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Global Potential of Biogas

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"By coming together as an industry, we can drive the change needed to make anaerobic digestion and biogas thrive. Our mission is clear: to raise global awareness of biogas technologies and encourage their uptake as solutions to the challenges of our times."

David Newman, President
World Biogas Association

WORLD BIOGAS ASSOCIATION

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Lead Author
Dr Sarika Jain

Contributors
David Newman
Ange Nizhou
Harmen Dekker
Pharoah Le Feuvre
Hannah Richter
Frederic Gobe
Charlotte Morton
Rebecca Thompson

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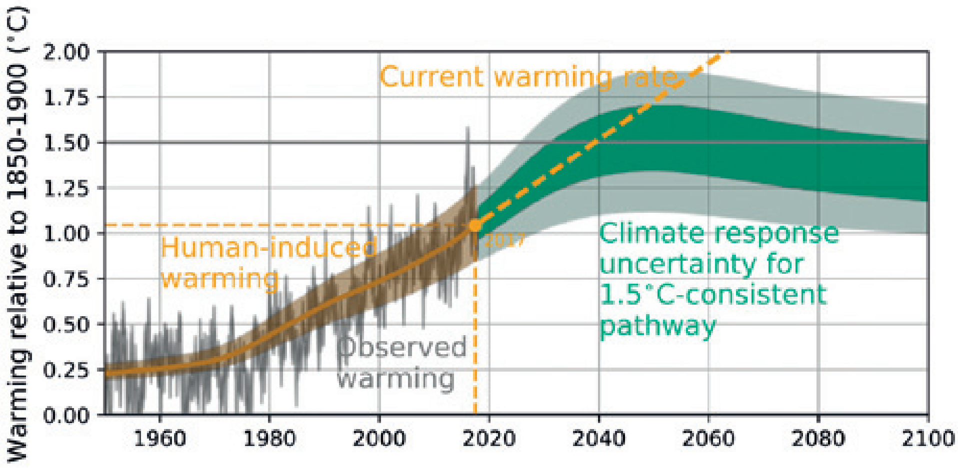
1. Introduction

1.1 Context

We are living in the Anthropocene, the era of Man. It may well be the shortest era ever if we continue to disregard the planetary limits to well-being – biodiversity loss; massive pollution from (among other wastes) plastics; desertification; intensification of weather events; loss and pollution of fresh water; and deforestation. These are all either a result of or contributing to climate change.

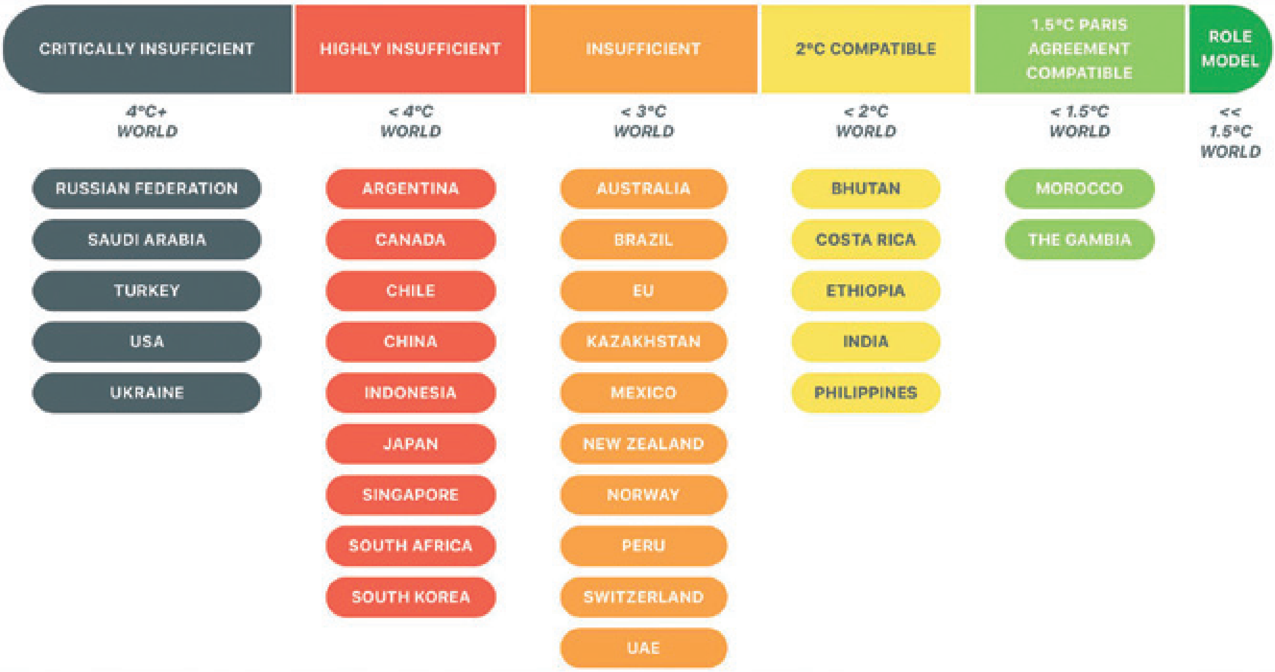
The United Nations' IPCC Special report of 2018 gives us until 2030 before climate change becomes irreversible. We will have emitted enough carbon into the atmosphere to render attempts to keep global temperature rises below 2°C by 2100, the target of the Paris Accords, impossible. That same report illustrates how a world which is on average 2°C hotter will be a hostile environment for many millions of the planet's inhabitants. Further evidence was provided by the US National Oceanic and Atmospheric Administration in May 2019 reporting that global atmospheric methane levels have risen from 1650ppb in 1985 to over 1860ppb today and continue to rise.



