to provide sufficient feedstock resources to meet increasing energy demand. More advanced feedstocks such as micro and macro-algae are now receiving attention as an alternative to the more traditional land based biofuel production. Non-biological sources of renewable gas such as power to gas are also considered to have high potential in expanding the overall energy resource to 2050. Recent EU policy measures have encouraged the development of such pathways suggesting progressively increasing obligations. The share in renewable and low-carbon transport fuels (excluding first generation biofuels and including for electrification) is required to increase from 1.5% in 2021 to 6.8% in 2030, with advanced biofuels to make up at least 3.6% by that time (EC, 2016).

### 3.1 The role of seaweed in future biomethane production

Third generation, advanced biofuel sources such as macro-algae (seaweeds), do not require arable or agricultural land for production. Moreover, seaweeds that are farm cultivated at sea may offer a sustainable alternative to more traditional crops with higher growth rates. Rich in carbohydrates and with low lignin content, seaweeds represent an attractive feedstock for biomethane production with a variety of seaweeds such as *S. latissima*, *L. digitata*, *S. polyschides* and *A. nodosum*, investigated in literature (Tabassum et al., 2017). Table 3.1 presents energy yields from a number of different seaweeds. However, different seaweed species vary in composition, with respect to carbohydrate and protein content; this variance is also influenced the time of year at which they are harvested. Specific growth conditions such as temperature, nutrient availability and sunlight alter this composition. Thus, the time of harvest is critical in maximising the total biomethane production from seaweed. Seasonal variation of seaweeds is also an important characteristic in terms of the concentrations of polyphenols and ash, both of which, in high concentrations, may inhibit the anaerobic digestion process and lower the attainable biomethane yields. The ash in seaweeds is predominantly salt (chloride) and is evident in much higher levels than more traditional crop feedstocks.

Procuring a secure source of feedstock is vital to the development of a seaweed biomethane industry. In the short term, seaweeds from natural stocks may be digested for their energy content and may even provide a method of waste treatment. Eutrophication is a common cause of green tides, whereby green seaweed washes up on the shorelines of bays or estuaries due to excess nitrogen run-off into water streams, as occurs in Ireland, Japan and France. Green seaweed can pose a health risk and must be removed; for instance, *Ulva Lactuca* (sea lettuce) can generate high concentrations of the toxic gas  $H_2S$ . Co-digestion of seaweeds such as *Ulva Lactuca* with farm slurry for example can provide a mutual synergy by optimising carbon to nitrogen (C:N) ratios in the digestion process and supplying essential trace elements required by the anaerobic microbial consortium (Allen et al., 2013).

**Table 3.1 Potential methane and energy yields from seaweed in Ireland (Tabassum et al., 2017)**

Seaweed species	L CH <sub>4</sub> kg VS <sup>-1</sup>	GJ ha <sup>-1</sup> yr <sup>-1</sup> *
<i>S. latissima</i>	342	52 – 384
<i>S. Polyschides</i>	263	52 – 191
<i>A. Esculenta</i>	226	41 – 307
<i>L. digitata</i>	254	38 – 96
<i>L. hyperborean</i>	253	38 – 96

\* Dependent on the specific methane yield, volatile solids content and seaweed yield per hectare. These values account for both basic and optimistic harvesting potentials.

Cultivation of seaweeds for biomethane production may provide a more long-term strategy. One method of interest is combining seaweed cultivation with existing fish farms, known as integrated multitrophic aquaculture (IMTA). The advantage of IMTA is that a form of bioremediation occurs, in that the seaweed absorbs the nutrient-rich waste produced from the fish in their growth. This can increase growth productivity of the seaweed. In terms of seaweed preservation and storage, drying seaweeds is energy intensive and relies on fossil fuels, which is unsustainable. An alternative approach involves the ensiling of seaweed, similar to methods in the ensiling of crops on farms, and may even increase the available biomethane yield from the seaweed by digesting any silage effluent produced (Herrmann et al., 2015). Research investigating the seasonal variation of seaweed, combined with effective ensiling methods, will enable the provision of a year-round supply of high quality biomass.

### 3.2 Micro-algae and the circular economy

Micro-algae are unicellular algal species that can be cultivated and used for biomethane production through anaerobic digestion. As a feedstock, micro-algae offer higher growth productivity than traditional energy crops, require no land and have the potential for carbon savings through sequestration. The cultivation of micro-algae can be achieved in growth systems such as open raceway ponds or more expensive photobioreactors. The advantage of using micro-algae for biomethane production is that no specific algae strains are required, unlike for biodiesel production. However, micro-algae are considered a more challenging substrate for digestion due to a high nitrogen content, which results in a low C:N ratio (typically less than 10). To overcome this, co-digestion of micro-algae with carbon rich feedstocks such as barley straw, beet silage or brown seaweed has been proposed (Herrmann et al., 2016). Such methods can allow for an

increase in the digester loading rate and improvement of biomethane yields as compared to the mono-digestion of micro-algae. Thermal, mechanical, chemical and biological pre-treatments have all been investigated to increase the solubilisation of micro-algae by attacking the cell walls and thus to increase the obtainable energy yield from the feedstock.

Micro-algae are very interesting feedstock in that potentially they can also be used to upgrade biogas to biomethane. The CO<sub>2</sub> in biogas (typically 40-50%) can be captured through micro-algae growth in a photosynthetic process. This novel method of biogas upgrading may be advantageous in that it could potentially offset the cost of a traditional biogas upgrading system. Care must be taken in situations whereby CH<sub>4</sub> in the biogas and O<sub>2</sub> from micro-algae respiration could exist together at explosive levels. This threat may be overcome in systems such as high rate algal ponds coupled with external absorption columns (containing alkaliphilic bacteria) or incorporating biofixation of CO<sub>2</sub> in a bicarbonate/carbonate cycle. These microalgae biogas-upgrading systems are at a low technology readiness level (TRL) but can potentially provide a biomethane-standard end product.

From a biorefinery perspective, micro-algae can be used for biodiesel production through the transesterification of lipids with the remaining residues post extraction utilised for biomethane production. The digestate produced from the digestion process can potentially be used as a nutrient source for the cultivation of micro-algae, avoiding the external purchase of such nutrients. Other sources of CO<sub>2</sub> generation besides biogas from anaerobic digestion include power plants and distilleries, which may also be taken into consideration for micro-algae growth. Micro-algae, as a third generation, advanced biofuel substrate, can employ circular economy concepts and provide a cascading bioenergy system with regards to feedstock production, gas upgrading and nutrient recycling.

It must be noted that these technologies are not mature and algal biomethane systems may be overly expensive. Projects such as the EU funded All-Gas project (<http://www.all-gas.eu/en/home>), which aim to demonstrate the integration of the full production chain of algae to biofuels (including transport fuel) should advance the TRL significantly. Full scale application will involve certain challenges such as technology costs and geographical and seasonal constraints of micro-algae growth (Zhu et al., 2016).

## 4. Gasification to expand the biomass and biomethane resource

Woody residues, such as forest thinnings, and crops such as short rotation coppice (SRC) willow are considered second generation biofuel substrates that are also suitable for biomethane production. With high dry solids content (typically greater than 40%), such feedstocks are more suited to gasification technologies than anaerobic digestion for energy conversion. Gasification is a thermochemical process (using high temperatures in excess of 700°C) that converts lignocellulosic biomass to syngas, which can be purified and upgraded in a methanation phase to produce biomethane. The technology when including methanation is not as mature as anaerobic digestion; it is also operated on a much larger technology scale and hence requires substantially more capital investment. Nonetheless, in terms of the future production of green gas, gasification-methanation can play an important role.

A successful application of the technology has been demonstrated in Gothenburg GoBiGas plant (Figure 4.1). This project was developed as a proof of concept for the gasification-methanation technology in providing a potential avenue for expanding the growth of biomethane to meet the increasing demand in Sweden. Plant costs are estimated at €150 million and the system has the potential to fuel 15,000 cars (GEODE, 2016). A second phase is planned in which a much larger scale plant will be developed; biomethane production will increase from 160 GWh/a (0.58 PJ/a) to a capacity of 800 GWh/a (2.88 PJ/a) (Alamia et al., 2016). Ultimately the two plants could potentially provide up to 1TWh – a resource equivalent to the total biogas produced in Sweden at present, enough to fuel 100,000 cars (GEODE, 2016).



Figure 4.1 The GoBiGas plant in Gothenburg is the first of its kind in the world, injecting biomethane from thermal gasification and methanation to the natural gas grid of Gothenburg. At full production, the 20 MW methane plant will deliver 160 GWh/yr. (Photo: Used with permission of Rob Vanstone and Göteborg Energi, Sweden).

## 5. Advanced smart grid technologies

### 5.1 Facilitating intermittent renewable electricity

In the future our energy system will undergo a transition towards sustainable and renewable energy sources. Renewable energy sources are different from conventional fossil energy sources due to their low life-cycle carbon emissions and their intermittent nature. Sustainable electricity production is highly dependent on weather conditions. The intermittent nature of solar and wind energy means that matching the supply and demand of sustainably generated electricity is challenging. Consequently there will be a greater need for energy storage and flexibility of the energy infrastructure in the future. During the winter season, the demand for energy can be many times higher than in the summer in colder climates. However during the summer in warm climates, air conditioning can lead to very high energy demand. Energy carriers need to be available and flexible to match energy demand.

The share of renewable electricity in the EU is expected to increase significantly to 2050, potentially representing between 64-97% of the electricity mix (Collet et al., 2016). On a global scale, the total wind installation has increased from 17GW to 318GW since the turn of the century (Götz et al., 2016). Storage of intermittent renewable electricity will be required in countries where the installation of wind and solar devices has been significant. For instance, Finland has significant solar irradiation on long summer days meaning electricity generation could potentially be high; however, energy consumption

is highest in the winter (Tsupari et al., 2016). The UK has forecasted onshore wind capacity to increase almost four-fold by 2035 to 21GW, and this could be surpassed by offshore wind capacity in the same time period, estimated at 37.5GW (Qadrnan et al., 2015). In Denmark, Spain, Portugal, Ireland and Germany, an increase in installed wind capacity has also been evident, already contributing ca. 9-34% of the electricity supply (Götz et al., 2016). The intermittency of electricity generated through wind and solar platforms is problematic as often, supply does not match with times of high consumer demand. Although the current curtailment of renewable electricity is typically due to constraints on the electricity transmission lines, the increased share of electricity from intermittent renewable sources is likely to compound this problem. This is exemplified by considering wind electricity providing 40% of a country's electricity. If the capacity factor of wind generation is 30% then when the wind is blowing it can provide 133% of the average electricity demand at a given time. If this resource coincides with low demand by night, a significant storage capacity is required or a significant electricity spillage may transpire.