Source: IPCC Special Report on Global Warming of 1.5°C, Chapter 1 – Technical Annex 1.A, Fig. 12

A growing sense of urgency has led to the UK being one of the first countries to declare a 'climate emergency' and to legally commit to net zero emissions by 2050; a similar declaration from the Scottish Government and many local governments around the globe on the climate emergency shows the list is growing, as you can see here **https://climateemergencydeclaration.org**

The pressure is building upon governments to improve their climate policies but there is still an awful gap between what is needed and what we are committing to. Indeed, on one calculation just two nations globally are on track to implement policies that limit global warming to 1.5°C by 2100: Morocco and the Gambia. Even the EU nations are collectively on track for a 3°C temperature rise by 2100, not comforting news for those of us who live in Europe and believe in a somewhat self-congratulatory way that we are leading on the issue.



Source: Climate Action Tracker November 2017

The message is that wherever you are, whatever you do, there is now no time to lose to reduce your carbon footprint dramatically. Every industry, policymaker and individual must now look at what they can do to mitigate climate change.

This report aims to highlight the potential of anaerobic digestion as a technology to generate renewable energy, abate GHG emissions and recover nutrients, as well as the role it can play in meeting the climate change targets under the Paris Agreement.

Our industry is already leading in reducing GHG emissions by capturing the methane that would otherwise have entered the atmosphere from rotting food waste, sewage, farm wastes and agri-industrial process wastes. Capturing this methane and transforming it into electricity, heat or fuel are processes that have matured and are rolled out in many countries on small and large scale. However, there is a great deal more potential to absorb uncontrolled greenhouse gasses as well as reduce reliance on fossil fuels to produce energy. This report shows we are currently capturing approximately just 2% of the global potential.

While making these contributions the biogas industry can also help provide food security, manage waste, protect water bodies, restore soil health, improve air quality, promote health and sanitation and provide employment. As humanity urbanises, the health of billions of humans depends upon managing waste correctly in cities and our industry is one of the solutions to doing so, especially urban food waste and sewage.

1.2 Anaerobic digestion

Anaerobic digestion (hereafter AD) is a series of biological processes in which micro-organisms digest plant and/or animal material in sealed containers, producing biogas, which is a mixture of methane, carbon dioxide and other gases. The organic material left over, known as digestate, is rich in organic matter and nutrients such as nitrogen, phosphate and potash.

An on-farm anaerobic digester plant showing the gas storage tank and digesters[1]

A wide range of organic matter, such as domestic and commercial food waste, municipal and industrial sewage, agricultural material and livestock manures, can be treated in such plants to produce energy both at small scale (e.g. households and farms) and large scale (for entire cities).

For this report, 'organic matter' means any material derived from recently living organisms.

The purpose of AD is to produce biogas and nutrients. Biogas contains methane and it is the combustion of methane which constitutes the energy component of biogas. This energy may be used in many different ways:

- Combusted directly in domestic stoves for cooking or used in gas lamps, for lighting, after minor treatment

Source: Bioenergy International[2]

- Combusted in boilers to generate heat; internal or external combustion engines to produce electricity; combined heat and power (CHP) plants to produce both heat and electricity; and tri-generation systems to provide cooling via absorption chillers in addition to heat and electricity.

Source: Clarke Energy

[1] www.afbini.gov.uk/publications/farm-small-scale-anaerobic-digestion-event

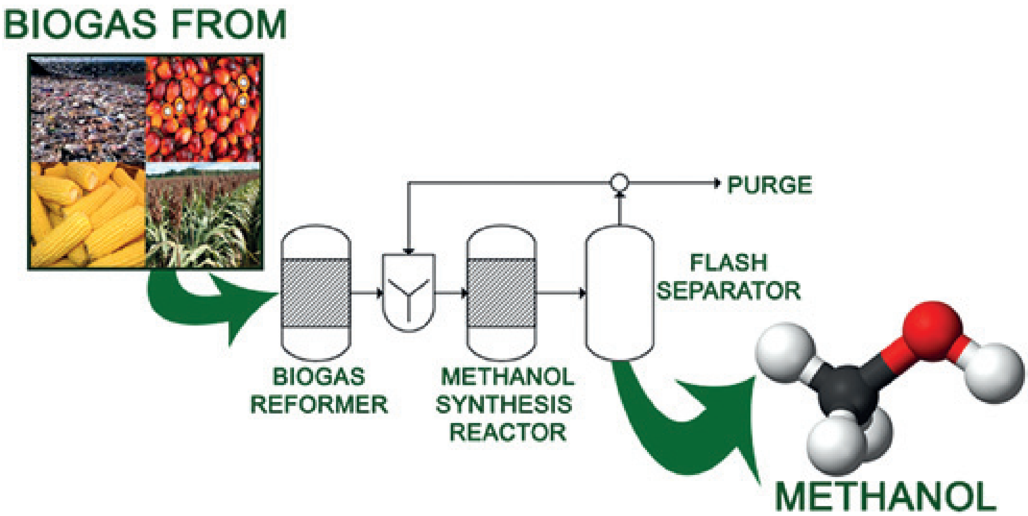
[2] https://bioenergyinternational.com/biogas/shift-biogas-helps-revive-forests-india

- Upgraded into biomethane to be used as vehicle fuel in gas-powered vehicles; to be used in place of natural gas in industrial, commercial and domestic uses; or pumped into gas grids to substitute natural gas supplied to households and businesses

Source: Bristol City Council

- Carbon dioxide may be extracted for commercial use, for example as a feedstock in greenhouses or for reconversion into fuels.

- Processed into higher value products such as bioplastics or biochemicals.



Source: Santos, Santos and Prata (2018)[3]

A co-product of the AD process is a material called 'digestate' or natural fertiliser, containing water, nutrients and organic carbon suitable for soils. Digestate is the remaining part of the feedstock originally fed into the digester once the gas is extracted. The digestate may be used as a bio-fertiliser and applied to land as 'whole digestate', composted, or separated into liquid and solid fractions before being applied to land. Elemental fertilisers may also be extracted from digestate for more targeted applications.

Source: Farmers Weekly UK, 10 February 2016

[3] www.sciencedirect.com/science/article/pii/S0959652618307698

1.3 Benefits of anaerobic digestion

Our industry is acutely aware of its responsibilities yet is often reticent to talk about its many, diverse benefits. We have to take responsibility for ensuring that our plants are run efficiently, respecting the highest health and safety standards and reducing potential gas leakages. At the same time, we need to make sure that the wider world understands the benefits our industry can bring to the debate around sustainability. A WBA factsheet on how the industry contributes to achieving the Sustainable Development Goals is available on our website[4].

Many of the UN Sustainable Development Goals, including 2, 3, 5, 6, 7, 9, 11, 13 and 15 can be partially or wholly achieved through the application of AD technologies. The treatment of organic waste through AD has multiple benefits in the form of:

RENEWABLE ENERGY PRODUCTION:

- Production of baseload energy for sustained energy use;
- Production of energy that can be stored and used to meet peak load demand;
- Generation of electricity for injection into the electricity grid;
- Off-grid, localised energy production for on-site use;
- Enhanced energy security from domestic sources;
- Reduced dependence on fossil-fuel energy;
- Generation of heat from CHP units within biogas plants;
- Generation of biomethane for vehicle fuel; and
- Generation of biomethane for onsite, local or injection into the natural gas distribution network.
- Generation of energy in combination with other forms of power generation, e.g. together with wind and solar power
- Energy storage: biogas can be stored for use when needed acting as a "battery" to accompany intermittent renewables such as wind and solar.