Opportunities to use and/or store the excess production of sustainable electricity must be found. Existing electricity storage methods include batteries, flywheels, compressed air energy storage (CAES) and pumped hydroelectric storage (PHS). However these particular technologies may be limited as they do not store large

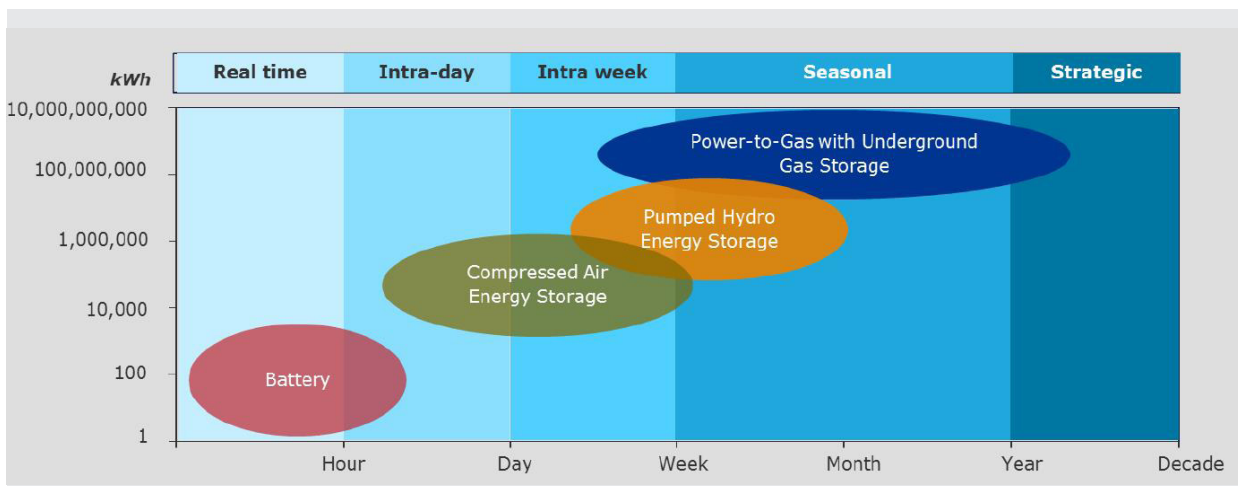


Figure 5.1 Electricity storage capacity and duration (source: DNV GL)

quantities of energy for long periods of time (Walker et al., 2016) and often rely on specific geographical features. Figure 5.1 illustrates the different electricity storage methods and their respective capacity. Renewable gas systems can support the increasing proportion of intermittent renewable electricity through two principle methods: 1) as a storage mechanism for curtailed renewable electricity, with conversion of the energy vector to gas (power to gas) which is available for similar use as that of natural gas; and 2) as a support to intermittent renewable electricity generation through demand driven biogas systems.

## 5.2 Demand driven biogas systems

With increasing wind, wave and solar deployment, the amount of variable renewable electricity on the electricity grid will increase. Such renewable devices are not considered “dispatchable” (cannot be turned on or switched off at any given time) and so electricity supply does not always match electricity demand – for example when the wind is not blowing and the demand for electricity is high. Currently, carbon intensive fossil fuels (such as combined cycle gas turbines) are used to back up the electrical load when such intermittent devices cannot meet demand.

Bioenergy can be made dispatchable on demand. Biogas generated from anaerobic digestion can be stored onsite and fed to a CHP unit for electricity production when required. Alternatively, to minimise the cost of biogas storage onsite, the feeding regime of the digester can be varied to generate biogas at a specific time to match high electricity demand. This is known as a demand driven biogas system and often the biogas plant operator may receive a premium rate (price) for the electricity

production through such operation. Furthermore when the biogas plant is not supporting the electrical grid it can produce biomethane (via biogas upgrading). Thus potentially an anaerobic digestion facility can support both the electricity grid and gas grid (Figure 5.2). Previous literature studies have modelled a continuously operating 435 kWe continuously fed digestion system, which when converted to demand driven, operated as a 2 MWe CHP unit for 60 min per day, whereby 21% of biogas was used in the CHP generator and 79% was supplied to the biogas upgrading system (O’Shea et al., 2016c).

## 5.3 Power to Gas

Power to Gas (PtG) is an emerging smart grid concept whereby electricity (preferably surplus renewable electricity) is converted to methane for storage purposes. When electricity storage is challenging and current infrastructure does not support long-term management of this problem, the PtG process converts the energy vector from electricity to gas, which can be injected into the gas grid. PtG uses electrolysis, powered by electricity, to split water ( $H_2O$ ) into hydrogen and oxygen. To convert the hydrogen from electrolysis to renewable green gas in the form of methane, a source of  $CO_2$  and a methanation phase are necessary. Figure 5.3 contains a flow diagram that describes the flows on a proportional basis. It visualises the material flows and the mass efficiency of the process can be estimated. The flow diagram also demonstrates that only part of the electricity is converted to hydrogen and only a proportion of the hydrogen is converted to methane. Methane is then mixed with small quantities of other gases ( $CO_2$  maybe used to reduce volumetric energy den-

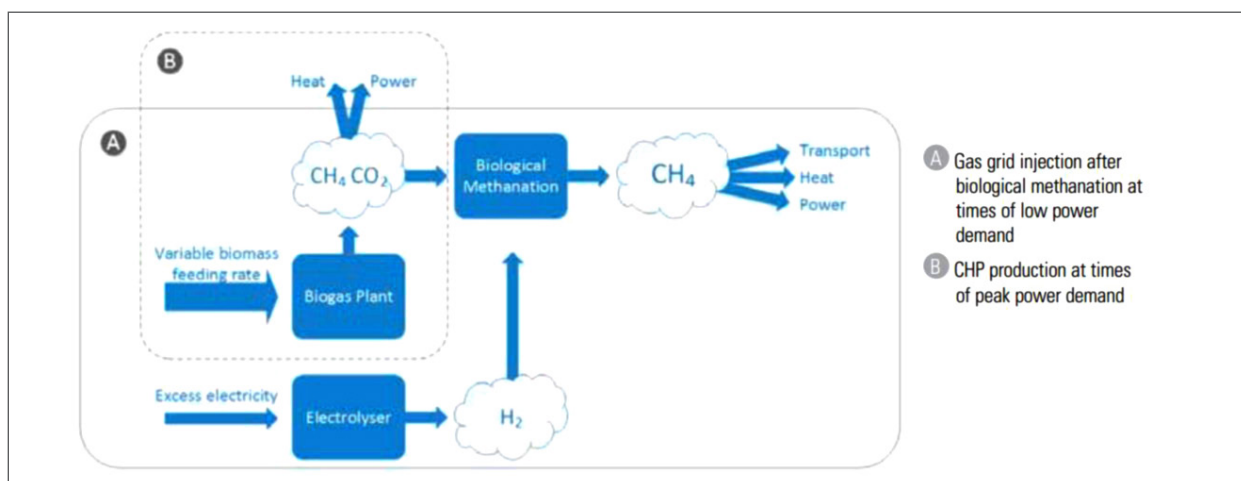


Figure 5.2 Combination of (A) power to gas system with (B) demand driven biogas system (Ahern et al., 2015; Persson et al., 2014)

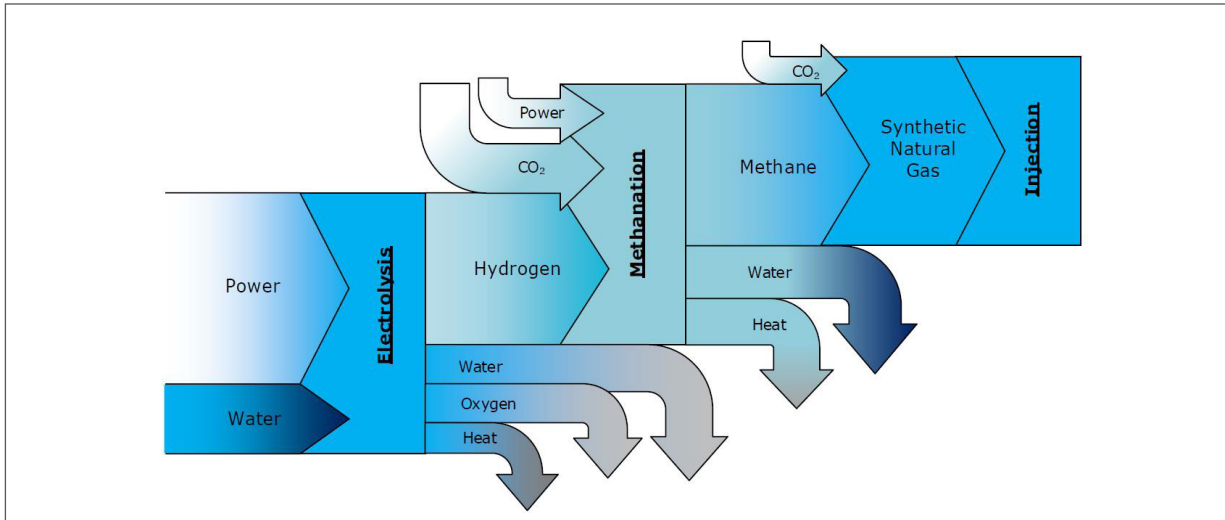


Figure 5.3 Product flows in the Power-to-Gas concept (source: DNV GL)

sity and propane to rise it) in order to comply with the local gas-quality specification before it can be injected in to the gas grid. Both electrolysis and methanation processes release heat.

Three main technologies reported for electrolysis are: the alkaline electrolyser; the polymer electrolyte membrane (PEM); and the solid oxide electrolysis cell (SOEC). Alkaline and PEM are considered low temperature technologies; SOEC is a high temperature process at a low TRL and is intended to improve the efficiency considerably (Parra & Patel, 2016). Alkaline electrolysis is at a more mature stage of development than PEM or SOEC and is commercially available with modules up to 2.5MWe (Schiebahn et al., 2015). However, in the future, higher process efficiencies may be potentially viable in PEM and SOEC technologies. When evaluating electrolysis units, the most important features for PtG include conversion efficiency to hydrogen, cold start up flexibility, and operational lifetime (Götz et al., 2016). PtG requires a quick start up time from the perspective that the system may be turned off and on to match times when electricity is cheap (as would be the case if the electricity source was curtailed electricity). PEM is a faster technology than alkaline but is more expensive since the technology requires noble catalysts such as Pt, Ir, Ru (Schiebahn et al., 2015). Any future enhancements in electrolysis may depend on the high efficiency associated with SOEC technology (greater than 90%), which is currently at a low technology maturity.

The methanation step can be catalytic or biological; both methods adhere to the process of combining hydrogen and CO<sub>2</sub> (at a ratio of 4:1) to produce methane

and water ( $4\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$ ). For catalytic methanation, a form of catalyst (typically nickel-based) is used making it less robust than biological methanation to contaminants in biogas. Biogas used in catalytic methanation typically requires a cleaning step between production and methanation. Catalytic methanation operates at a high temperature range of 200-500°C with high pressures of 1-100 bar (Götz et al., 2016). Biological methanation uses hydrogenotrophic methanogenic archaea to convert the hydrogen and CO<sub>2</sub> to methane, as opposed to catalysts. The biological method can be “in-situ” whereby hydrogen is injected directly into an anaerobic digester and combines with the CO<sub>2</sub> in biogas; or “ex-situ” in which both hydrogen and CO<sub>2</sub> are introduced to an external methanation reactor. The source of CO<sub>2</sub> for PtG can be provided by biogas plants, large CO<sub>2</sub> emitters in industry (such as distilleries), or wastewater treatment plants (WWTPs) where cheap, concentrated sources of CO<sub>2</sub> can be accessed (O’Shea et al., 2017).

PtG has been demonstrated for proof of concept in laboratory studies. On a larger scale, two projects aiming for commercial viability with regards to PtG with biological methanation are the Electrochaeta – BioCat project (Denmark) and MicrobEnergy – BioPower2Gas project (Germany); with both utilising biogas plants for the source of CO<sub>2</sub> (Bailera et al., 2017). The cost of electricity is deemed to be a very significant factor in the development of PtG systems. As discussed, lower electricity prices could be available through curtailed renewable electricity. A system conflict exists between: short operating times using cheap electricity and oversized electrolysis systems; and long operation times with more

## 6. Country case studies: future strategies for biomethane

expensive electricity and cheaper capital costs. Literature studies give examples whereby green gas can be produced from a PtG system at €1.80/m<sup>3</sup> when the price of electricity is €0.05/kWh, decreasing to €1.10/m<sup>3</sup> when electricity is purchased at €0.02/kWh (Vo et al., 2017).

PtG systems can provide a valuable control function for the electrical grid in its capability to utilise curtailed electricity in real time and produce green gas. The technology costs for electrolysis and methanation must be defined as the levels of curtailed electricity become apparent in the future. Utilising the full value chain of PtG systems can make such projects more financially viable (Breyer et al., 2015). For instance, oxygen generated through electrolysis can offer a valuable by-product with a monetary value. The cascading bioenergy system could use this oxygen in a gasification plant. For example a study by McDonagh et al. (2018) suggested an levelised cost of energy (LCOE) of a catalytic PtG system of €124/MWh with costs dominated by electricity charges (56%) and CAPEX (33%). Valorisation of the produced oxygen could reduce the LCOE to €105/MWh. An additional payment for ancillary services to the electricity grid (€15/MWh for 8500h p.a) would further lower the LCOE to €87/MWh.

In 2012, the European Power to Gas Platform was founded by DNV GL. Its members are European Transmission and Distribution System operators, branch organisations and technology suppliers. The Platform facilitates the dialogue between these stakeholders and provides them with a forum to gain and exchange knowledge and explore the conditions under which PtG can be successful. Within the Platform, knowledge gaps related to the PtG concept and its implementation are identified and, where possible, investigated in internal studies. These studies include expected curtailments in different European countries towards 2030, business cases of PtG pathways and compatibility aspects of different CO<sub>2</sub> sources for methanation. Recently, a study has been finalised which investigated the role of PtG in a purely renewables based European energy system. The Platform member's common goal is to realize the energy transition as cost-effectively as possible.

### 6.1 Ireland

To date, the Republic of Ireland (with a population of ca. 4.5 million people) has made significant progress in generating renewable electricity; approximately 25% of power generation comes from renewable sources such as wind. However, Ireland has struggled to make progress in renewable heat and transport. In 2013, the total final energy consumption in Ireland for transport and thermal energy was 179PJ (55 TWh) and 187PJ (52 TWh), respectively. Currently there is a 6% gap to reach the 12% renewable energy supply in heat (RES-H) target for Ireland, which equates to about 3 TWh a<sup>-1</sup> (10.8 PJ). Many large energy users in the food and beverage industry are committed to procuring green energy through their energy supplier. The Irish Renewable Heat Incentive (RHI) for biomethane injection is expected to be announced by the government in 2018. This commodity support will potentially act as the catalyst to mobilise growth in the biomethane sector in the coming years. Although there has been a relatively small uptake so far in biogas and biomethane in Ireland, a variety of biomass resources such as grass, agricultural residues and food waste are available which could substantially increase renewable gas production. The total theoretical resource is assessed as per Figure 6.1.

Grass is the predominant crop feedstock available in Ireland. Ireland has 4.4 Mha of agricultural land, which is comprised of over 90% grassland. With a temperate climate, high yields of grass per hectare (10 tDM ha<sup>-1</sup>) are readily achievable. Grass silage (preserved grass) is traditionally used as a feed for Ireland's livestock. Ireland has a large agricultural industry that will account for ca. 35% of the country's total GHG emissions by 2020. Production of grass in excess of the quantity required for livestock feed has been identified as the biomass of most potential for anaerobic digestion. This grass resource has previously been estimated in literature at ca. 1.7 Mt DM a<sup>-1</sup> (McEniry et al., 2013), available in excess of livestock requirements and could be used for biomethane production.

Legislation on the collection of food waste and the introduction of high landfill levies has encouraged its disposal through other means in Ireland. Food waste (and the organic fraction of municipal solid waste) is a commonly identified feedstock for anaerobic digestion, as it can achieve high specific methane yields (SMYs). It is considered the low hanging fruit as a digestion feedstock as it is a waste stream that can potentially accrue a gate fee (for the operator) as opposed to energy crops which have a production cost, supporting the economic feasibility of such digesters. The composition of food waste is variable depending on origin, that is, whether it is sourced from rural or urban areas. Estimates of the collectable household food and garden waste have been made for Ireland by multiplying population numbers by the quantity of waste available; it has been assessed that 138,588 t Volatile Solids (VS) a<sup>-1</sup> of food waste is potentially available in Ireland (O'Shea et al., 2016a).

Residues from agriculture in Ireland include for farm slurries, slaughterhouse wastes and processing wastes from the production of milk and cheese. Typically these residues are land spread; however, such wastes can also be considered a valuable resource for energy production as they incur no cost and can achieve very high GHG emissions savings on a whole life cycle basis (compared to the fossil fuel displaced) due to the removal of fugitive methane emissions in open slurry storage tanks. The majority of slurry will come from Ireland's dairy herd, where slurry is collected in pits when the animals are housed inside in winter. Pig slurry may also be a viable feedstock as it is collected year round. Slaughterhouse wastes typically comprise of paunch (material extracted from the stomach of the animal) and sludge (from the wastewater treatment process), both organic by-products suitable for digestion and biomethane production. Milk processing waste is generated at dairy produce facilities and typically comes in the form of an effluent or

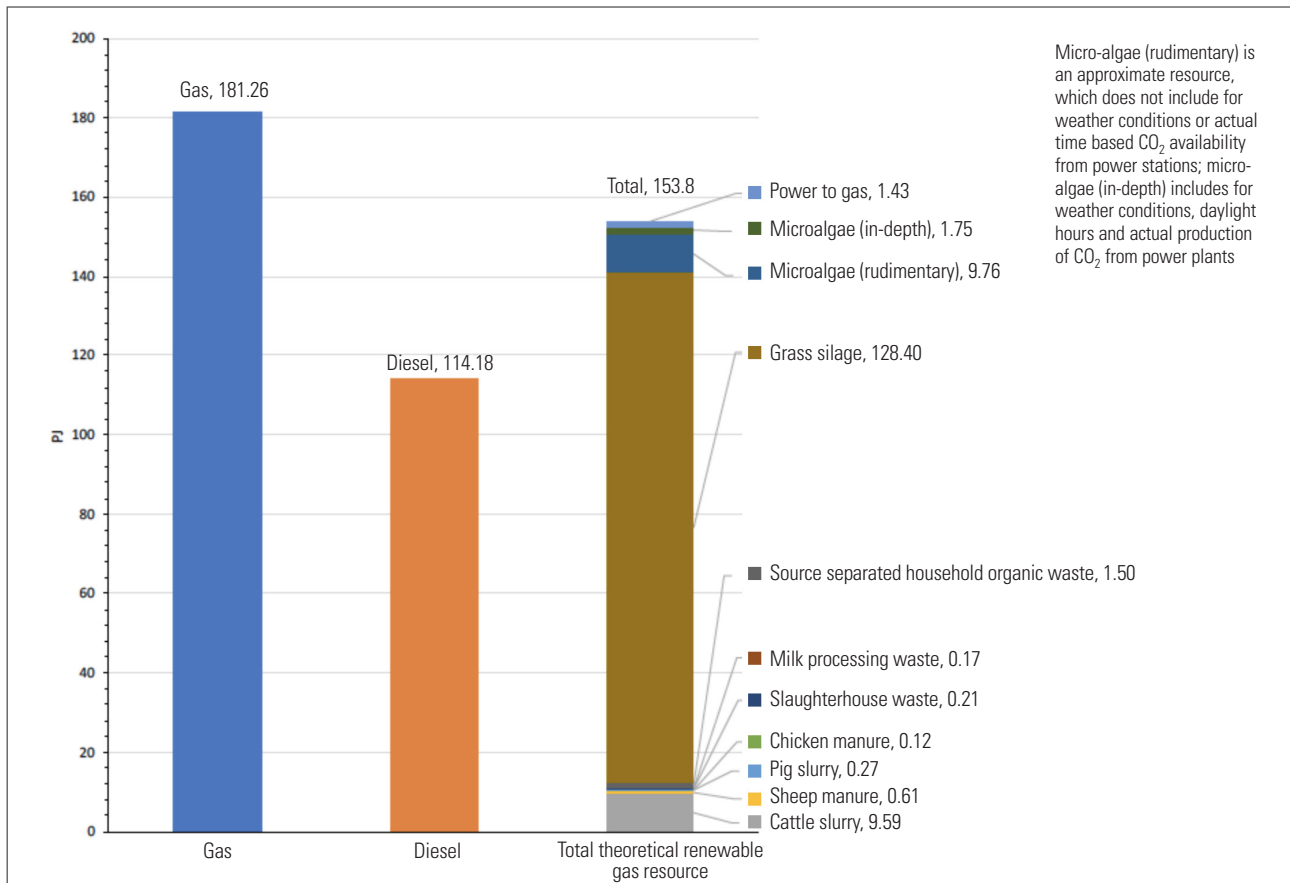


Figure 6.1 Ireland's total theoretical biomethane potential resource from identified feedstocks as compared to natural gas consumption and diesel consumption. Data on gas demand and diesel demand adapted from (Howley & Holland, 2016; O'Shea et al., 2016a; O'Shea et al., 2016b).



sludge. The residual sludge from primary and secondary wastewater treatment processes may also be digested for biomethane in Ireland. Many wastewater treatment plants already have digesters onsite as part of their treatment process in reducing the organic content of their effluent streams.

Several studies have been published on Ireland's total biomethane production potential, which ranges from about 4–50 TWh a<sup>-1</sup> (15 to 180 PJ a<sup>-1</sup>) depending on feedstock mobilisation assumptions. The total practical resource (as opposed to potential resource) of biomethane identified by O'Shea et al., (O'Shea et al., 2016a; O'Shea et al., 2016b) based on currently available resources in Ireland was 27.8PJ as indicated in Figure 6.2. If this biomethane resource was used for transport or thermal energy it could provide ca. 15% renewables in either sector. A recent study by the Sustainable Energy Authority of Ireland (SEAI) on Ireland's renewable gas potential has indicated that as many as 900 digesters, ranging in size from 500 kW<sub>e</sub> (CHP) to 6000 kW<sub>e</sub> (biomethane), would be required to exploit the existing and future biomass available nationally (SEAI, 2017). The future resource from biomethane was reported in this study as ca. 22 PJ which would result in GHG emissions savings of 2 Mt CO<sub>2</sub>eq, equivalent to 3.7% of the total national GHG emissions in the baseline year 1990. A recent study published by the EU Commission in March 2017 (Kampman et al., 2017)

highlights Ireland's potential to produce the most renewable gas per capita within the EU by 2030, with a realistic potential of 13 TWh a<sup>-1</sup> (47 PJ a<sup>-1</sup>).

Mobilising Ireland's biomethane potential has been the focus of much research, strategy development and solution design within Gas Networks Ireland (GNI). GNI owns and operates over 13,500 km of transmission and distribution gas pipelines in Ireland (with approximately 680,000 connections to homes and businesses). GNI are committed to facilitating renewable gas in decarbonising energy supply to customers, particularly in the heat and transport sectors. Based on detailed assessments of the many biomethane solutions throughout Europe, GNI identifies the "Hub and Pod model" as the model with the most potential to maximise the mobilisation of biomethane in Ireland. This model incorporates road transport of biomethane in compressed trailer units from biogas production facilities located remotely from the gas network (Pods) to centralised injection facilities connected to the gas network (Hubs). Such a solution could maximise the potential for Irish farmers, as biogas production can be located remote from the gas network on farm scale biogas Pods, with clusters of biogas Pods feeding biomethane to centralised grid Injection Hubs. Assuming ongoing biomethane policy supports, GNI predicts the growth rate of biomethane injection facilities to grow with up to 43 centralised Hubs in place by 2030, with an average of

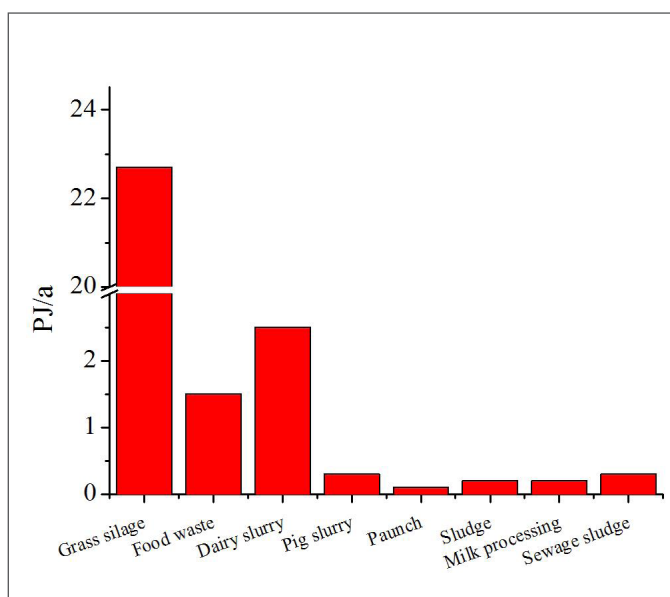


Figure 6.2 Ireland's practical biomethane resource from identified feedstocks (O'Shea et al., 2016a; O'Shea et al., 2016b),