CLIMATE CHANGE MITIGATION:

- Reduced greenhouse gas emissions and particulate emissions by substituting fossil fuels such as coal and oil as energy supplies to buildings, homes and industry;
- Reduced greenhouse gas emissions from vehicles by substitution of diesel and gasoline with biomethane as fuel;
- Reduction of uncontrolled methane emissions in dumps and landfills and generation of renewable energy from untreated food and other organic wastes;
- Capture of biogas from landfills avoiding methane emissions;
- Substitution of synthetic and mineral fertilisers with digestate bio-fertiliser;
- Reduction of deforestation by replacing solid-biomass-based domestic fuels with biogas; and
- Using digestate to restore the carbon storage and sequestration capacity of soils.

CONTRIBUTING TOWARDS A CIRCULAR ECONOMY:

- Improving the self-sufficiency and sustainability of industries by extracting the energy from their own effluents and using it for the self-generation of electricity and/or heat; and
- Recirculating nutrients and organic matter in organic wastes through AD and returning them to the soil in the form of digestate bio-fertiliser.

IMPROVING URBAN AIR QUALITY:

- Substituting biomethane for fossil fuel in vehicles;
- Substituting biogas for solid fuel for domestic cooking and heating;
- Avoiding the uncontrolled release of methane from landfills, which then acts as an ozone precursor in the atmosphere, deteriorating air quality.

CONTRIBUTING TOWARDS FOOD SECURITY:

- Restoring soils through the recycling of nutrients, organic matter and carbon;
- Decreasing dependence upon inorganic fertilisers
- Recirculating phosphorus, which is essential for the growth of plants.

[4] www.worldbiogasassociation.org/factsheet-3-how-to-achieve-the-sustainable-development-goals-through-biogas-2017

IMPROVING HEALTH AND SANITATION THROUGH BETTER SOLID WASTE MANAGEMENT:

- Treating and recycling organic wastes to reduce odours and the spread of diseases from uncontrolled dumping;
- Preventing spread of diseases through collection and proper management of organic waste;
- Improving sanitation and hygiene through decentralised and local treatment of organic and sewage waste;
- Protecting water bodies;
- Reducing the carbon load of wastewater to reduce impact on water bodies.

ECONOMIC DEVELOPMENT AND JOB CREATION

- Generating short-term construction employment and long-term equipment manufacturing and maintenance employment, as well as plant operations employment;
- Encouraging growth of new enterprises by providing reliable electricity that can be stored and used when needed, i.e. baseload energy;
- Generating employment in the waste sector by collecting food and other biogenic wastes separately and through sales of digestate; and
- Improving quality of life in marginal farming communities and reducing migration from these by improving crop yields and sanitation, lighting and heating.

In addition to contributing to the United Nations Sustainable Development Goals, the AD of organic waste has the following advantageous characteristics:

- **DIVERSE AND LOCAL FEEDSTOCK** – AD is a flexible process and can take multiple, locally available feedstocks in varying quantities, including household food waste, abattoir waste, brewery slops, fruit waste and palm oil mill effluents. It must be noted that some operational aspects of a biogas plant need to be adjusted for variation in feedstock to sustain the biological process and optimum gas production.
- **FLEXIBILITY OF SCALE** – AD has no minimum scale of implementation and its maximum scale is limited only by the amount of feedstock available within feasible distances. AD can provide anything from cooking gas for one family to baseload energy for a manufacturing facility, depending on the size of the plant and feedstock. It can be implemented to digest food waste of a family, community, restaurant, industry or city.
- **FLEXIBLE USE OF BIOGAS** – Biogas can be utilised in a way that is most beneficial for the generator. If the plant is built onto a distillery, biogas produced can be used to generate heat; if the plant is run on municipal food waste, then the biogas can be upgraded and used as fuel for collection vehicles or local public transport buses; if there is a need for electricity, the best use may be generation of electricity via a CHP engine.
- **MULTIPLE REVENUE STREAMS** – Each of the products and by-products of AD – electricity, heat, cooling, biomethane, carbon dioxide, digestate and elemental fertiliser – can be a revenue stream. For example, a biogas plant employing a CHP engine can generate income or reduce expenditure from the electricity and heat generated and the digestate produced. Similarly, a biogas plant upgrading biogas to biomethane can generate income from the biomethane and also potentially from carbon dioxide and digestate.