Table 6.1 Gasification-methanation of willow for biomethane in Ireland (Gallagher & Murphy, 2013)

Gasification feedstock		Conversion	Unit
SRC willow	6,800	Required for one 50MW <sub>th</sub> gasifier	ha a <sup>-1</sup>
	74,800	For eleven 50MW <sub>th</sub> gasifiers	ha a <sup>-1</sup>
	1,795,200	assuming 24 t/ha	t a <sup>-1</sup>
	15.8	Lower heating value (LHV) 8.8 GJ/t	PJ a <sup>-1</sup>
	10.3	Process efficiency @ 65%	PJ a <sup>-1</sup>

Table 6.2 Potential methane resource from power to gas in Ireland adapted from (Ahern et al., 2015)

Electricity	Conversion	Unit
4.5	consumption in 2015	Mtoe a <sup>-1</sup>
188	consumption in 2015	PJ a <sup>-1</sup>
75	assuming 40% renewable electricity (RES-E)	PJ a <sup>-1</sup>
5.3	assuming 7% curtailment	PJ a <sup>-1</sup>
4.0	assume 75% efficiency conversion to H <sub>2</sub>	PJ a <sup>-1</sup>
3.0	assume 75% methanation efficiency	PJ a <sup>-1</sup>

8 biomethane production Pods supplying each hub (over 300 on-farm anaerobic digestion Pods nationwide). This scenario would see  $11.5 \text{ TWh a}^{-1}$  ( $41.4 \text{ PJ a}^{-1}$ ) of biomethane supplied to energy customers which would be approximately 20% of predicted natural gas demand in 2030.

In addition to this, GNI are supporting the creation of a biomethane market in Ireland by co-funding other major projects through the Gas Innovation Fund. The Causeway Project will examine the impact of increased levels of Compressed Natural Gas (CNG) fast refill stations and renewable gas injection on the operation of the gas network in Ireland and is co-funded by the European Union through the Connecting Europe Facility. The project will deliver 14 fast fill public access CNG stations installed by the end of 2019.

Furthermore the Green Gas Certification Scheme project which is co-funded by the Department of Communications, Climate Action and Environment, Department of Jobs, Enterprise and Innovation as well as GNI and the Renewable Gas Forum of Ireland was launched in April 2017, and aims to devel-

op a comprehensive methodology for a certification scheme that facilitates biomethane trading for both renewable heat and transport markets. It is anticipated that such certification and independent traceability of Guarantees of Origin and sustainability criteria will be mandated in the updated RED as well as demonstrating compliance with EU and national targets.

For advanced technologies in Ireland, gasification studies have shown an indigenous supply of willow could feed eleven 50MWth gasifiers located on the gas

grid; each gasifier would require 6,800 ha of willow (Gallagher & Murphy, 2013). The energy resource from gasification is extrapolated in Table 6.1. Future renewable gas production could increase by  $10.3 \text{ PJ a}^{-1}$  by the introduction of eleven 50MWth gasifiers, increasing Ireland's total theoretical energy resource to ca.  $38 \text{ PJ a}^{-1}$ . Ireland is also examining the concept of storing surplus electricity as a gas through PtG systems. A recent literature study (Table 6.2) indicates that a resource of ca.  $3 \text{ PJ a}^{-1}$  would be available based on 7% renewable electricity curtailment in 2015. It is not feasible to operate based solely on curtailed electricity as the CAPEX based on low run hours would generate a low capacity factor and expensive renewable gas (McDonagh et al., 2018). The theoretical resource is assessed as  $1.43 \text{ PJ}$  in Figure 6.1.

## 6.2 The Netherlands

At present, the Netherlands produces ca.  $4 \text{ TWh a}^{-1}$  ( $14.4 \text{ PJ a}^{-1}$ ) of biogas, which is primarily used for electricity and heat. Approximately  $900 \text{ GWh a}^{-1}$  ( $3.24 \text{ PJ a}^{-1}$ ) of biomethane is also injected to the natural gas grid.

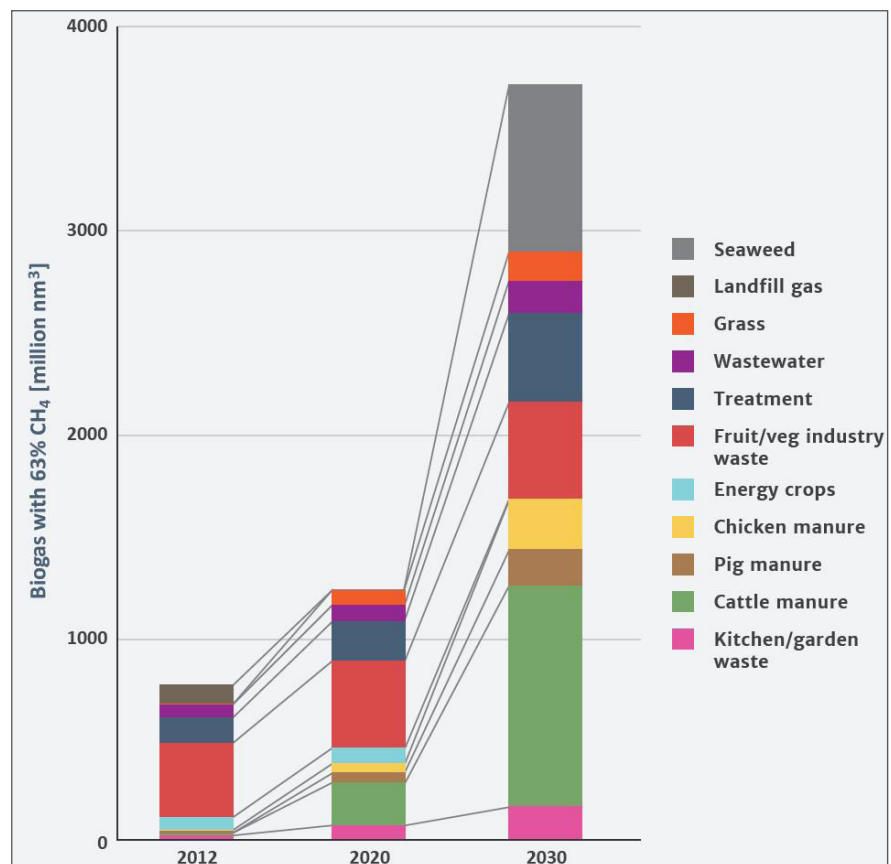
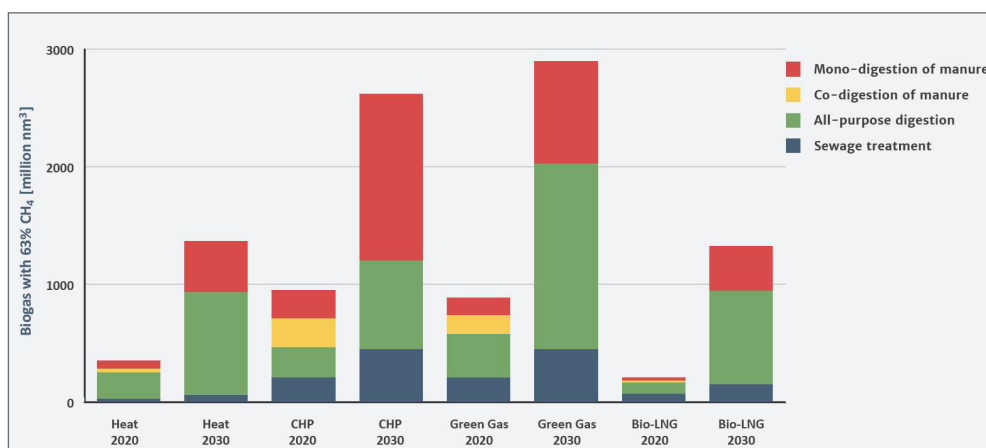


Figure 6.3 Biogas resource potential in the Netherlands (Green Gas Forum, 2014) (Groen Gas Nederland (GGNL))



◀ Figure 6.4 Maximum potential per marketing route for biogas in The Netherlands (Green Gas Forum, 2014) (Groen Gas Nederland (GGNL))

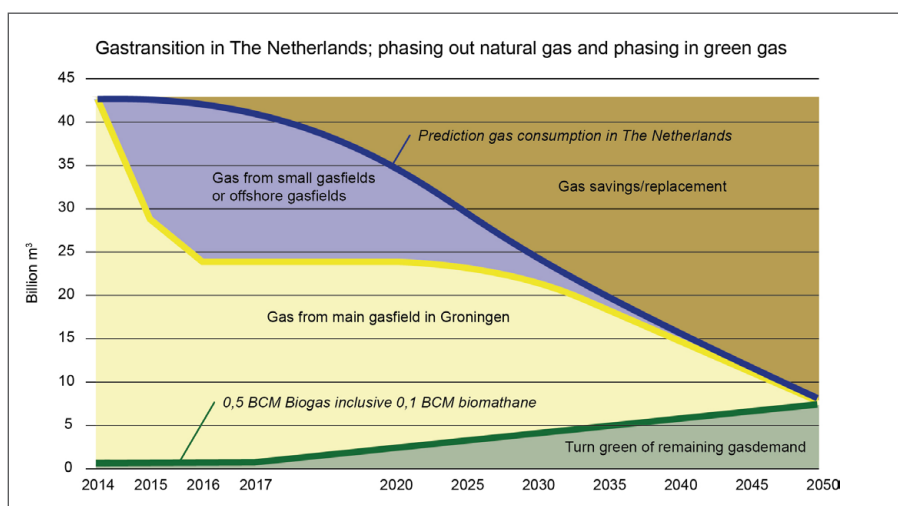
Figure 6.5 Gas development route to 2050 for the Netherlands (Source: Ton Voncken, Groen Gas Nederland (GGNL)) ▼

The Green Gas Roadmap for the Netherlands was published in 2014 and estimated the potential for biomethane production in the country. Predictions for biogas production, and thus  $\text{m}^3$  of natural gas equivalent, were made for the years 2020 and 2030. An illustration of the potential is shown in Figure 6.3.

It is estimated that 0.75 billion  $\text{m}^3$  of natural gas equivalent (biomethane) could be produced by 2020 with this resource increasing to 2.2 billion  $\text{m}^3$  of natural gas equivalent by 2030 (Green Gas Forum, 2014). This is equivalent to approximately  $25 \text{ PJ a}^{-1}$  in 2020 and  $77 \text{ PJ a}^{-1}$  in 2030, a significant resource (Green Gas Forum, 2014). The method by which the renewable gas will be applied to market in the Netherlands will be site specific – dependent upon whether there is a demand for heat and electricity (CHP), or direct injection to the gas grid or as a transport fuel. Figure 6.4 highlights the impact of different digestion feedstocks, and their respective biogas production, in terms of their maximum potential in each route to market.

Figure 6.5 outlines the development route for the Netherlands. The guiding principle is that, even when energy conservation is implemented and natural gas is replaced with other sustainable energy options, demand for gas will always remain. This will then be met in full using gas from renewable sources.

For PtG in the Netherlands, DSO Stedin, DNV GL, Community of Rotterdam and the housing association Ressorst Wonen carried out a demonstration project that investigated the use and applicability of the technology. Prior to the realisation of this project, the technical de-



sign guidelines, process criteria and principles were determined. These formed the basis for demonstrating PtG in a realistic environment with every element of the value chain considered, from production to end-use. The project entailed the production of sustainable electricity from solar panels, which was subsequently converted into synthetic gas (of natural gas quality), via hydrogen and methane and was applied in the gas-fired boiler of nearby buildings. The produced synthetic gas complied with all the specifications that apply to injection into the Dutch gas grid. In the implementation of the project, practical information was obtained about the technical feasibility of the complete system and the individual system components. For example, the conversion of electricity into hydrogen and oxygen was performed with an energetic efficiency of 47%. The remainder of the energy - in the form of heat - could not be used locally. Heat is also released during the catalytic conversion of hydrogen and  $\text{CO}_2$  and this heat was not used either. The energetic efficiency of this methanation process was assessed at 73%. The energy balance of the complete PtG system (including methanation) demonstrated an energetic efficiency

of 35%. It should be remarked that the efficiencies of the latest electrolyzers (for higher capacities) are significantly higher than the one used in this project. Besides optimising the energetic efficiency, it is important that the outgoing gas complies with the specifications that apply to injection into the gas grid. The Dutch distribution network requires gas to contain no more than 0.1 mol% hydrogen. The optimum settings of the methanation process are therefore a compromise between the highest achievable energetic efficiency and the outgoing hydrogen concentration.

### 6.3 The United Kingdom (UK)

*The following section is based on the information from the Energy and Utilities Alliance (2017) and Future of Gas (2017) publications.*

The uptake of anaerobic digestion in the UK over the past number of years has been significant to the extent where capacity is now sufficient to power over a million homes. The number of plants has risen to 559; biomethane plants will total 144 when current projects under construction are complete. The total energy generation from anaerobic digestion in 2017 stands at 10.7TWh. It is suggested that increases in feedstock availability/uptake, an update in legislation regarding the RHI scheme and availability of agricultural payments for energy generation on farms could see the total energy yield increase to 78TWh. This would be considered a significant socio-economic benefit given the UK's dependency on gas as a fuel. Almost 50% of the UK's primary energy needs in relation to power generation and heat is supplied by gas and this gas is also responsible for 40% of the UK's GHG emissions.

In terms of the green gas strategy of the UK, two policy scenarios have been proposed. The first involves the removal of gas as an energy carrier with decarbonisation of the electricity system; whilst the second involves decarbonising the gas grid. However, rather than reducing the need for gas in the future, it is expected that the UK will have an increasing gas industry; this is proposed as the preferred route as consumers are already familiar with and connected to the existing gas grid. The UK has an advanced natural gas grid infrastructure that supplies heat energy to 85% of homes. Decarbonisation of the gas system could be achieved through the production of renewable gas. Offering a source of renewable or green gas going forward would provide significant advantages in terms of sustainability.

The UK government has indicated a strong interest in the production of renewable hydrogen (as well as methane). More specifically the Department of Business, Energy and Industrial Strategy (BEIS) has invested £25m in developing a supply chain for hydrogen in the UK. Hydrogen will be produced through steam reforming of methane. If this is associated with carbon capture there is a decarbonisation effect as combustion does not produce CO<sub>2</sub>. The CO<sub>2</sub> from steam reforming can be stored in depleted offshore gas reservoirs. Hydrogen gas pipeline infrastructure could be established in the UK by 2030. The implementation of hydrogen gas can utilise a dedicated hydrogen grid or may involve a hydrogen-methane blend in the existing gas grid. Cluster projects include for developments in Leeds, which is assessing 100% hydrogen and the Liverpool-Manchester area, which is investigating a hydrogen-methane blend. The advantage of a hydrogen-methane blend is that it would involve lower costs as no new infrastructure would be required. Additional studies are underway examining how much hydrogen can be added to the existing gas network without affecting its operation. Although it is still unclear how these pathways will unfold, a combination of options are likely to occur; for example, 100% hydrogen could be used in local hydrogen grids, biomethane plants can supply the existing natural gas grid and hydrogen can also be added as a blend at safe levels to the existing network.

By 2050, it is proposed that 28% of the UK's heat could be provided by hydrogen. Overall the gas demand in the UK will rise, estimated at 130% of the 2016 levels, with 55% supplied by hydrogen. From a transport perspective, heavy goods vehicles (HGVs) and buses are also expected to be powered by hydrogen with a take up of electric vehicles (EVs) in the private car sector. At present in the UK, a two year trial has been initiated to compare a variety of gas powered trucks against their diesel fuelled counterparts. The project will act as a proof of concept, investigating factors such as vehicle performance, fuel efficiency, reliability and cost. The environmental benefits of gas powered vehicles in the potential reduction in GHG emissions will also be examined.

The UK will also see the development of a commercial bioSNG plant that can convert black bag waste into green gas suitable for grid injection. The plant will accept 10,000 t a<sup>-1</sup> of waste and produce 22GWh of gas – enough to fuel 40 trucks or heat 1,500 homes whilst achieving significant GHG emissions savings (5,000 t a<sup>-1</sup>). The technology itself can achieve between 80-190% GHG

emissions savings as compared to the fossil gas comparator depending on whether the CO<sub>2</sub> stream from the process is captured. Success in such a project will ultimately lead to further deployment of this pathway in the UK. The potential resource has been estimated at 100TWh a<sup>-1</sup> of green gas, which is equivalent to fuelling all of Britain's HGVs or supplying one third of the UK's domestic gas demand.

#### 6.4 Italy

*The following section is based on information from Bozzetto et al. (2017).*

The Italian biogas sector has grown to be the second largest in Europe (only behind Germany). In 2015, the output was 1,450 MWe, which originated from 1,900 digesters with a thermal biogas equivalent of 25 TWh (90PJ a<sup>-1</sup>). Co-digestion of crops and livestock residues are estimated to make up ca. 30-35% of the energy produced in the biogas and this figure could double by 2030. Figure 6.6 indicates the rise in biomethane resource in Italy over the last decade.

By 2030 the total biogas potential in Italy is estimated to reach 10 billion Nm<sup>3</sup> per annum accounting for agricultural crops and residues, organic municipal waste and other feedstocks. The resource is equivalent to 100TWh a<sup>-1</sup> (360 PJ a<sup>-1</sup>). Such ambition is thought to promote a more sustainable and competitive agricultural industry in Italy, lowering the fossil fuel dependency on farms and promoting the use of biofertilisers. Furthermore by 2050, the total estimated biogas resource is proposed to increase to

18.5 billion Nm<sup>3</sup> per annum with 75% of this resource coming from the co-digestion of biomass as opposed to the direct mono-digestion of crops. This resource of 185TWh (666PJ a<sup>-1</sup>) is 1.5 times the current national fossil fuel production in Italy.

To increase the resource of biomethane in Italy, gasification is once again identified as a technology of interest. Forestry materials can be diverted from direct combustion, which is deemed to have implications in terms of air pollution, and used for biomethane through gasification. However issues such as biomass procurement, technology cost and sustainability in relation to GHG emissions savings must be established prior to full technology deployment.

In Italy, PtG systems are recognised as a non-biogenic future pathway for biomethane. The potential to couple such systems with the upgrading of biogas is suggested as favourable. Other CO<sub>2</sub> sources such as flue gases from power plants and CO<sub>2</sub> from ambient air are also advocated for methanation with renewable hydrogen but are suggested to come at a higher cost.

Including for advances in technology (gasification and PtG), the total biomethane (renewable gas) yield in 2050 for Italy is estimated to be 300-350 TWh (1080–1260 PJ). This is viewed as a significant platform on which to reduce the country's reliance on fossil fuel imports whilst utilising the existing gas grid infrastructure. Figure 6.7 illustrates the potential growth in renewable gas production in Italy in the future.

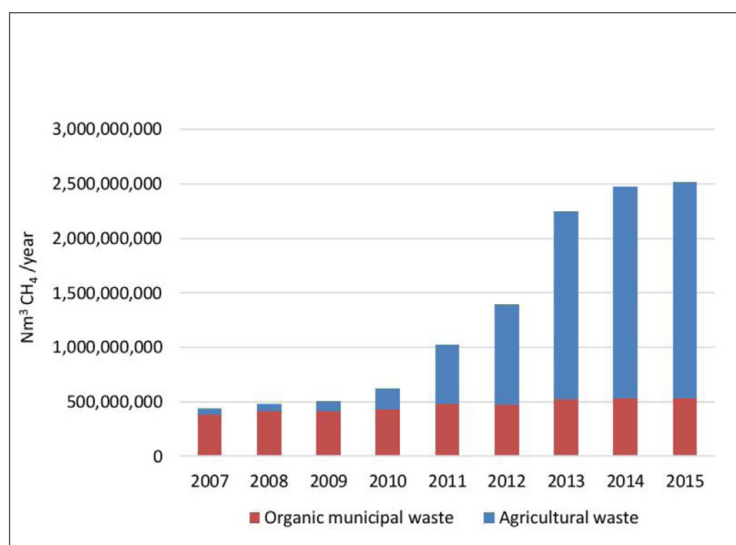


Figure 6.6 Increase in biomethane resource in Italy (Bozzetto et al., 2017)

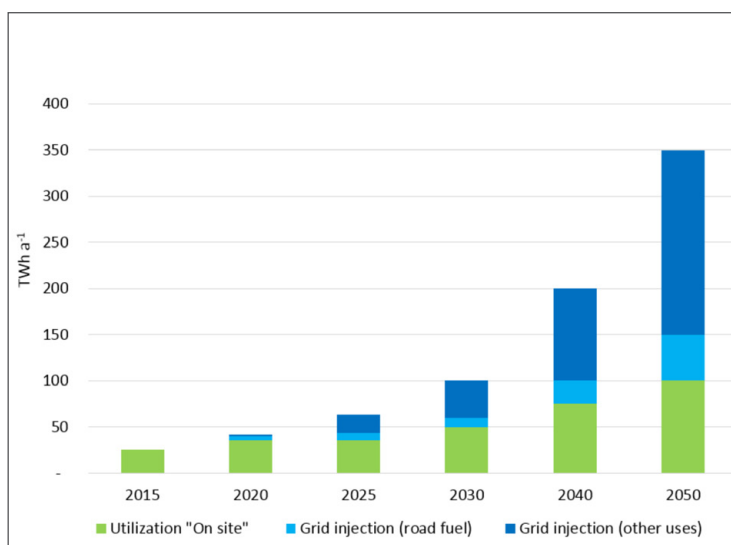


Figure 6.7 Potential future renewable gas production in Italy (Bozzetto et al., 2017)

## 6.5 Denmark

The following section is adapted from the following publications: *State of Green (2017a), (2017b), (2017c)* and includes for input from NGF Nature Energy.

The production of biogas in Denmark is rapidly increasing and is mainly based on the on-farm digestion of manure and digestion of sewage sludge in cities. A smaller number of biogas plants are industrial, or land-fill plants treating organic wastes. Biogas production in Denmark is spread throughout the country and is considered a combined process for both energy production and waste treatment. In particular, Denmark has significant potential for biomethane production due to high animal densities in rural areas and a well-developed gas infrastructure. The gas network provides for more than 400,000 households in Denmark.

Denmark also plans to exhibit one of the world's largest biogas facilities, under development by NGF Nature Energy. The facility in Korskro will boast a biomass capacity of over 1 Mt a<sup>-1</sup> producing 45.4 MW a<sup>-1</sup>, which can heat 26,000 homes. Full operation of the plant is expected in mid-2018. Currently NGF Nature Energy has 4 biogas plants in operation, with a further 12-17 domestic projects in the pipeline. Such projects typically involve securing binding long-term contracts with all major suppliers and procuring a secure source of biomass. The NGF Nature Energy plant in Holsted (20MW) has attained certification under the EU RED, which documents that the biomethane is sustainability produced from second generation biofuel sources. The plant processes 400,000 tonnes of feedstock, which includes for

agricultural waste, abattoir waste and food waste. The upgraded biogas from the plant is injected to the natural gas grid. Farmers in the surrounding area have 30% ownership of the Holsted plant, and the plant provides them with an added revenue stream (GEODE, 2016).