The report presents the global potential for energy generation, greenhouse gas abatement and nutrient recovery via anaerobic digestion of waste and sustainably grown energy crops. We recognise that measuring many of these diverse inputs and outputs is subject to some degree of variation.

The report begins with introducing the anaerobic digestion technology and its outputs. It then presents data on where the current status in implementing this technology globally. This is followed by an analysis of five widely available feedstocks for anaerobic digestion: livestock manure, sewage, food waste, crop residues and energy crops. It is followed by an analysis of what can be achieved collectively by the industry if the technology is deployed to its full potential.

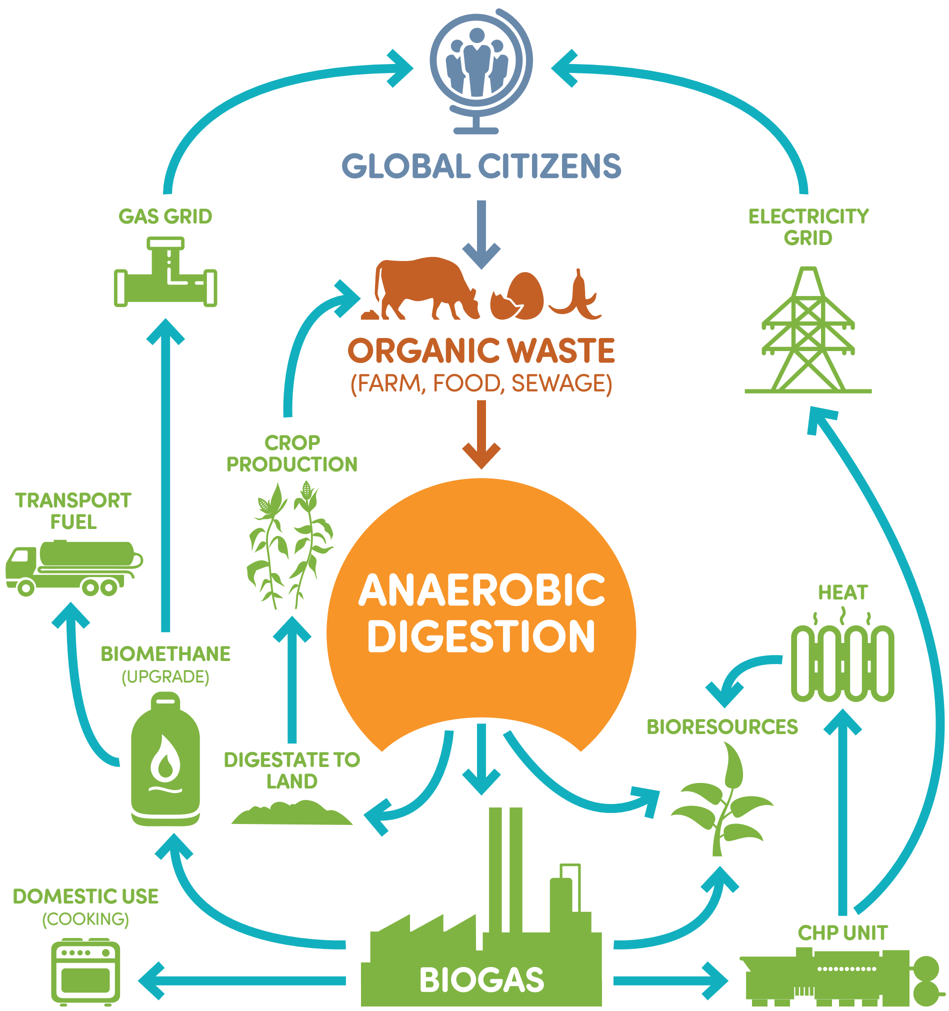
1.4 Anaerobic digestion technology and its outputs

A biogas plant consists of a reception area, where the feedstock from various sources is received. The waste resides in the reception area for some hours whilst it is loaded into the next stage: pre-treatment.