The total production of biogas is expected to more than triple in Denmark from 2012 to 2020, reaching a total annual production of 15 PJ. To date the majority of the produced biogas is used in electricity production. In the future it is expected that a greater share of the produced biogas will be upgraded to biomethane and delivered to the natural gas grid. Figure 6.8 shows the historical and expected future biogas production and its use in Denmark from 2012 to 2020. Already Denmark holds the highest share of green gas in Europe at 11% of natural gas consumption. Denmark has set ambitious targets to supply the existing gas grid with 100% green gas by 2035 through the use of food, industrial and agricultural wastes. If this was to happen, Denmark would become the first EU state to be 'free' of any natural gas dependency. Furthermore, the gas grid is seen as a key to the future of green energy systems in Denmark. Projects whereby decentralised systems producing renewable gas are subsequently injected to the distribution gas grid have grown significantly in recent years with 21 such developments from 2014 – 2017. Ultimately, green gas is expected to offset the equivalent of 800,000 tonnes of CO<sub>2</sub> in Denmark by 2018.

Government policy has supported the biogas industry in Denmark and this has led to some of the initial success. Continuing with the right framework condi-

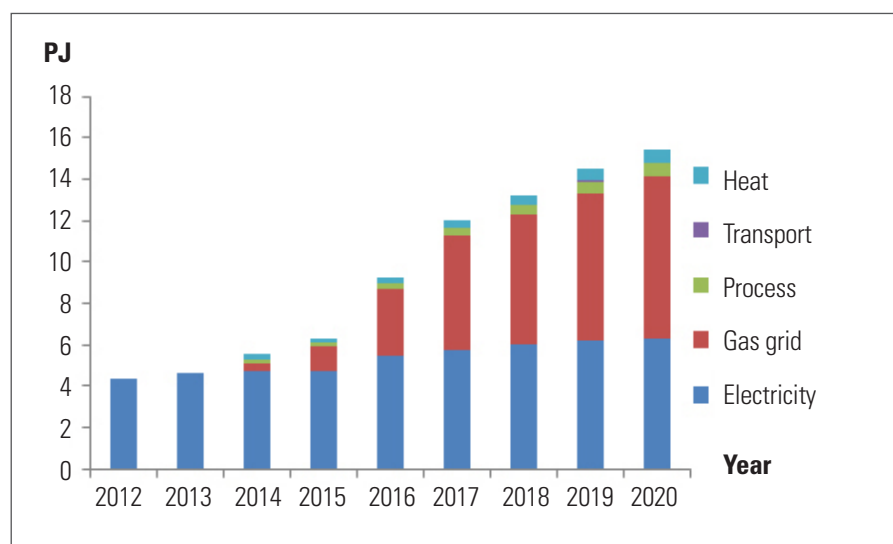


Figure 6.8 Historical and future biogas production and its use in Denmark 2012-2020. (Source: Jakob Lorenzen; Dansk Fagcenter for Biogas; Danish Energy Agency)

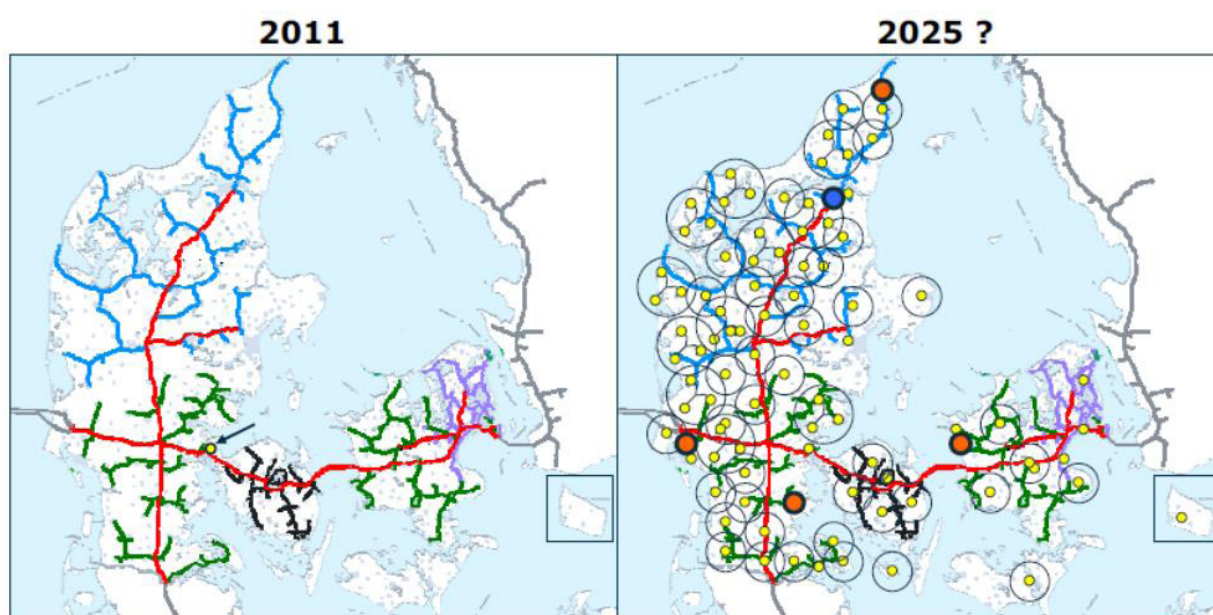


Figure 6.9 The gas grid and the future use of the gas grid with biogas plants (yellow dots) connected to the gas grid in Denmark. (Source: Jakob Lorenzen; Dansk Fagcenter for Biogas)

tions, the potential for green gas in Denmark is proposed at 72 PJ in 2035 equivalent to the expected gas consumption in the country by then. Current gas consumption is ca. 120PJ but it is estimated to decrease to 60-80PJ by 2050; this is because both district and local heating are moving away from gas technologies for a number of reasons although this may not be necessary if green gas can be provided. This resource of 72PJ is principally based on a rise in availability of manures and wastes, improved biogas production efficiencies and an increase in the digestion of straw.

The current Danish energy system is heavily based on wind power due to the historical focus on the wind power industry. Thus in the future, the Danish energy system will consist of a large amount of fluctuating power. In order to cope with this, the need for a storable (dispatchable) energy source will increase. In this case, biogas and biomethane will be an important energy source. Gas from the North Sea is currently on the decline so the focus for Denmark has been on indigenous resources, which will also mitigate any geo-political risks. Figure 6.9 illustrates the existing gas grid in Denmark and the future use of the gas grid with connected biogas plants (yellow dots).

A national initiative between three gas distribution companies HMN Naturgas, Dansk Gas Distribution and NGF Nature Energy has been developed to inform and

assist in the transition for green gas in Denmark. An investment of over €7 billion on the gas network by these three companies will continue to ensure a safe, reliable supply of gas to its consumers. The perspective in Denmark is that not one source of energy will be required going forward and that different energy sources must complement and supplement for higher efficiency; for example, gas supporting wind energy when the wind is not blowing and solar energy when the sun is not shining. There is an emphasis on integration of technologies and the gas distribution network is a key element supplying CO<sub>2</sub>-neutral gas. Accounting for more advanced technologies such as electricity storage through PtG (with methanation) could increase the resource to 100 PJ.

From a transport fuel perspective biomethane is also seen as a valuable solution in Denmark. The first CNG service station is planned for development in Odense while the first CNG project for public transport is being developed with a commercial CNG station in Fredericia.

## 7. Integration of renewable green gas systems

Integration of green gas technologies will be fundamental to providing sustainable renewable energy systems and reducing GHG emissions. The aforementioned technologies (anaerobic digestion, gasification-methanation, PtG, micro-algae biogas upgrading) and feedstocks (energy crops, agricultural residues and wastes, food waste, micro-algae, IMTA seaweed, woody crops) outlined in this report can also ensure an indigenous supply of renewable energy. By-products of the different technologies must be further amalgamated to ensure the use of the full supply chain and a circular economy. For instance, liquid digestate effluent produced from anaerobic digestion could be used as a culture medium for cultivating micro-algae. The CO<sub>2</sub> in the biogas from the same digester could be used as a carbon source for micro-algae growth. The resulting micro-algae harvest could provide feedstock for the digester. Alternatively, CO<sub>2</sub> in biogas could be directed to a biological methanation system for the benefit of PtG. The oxygen from electrolysis could be used in the gasification process with solid digestate used as feedstock. Such integration defines cascading bioenergy systems as illustrated in Figure 7.1, which facilitates greening of the natural gas grid using sustainable technologies and processes for the production of biomethane.

The most recent proposals for the recast of the EU RED has recommended a significant push for advanced biofuels to drive the reduction of GHG emissions in the energy sector. It is proposed that advanced biofuels make up at least 3.6% of all transport fuel by 2030 whilst first generation biofuels originating from food based crops are to be limited to 3.8%, down from the current limit of 7%, by 2030. The emphasis on biofuel sustainability is also addressed. Targets of 70% GHG savings are proposed for transport biofuels and 85% potentially for renewable heat compared to the fossil fuel comparator on a whole life cycle analysis basis. Through cascading bioenergy systems, biomethane can provide a sustainable renewable energy source. This will be ever more important going forward with stricter GHG emission reduction targets for biofuels.

Not all renewable gas is biogas, as described in this report a range of options exist. The integration of technologies – anaerobic digestion, gasification-methanation and PtG – as shown in Figure 7.1, should provide a platform for which the maximum quantity of green gas can be produced. On a European scale, it is reported that there is currently ca. 18 billion m<sup>3</sup> per annum of renewable gas being produced; this is approximately 4% of the total gas market

(450 billion m<sup>3</sup>). With cascading bioenergy systems the outlook for renewable gas is promising. Studies have indicated that the same gas demand will be needed in Europe in 2050 as today but that 76% of the gas could be renewable (EURATIV, 2017). This indicates significant uptake of renewable gas technologies going forward.

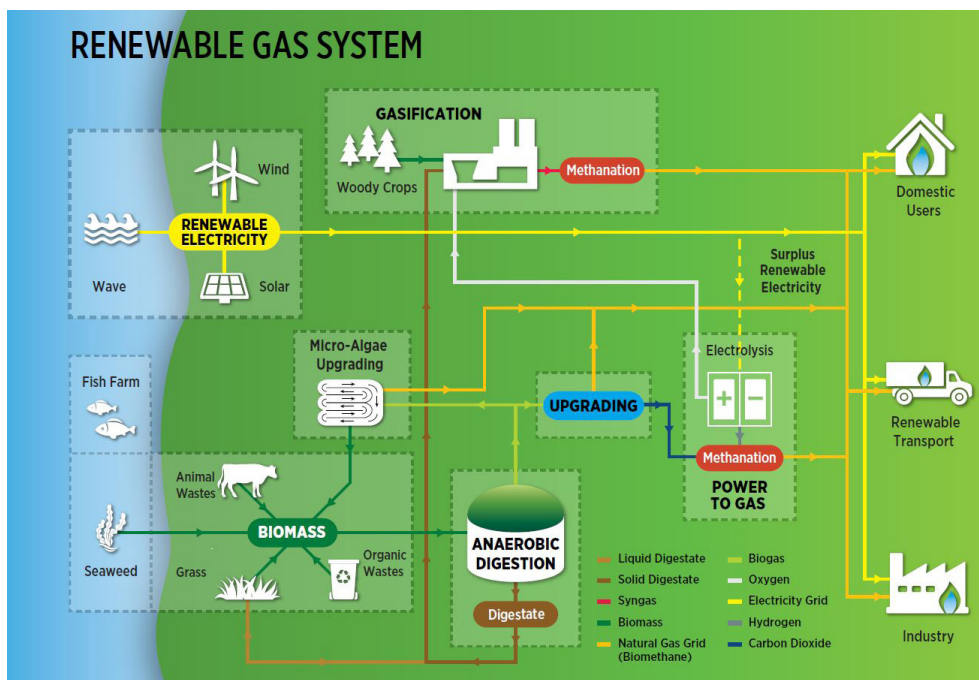


Figure 7.1 Example of a future integrated cascading biomethane energy system (Source: Green Gas Brochure, [www.MaREI.ie](http://www.MaREI.ie))



## 8. Grid injection: challenges and solutions

### 8.1 Biomethane injection to the natural gas grid

As stated, biomethane can be derived from the upgrading of biogas generated from anaerobic digestion plants or from methanation of syngas produced from gasifiers. If biomethane is to be injected to the gas grid, the specific gas quality requirements of the grid must be satisfied. The gas grid is a dynamic system in which gas is inserted and removed. In particular for the distribution grid, gas should only be injected depending on the gas consumption of the end-users connected to this specific distribution grid. Gas input and gas output must be balanced, otherwise the pressure of the system may be affected. Injection of biomethane in relatively small amounts to the grid with an existing high gas flow (such as in the transmission grid) is therefore not a big challenge in terms of holding this balance. However, in cases where relatively large amounts of biomethane are to be injected in the gas system with a comparably low gas demand, problems can become evident in grid balancing. Particular attention must be paid to the summer trough when gas demand decreases. Thus, biomethane produced locally should be injected to the grid in a decentralised manner; this is a fundamental change to traditional gas distribution systems which are developed from centralised

injection points in the grid to decentralised consumption of gas down the grid. Decentralised injection can therefore sometimes conflict with the existing infrastructure developed and with the gas demand in local situations. This gas flow is upstream oriented while traditional gas flow is downstream oriented only.

Figure 8.1 presents the case of biomethane injection to a grid at a constant flow. The gas demand will be dependent on the time of year and temperature. During winter there will be a higher gas demand than summer. In the case of the biomethane production capacity (represented by the dark green bar) it can be expected that grid injection will not conflict with gas demand at any time. However when the biomethane production increases (to the level indicated by the light green bar) then constant grid injection is not feasible anymore.

### 8.2 Approaches to balancing the gas grid in biomethane injection

A general approach for grid injection and other innovative methods that can contribute in balancing the gas grid in the case of biomethane injection are presented below.

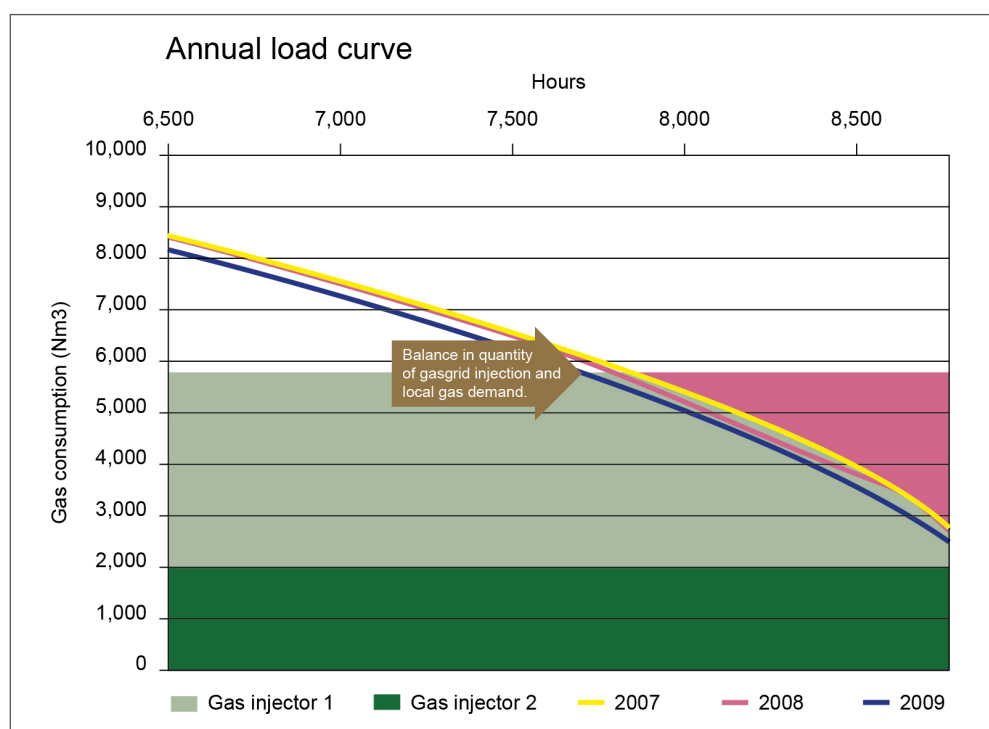


Figure 8.1 Relationship between gas consumption, annual load curve, decentralised gas points and injection levels (Source RVO; Netherlands)

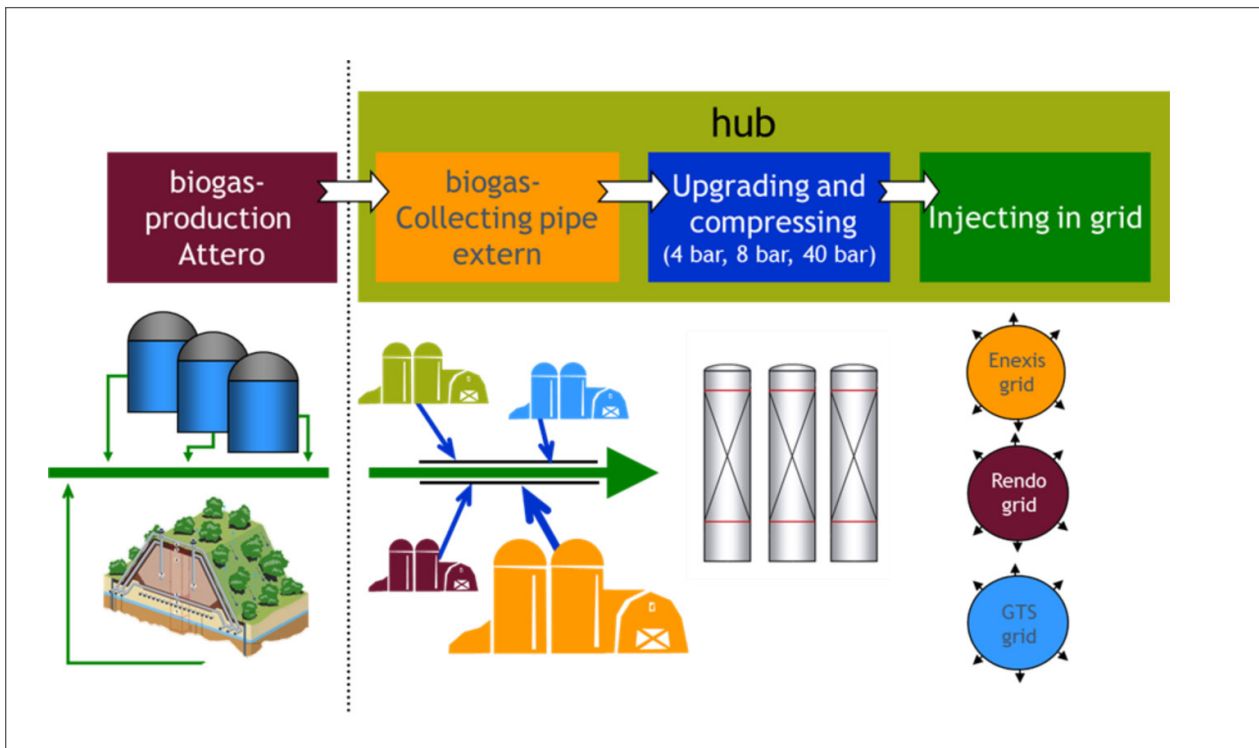


Figure 8.2 Schematic illustration of the Wijster green gas hub (from: <http://task37.ieabioenergy.com/case-studies.html>)

- Choose a logical point to connect to a gas grid: In the early stage of plant development, contact the grid operator responsible for grid connections in the region. An injection point must be chosen with a high enough gas demand during the year. This may necessitate extending the connection pipelines appropriately to the grid or connecting to a part of the gas grid with higher pressures.
- If a lengthy and expensive connection to the gas grid is required, other options may be considered. The grid operator may be able to connect some parts of the local gas grid to “increase” the gas demand. In this option the injected gas will flow to a wider area of gas consumers, thus the feed-in capacity of the biomethane plant will be able to be increased.
- It may be plausible to effect recompression of gas from a grid with lower transport capacity and lower pressure to a grid with higher pressure and gas flow. This measure will also increase the feed-in capacity for biomethane injection as a larger part of the gas grid becomes available.
- Development of biogas hubs: This approach involves a concentrated area of biogas producers in combination with a centralised biogas upgrading facility. The upgraded biogas can be injected at a higher pressure level of the gas grid with a higher gas flow. An example of this approach is the gas hub at Attero in Wijster in the Netherlands (Figure 8.2) in which several biogas facilities are combined with a single centralised upgrading facility; a number of grid injection points are operated in the distribution grid (DSO) and the transmission grid (TSO). There is also a grid connection associated with an agricultural biogas plant in proximity to this location. More connections are planned in the future. The full case study is available at the Task 37 website (<http://task37.ieabioenergy.com/case-studies.html>)
- Development of demand side management systems: An example of this is the SG3 project in which the set point of the gas pressure in the gas grid is lower during summer time. In this way a priority position for the biomethane injection can be achieved. The pressure set points of the grid are locally dependent. The set point of the lower pressure in the grid is critical. The gas demand has to be assured at all times. If the pressure drops below this set point then the valve to the TSO connection will be opened to secure the gas demand of all consumers connected to the grid.

## 9. Conclusion and Outlook

The principle of this measure is in using the storage capacity of the grid between a lower pressure level and the normal operating pressure in the grid.

- Another example of demand side management is the development of a green gas platform concept in which the grid operator can facilitate (through data transmission) between biomethane operation and gas consumption, for example, at a filling station. If the maximum level of grid injection occurs then the grid operator could transmit a signal to the filling station to open the valve to their gas storage in order to fill this storage.
- An alternative approach is the development of biogas based distribution systems. The difference with normal grid injection is that the baseload of the gas comes from biogas, which has not been upgraded. The biogas is just dried and desulphurised before use in this distribution system. The end applications should be able to operate with different calorific values of gas. If the locally available gas capacity is not enough to meet the local gas demand then natural gas can be added to this biogas distribution system. Therefore a mixing station is installed. The advantage of this system is that the costs for biogas upgrading are not necessary. This approach is applicable in new gas projects but also in areas undergoing renovation.



Figure 8.3 Biogas distribution system supplemented where necessary by natural gas injection (Source RVO; Netherlands)

Gaseous fuels have a significant role to play in future energy markets in industry (breweries, distilleries), in heating (buildings connected to the gas grid) and in transport in natural gas vehicles (NGVs). Biomethane produced from anaerobic digestion and gasification-methanation, and renewable gas from power to gas systems, can potentially achieve a large substitution of natural gas. A renewable gas industry would deliver significantly towards climate mitigation and support a renewable transition particularly in the transport and heat energy sectors, which are not as advanced as the renewable electricity sector. There is potential for a reduction in natural gas demand as an overall percentage of energy demand but to satisfy greenhouse gas reduction targets this gas will have to be decarbonised. Thus it is not essential to create a resource equivalent to present natural gas demand but to ensure those sectors, which will continue to use natural gas, use decarbonised gas.

Biomethane is presently sourced from a number of biomass sources; slurries, energy crops and food waste have already been successfully used to produce biomethane. In 2015, there were 459 biogas-upgrading plants in operation producing 1,230 M Nm<sup>3</sup> of biomethane (European Biogas Association, 2016) from these sources.