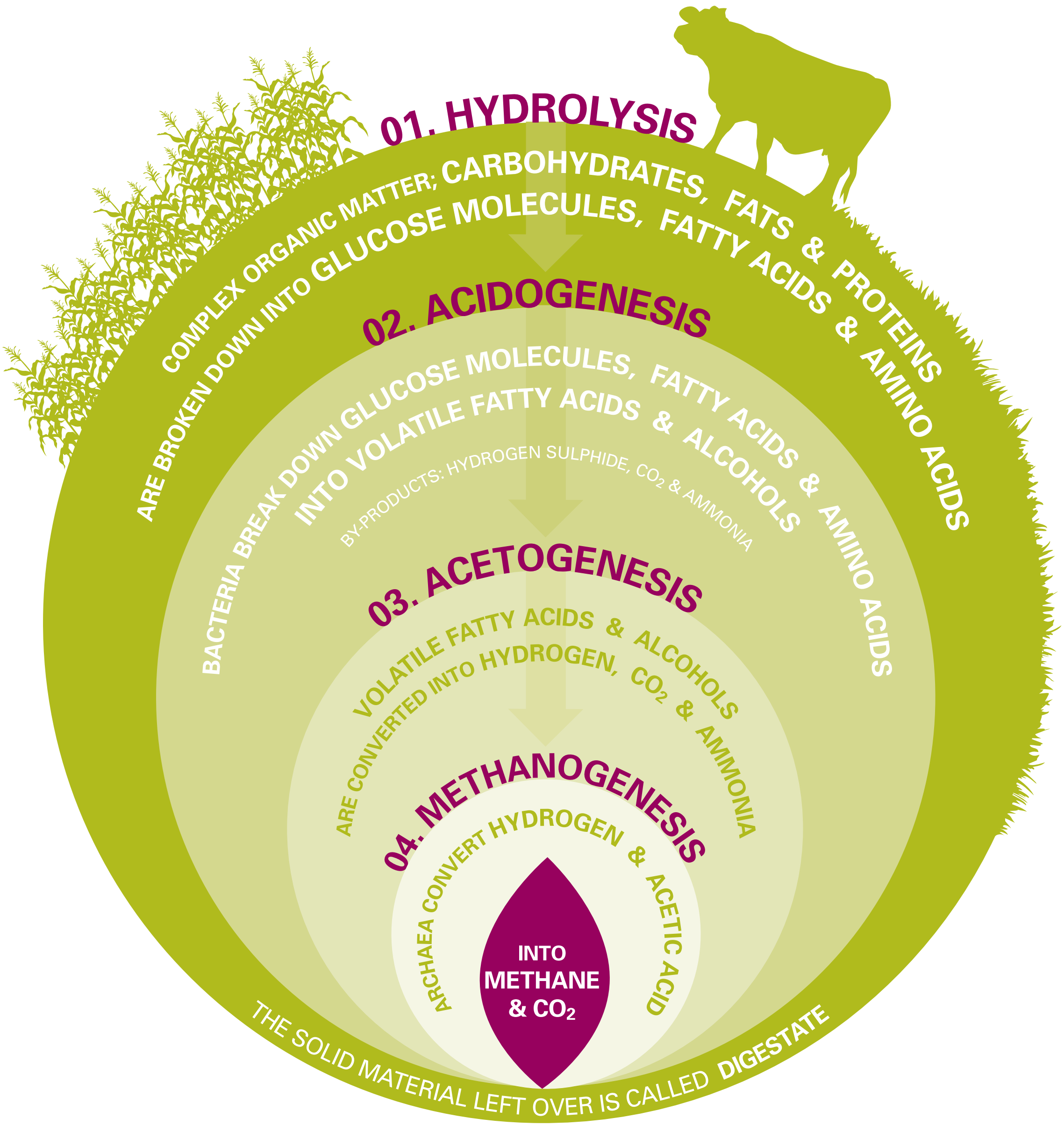
This generally involves washing, maceration of the feedstock, screening and pressing depending on the feedstock. Packaging, such as plastic bags, is stripped out, while any metallic items such as cutlery may be removed using magnetic devices to prevent damage to moving parts. In addition, grit (such as glass, egg shells, ceramics, bones and sand) may need to be removed at the pre-treatment stage, if the digester does not have an internal capability of extracting these. If not removed, grit may build up at the bottom of the tank over a period of time leading to loss of volume and failure of the system.