Future sources of biomethane will include macro- and micro-algae. Gasification-methanation of woody biomass can also be deployed at a much larger scale to produce renewable gas. Such technologies are at a low technology level but are being considered for future deployment.

Future innovations ideally would include for cascading bioenergy systems whereby CO<sub>2</sub> is captured and re-used leading to increased decarbonisation. These systems include for power to gas where electricity is converted to hydrogen and reacted with CO<sub>2</sub> to produce renewable methane. Micro-algae may also be used to capture CO<sub>2</sub>; the micro-algae may be used for further biomethane production or be used in a biorefinery.

Utilising all of the available deployment pathways, this report indicates that future production of green gas may account for as much as 26% of current natural gas demand in Ireland, 24% in the Netherlands, 8% in the UK, 44% in Italy and 75% in Denmark. Such levels of renewable gas indicate its importance as a future energy vector.

## References

- AHERN, E.P., DEANE, P., PERSSON, T., Ó GALLACHÓIR, B., MURPHY, J.D. 2015. A perspective on the potential role of renewable gas in a smart energy island system. *Renewable Energy*, 78, 648-656.
- ALAMIA, A., MAGNUSSON, I., JOHNSON, F., THUNMAN, H. 2016. Well-to-wheel analysis of bio-methane via gasification, in heavy duty engines within the transport sector of the European Union. *Applied Energy*, 170, 445-454.
- ALLEN, E., BROWNE, J., HYNES, S., MURPHY, J.D. 2013. The potential of algae blooms to produce renewable gaseous fuel. *Waste Management*, 33(11), 2425-2433.
- BAILERA, M., LISBONA, P., ROMEO, L.M., ESPATOLERO, S. 2017. Power to Gas projects review: Lab, pilot and demo plants for storing renewable energy and CO<sub>2</sub>. *Renewable and Sustainable Energy Reviews*, 69, 292-312.
- BOZZETTO, S., CURLISI, C., FABBRI, C., PEZZAGLIA, M., Rossi, L., Sibilla, F. 2017. The development of biomethane: a sustainable choice for the economy and the environment. Available from: <https://www.consortio-biogaz.it/wp-content/uploads/2017/05/LA-BIOGAS-REFINERY-ENG-2017-FINAL.pdf>.
- BREYER, C., TSUPARI, E., TIKKA, V., VAINIKKA, P. 2015. Power-to-Gas as an Emerging Profitable Business Through Creating an Integrated Value Chain. *Energy Procedia*, 73, 182-189.
- COLLET, P., FLOTTES, E., FAVRE, A., RAYNAL, L., PIERRE, H., CAPELA, S., PEREGRINA, C. 2016. Techno-economic and Life Cycle Assessment of methane production via biogas upgrading and power to gas technology. *Applied Energy*.
- EC. 2017. ANNEXES to the Proposal for a Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (recast) 2009/28/EC
- EC. 2016. DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the promotion of the use of energy from renewable sources. [http://eur-lex.europa.eu/resource.html?uri=cellar:3eb9ae57-faa6-11e6-8a35-01aa75ed71a1.0007.02/DOC\\_1&format=PDF](http://eur-lex.europa.eu/resource.html?uri=cellar:3eb9ae57-faa6-11e6-8a35-01aa75ed71a1.0007.02/DOC_1&format=PDF).
- ENERGY AND UTILITIES ALLIANCE. 2017. Green Gas – The low carbon solution for the future? . Available from: <https://www.eua.org.uk/uploads/5A002E205701E.pdf>.
- EURATIV. 2017. Gas lobby chief: 'In 2050, 76% of gas could be renewable'. Available from: <http://www.euractiv.com/section/energy/interview/gas-lobby-chief-in-2050-76-of-gas-could-be-renewable/>.
- EUROPEAN BIOGAS ASSOCIATION. 2016. 6<sup>th</sup> edition of the Statistical Report on European anaerobic digestion industry and markets.
- FUTURE OF GAS. 2017. Decarbonised gas: A future of gas programme sensitivity Available from: <http://future-ofgas.uk/wp-content/uploads/2017/10/Decarbonised-Gas-sensitivity.pdf>.
- GALLAGHER, C., MURPHY, J.D. 2013. What is the realistic potential for biomethane produced through gasification of indigenous Willow or imported wood chip to meet renewable energy heat targets? *Applied Energy*, 108, 158-167.
- GEODE. 2016. A sustainable Europe: green gas, green grids, green future. Available from: <https://drive.google.com/file/d/0BwfOJcyMDSzZT3NkaW5LaTJ2NUU/view>.
- GÖTZ, M., LEFEBVRE, J., MÖRS, F., McDANIEL KOCH, A., GRAF, F., BAJOHR, S., REIMERT, R., KOLB, T. 2016. Renewable Power-to-Gas: A technological and economic review. *Renewable Energy*, 85, 1371-1390.
- GREEN GAS FORUM. 2014. Green gas roadmap - Netherlands. Available at: <https://www.ecn.nl/publicaties/Pdf-Fetch.aspx?nr=ECN-O--15-058>.
- HERRMANN, C., FITZGERALD, J., O'SHEA, R., XIA, A., O'KIELY, P., MURPHY, J.D. 2015. Ensiling of seaweed for a seaweed biofuel industry. *Bioresource Technology*, 196, 301-313.
- HERRMANN, C., KALITA, N., WALL, D., XIA, A., MURPHY, J.D. 2016. Optimised biogas production from microalgae through co-digestion with carbon-rich co-substrates. *Bioresource Technology*, 214, 328-337.
- HOWLEY, M., HOLLAND, M. 2016. Energy in Ireland 1990 – 2015. Available at: [http://www.seai.ie/Publications/Statistics\\_Publications/Energy\\_in\\_Ireland/Energy-in-Ireland-1990-2015.pdf](http://www.seai.ie/Publications/Statistics_Publications/Energy_in_Ireland/Energy-in-Ireland-1990-2015.pdf).
- IEA Bioenergy Task 40 and Task 37. 2014. Biomethane Status and Factors Affecting Market Development and Trade. IEA Bioenergy.
- IEA Task 37 Energy from Biogas. 2016. Upgrading Plant List 2016. Available at: <http://task37.ieabioenergy.com/plant-list.html>.
- KAMPMAN, B., LEGUIJT, C., SCHOLTEN T. 2017. Optimal use of biogas from waste stream. An assessment of the potential of biogas from digestion in the EU beyond

2020. Available online at: [https://ec.europa.eu/energy/sites/ener/files/documents/ce\\_delft\\_3g84\\_biogas\\_beyond\\_2020\\_final\\_report.pdf](https://ec.europa.eu/energy/sites/ener/files/documents/ce_delft_3g84_biogas_beyond_2020_final_report.pdf).
- LIEBETRAU, J., REINELT, T., AGOSTINI, A., LINKE, B. 2017. Methane emissions from biogas plants -Methods for measurement, results and effect on greenhouse gas balance of electricity produced. *IEA Bioenergy: Task 37*: 2017: 12.
- MCENIRY, J., CROSSON, P., FINNERAN, E., MCGEE, M., KEADY, T.W.J., O'KIELY, P. 2013. How much grassland biomass is available in Ireland in excess of livestock requirements? *Irish J Agr. Food. Res.*, 52: 67–80.
- MURPHY, J.D., DROSG, B., ALLEN, E., JERNEY, J., XIA, A., HERRMANN, C. 2015. A perspective on algal biogas. *IEA Bioenergy*.
- O'SHEA, R., WALL, D.M., MCDONAGH, S., MURPHY, J.D. 2017. The potential of power to gas to provide green gas utilising existing CO<sub>2</sub> sources from industries, distilleries and wastewater treatment facilities. *Renewable Energy*, 114, 1090-1100.
- O'SHEA, R., KILGALLON, I., WALL, D., MURPHY, J.D. 2016a. Quantification and location of a renewable gas industry based on digestion of wastes in Ireland. *Applied Energy*, 175, 229-239.
- O'SHEA, R., WALL, D., KILGALLON, I., MURPHY, J.D. 2016b. Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise. *Applied Energy*, 182, 394-408.
- O'SHEA, R., WALL, D., MURPHY, J.D. 2016c. Modelling a demand driven biogas system for production of electricity at peak demand and for production of biomethane at other times. *Bioresource Technology*, 216, 238-249.
- PARRA, D., PATEL, M.K. 2016. Techno-economic implications of the electrolyser technology and size for power-to-gas systems. *International Journal of Hydrogen Energy*, 41(6), 3748-3761.
- PERSSON, T., MURPHY, J.D., JANNASCH, A.K., AHERN, E., LIEBETRAU, J., TROMMLER, M., TOYAMA, J. 2014. A perspective on the potential role of biogas in smart energy grids. *IEA Bioenergy, Task 37*.
- QADRAN, M., ABEYSEKERA, M., CHAUDRY, M., WU, J., JENKINS, N. 2015. Role of power-to-gas in an integrated gas and electricity system in Great Britain. *International Journal of Hydrogen Energy*, 40(17), 5763-5775.
- REUTERS. 2017. Engie plans to go green via biogas and renewable hydrogen. Available from: <https://www.reuters.com/article/us-engie-biogas/engie-plans-to-go-green-via-biogas-and-renewable-hydrogen-idUSKBN1DY22D>.
- SCHIEBAHN, S., GRUBE, T., ROBINIUS, M., TIETZE, V., KUMAR, B., STOLTEN, D. 2015. Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. *International Journal of Hydrogen Energy*, 40(12), 4285-4294.
- SEAI. 2017. Assessment of Cost and Benefits of Biogas and Biomethane in Ireland.
- STATE OF GREEN. 2017a. The Danish gas grid could be filled with green gas in 2035. Available from: <https://stateofgreen.com/en/profiles/state-of-green/news/the-danish-gas-grid-could-be-filled-with-green-gas-in-2035>.
- STATE OF GREEN. 2017b. New initiative focuses on the role of gas in the green transition. Available from: <https://stateofgreen.com/en/profiles/state-of-green/news/new-initiative-focuses-on-the-role-of-gas-in-the-green-transition>.
- STATE OF GREEN. 2017c. The world's largest biogas facility is being built in a gravel pit in Denmark. Available from: <https://stateofgreen.com/en/profiles/state-of-green/news/the-world-s-largest-biogas-facility-is-being-built-in-a-gravel-pit-in-denmark>.
- TABASSUM, M.R., XIA, A., MURPHY, J.D. 2017. Potential of seaweed as a feedstock for renewable gaseous fuel production in Ireland. *Renewable and Sustainable Energy Reviews*, 68, 136-146.
- TSUPARI, E., KÄRKI, J., VAKKILAINEN, E. 2016. Economic feasibility of power-to-gas integrated with biomass fired CHP plant. *Journal of Energy Storage*, 5, 62-69.
- VO, T.T.Q., XIA, A., WALL, D.M., MURPHY, J.D. 2017. Use of surplus wind electricity in Ireland to produce compressed renewable gaseous transport fuel through biological power to gas systems. *Renewable Energy*, 105, 495-504.
- WALKER, S.B., MUKHERJEE, U., FOWLER, M., ELKAMEL, A. 2016. Benchmarking and selection of Power-to-Gas utilizing electrolytic hydrogen as an energy storage alternative. *International Journal of Hydrogen Energy*, 41(19), 7717-7731.
- ZHU, L., YAN, C., LI, Z. 2016. Microalgal cultivation with biogas slurry for biofuel production. *Bioresource Technology*, 220, 629-636.

# IEA Bioenergy

## Task 37 - Energy from Biogas

IEA Bioenergy aims to accelerate the use of environmentally sustainable and cost competitive bioenergy that will contribute to future low-carbon energy demands. This report is the result of the work of IEA Bioenergy Task 37: Energy from Biogas.

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