After the pre-treatment process, the feedstock is fed to the digester where it undergoes decomposition in the absence of oxygen. This process can take place at different operating temperatures and system set-ups. During this process, biogas is released and collected in biogas storage tanks or in an inflatable dome. To reduce the sulphur content in biogas, it is piped to a desulphurisation unit. The biogas, which is rich in methane, may be processed further depending upon the desired end use: electricity, heat, cooling or vehicle fuel. Within the digester, the organic material that is left over after digestion, or digestate, is extracted and may then undergo pasteurisation, followed by composting or separation of wet and dry solids for application to agricultural land, depending on the use and regulations of the jurisdiction.

The AD process is shown in Figure below:



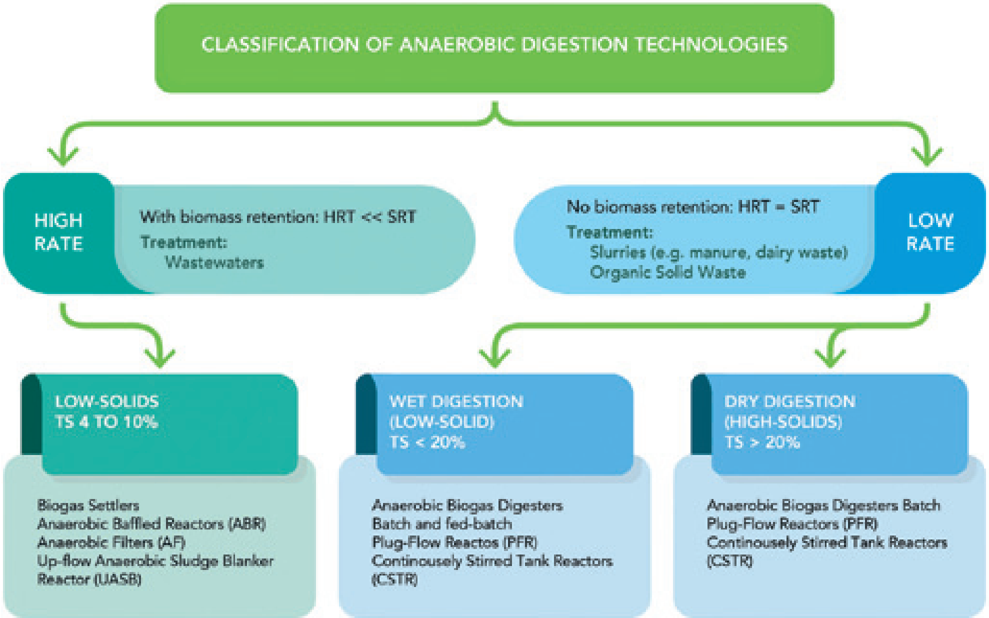
Many different types of anaerobic digesters are available. These vary in configuration, retention time, pre- and post-treatment requirements and operating temperature among other things, depending upon the principal feedstocks being treated. During AD, the breakdown of organic compounds is achieved by a combination of many types of bacteria and archaea (microbes). The biomass added to the digester is broken down into sugars, amino acids and fatty acids (hydrolysis), fermented to produce volatile fatty acids and alcohols (acidogenesis) followed by the conversion into hydrogen, carbon dioxide and ammonia and, finally, methanogens produce biogas from acetic acid and hydrogen.



Source: ADBA Practical Guide to AD

Anaerobic digestion takes place at two optimum temperature ranges, 35-40°C (mesophilic) and 55-60°C (thermophilic). Most AD plants around the world operate in the mesophilic range as less heat is required to maintain that temperature and also the digestion process is more stable under these conditions. Thermophilic reactors, though requiring greater attention to operate, are sometimes installed as they accelerate degradation rates, creating higher yields of biogas and reduce pathogens in the digestate produced.

Based on the constituents and consistency of the food waste treated, an anaerobic digester can be designed as a 'wet', 'dry', 'liquid' or 'co-digestion' system. The figure below provides information about these configurations.



The pre-treatment needed, digester configurations, operating temperature, need for pasteurisation and utilisation of biogas and digestate all vary based on type and quality of feedstock, climate and local economy. Each digester is, hence, designed and optimised individually.

1.5 Current status of the biogas industry

Although there is already a wide application of biogas technologies around the world the industry is still in its initial stages of development. The current status of the industry and the deployment of technology is discussed below.

The biogas industry can be analysed in 3 broad categories: micro digesters using biogas, scale digesters generating electricity and scale digesters producing biomethane.

MICRO DIGESTERS

Micro digesters have been used for at least several centuries. Indeed, if we go back in ancient history, we will find elementary biogas production during the Assyrian Empire 3000 years ago whilst more recognisably modern applications began to develop during the 17th century.

Micro digesters play a very important role in rural areas of developing countries, where they are an integral part of farming, waste management and energy security. There is a total of close to 50 million of micro-scale digesters operating around the globe with 42 million[5] operating in China[6] and another 4.9 million in India[7]. 700,000 biogas plants are estimated to have been installed in rest of Asia, Africa and South America[8].

[5] www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Dec/IRENA_Biogas_for_domestic_cooking_2017.pdf
[6] www.mdpi.com/1996-1073/12/3/429/htm
[7] www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf
[8] www.snv.org/sector/energy/topic/biogas

A small community biogas digester being installed in Uganda[9].

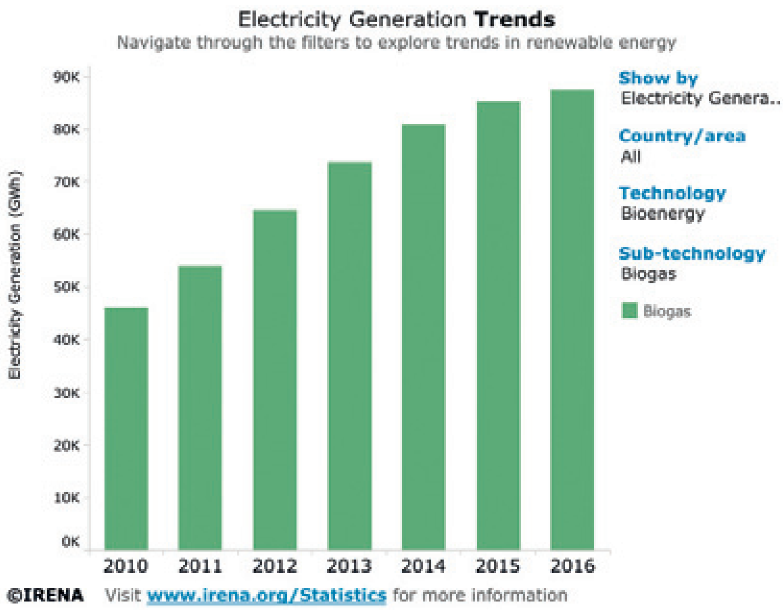
The biogas from micro-scale digesters is most often used in stoves for cooking or heating, displacing solid, high emission fuels like firewood and charcoal. A cumulative 50 million biogas stoves are used by about 126 million people for cooking primarily in China (112 million) and India (10 million). China produced 13 million cubic metres of biogas from digester installations for cooking in 2016, and India for 2 million cubic metres.[10]

SCALE DIGESTERS GENERATING ELECTRICITY

Generation of electricity from biogas is an established technology which has been widely implemented around the globe. This is most commonly done with a CHP engine with some form of heat recovery and use. A CHP engine can be linked to any operating anaerobic digester. For it to be economic, a CHP engine requires a minimum size. Operators of biogas plants are trying to maximise efficiency and income streams by increasing the utilisation of heat. There is also a growing interest in trigeneration which generates electricity, heat and cooling when needed.

In addition to the millions of micro digesters, there are a total of 110,448 biogas systems operating in China of which 6,972 are large scale (2015)[11]. Europe has 17,783 plants with 10.5 GW installed capacity (2017). Germany is the leader in the European market with 10,971 plants followed by Italy (1,655), France (742), Switzerland (632) and the UK (613)[12]. 2,200 anaerobic digesters with an installed capacity of 977MW operate in the USA[13]. The estimated biogas based installed capacity in India is 300MW[14]. Canada has about 180 digesters with 196 MW installed capacity[15]. On the basis of these numbers, it is estimated that there is a total of around 132,000 small, medium or large-scale digesters operating in the world.

The biogas industry is growing globally. IRENA statistics on global electricity generation from biogas show that it has grown from 46,108 GWh in 2010 to 87,500 GWh in 2016[16]. That is a 90% growth in six years.



[9] www.facebook.com/biodigesteruganda/

[10] www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf

[11] www.oav.de/fileadmin/user_upload/2_Termine/Allgemein/biogas_development_in_China.pdf

[12] EBA Statistical Report 2018

[13] World Biogas Association (2017) Market report - USA

[14] www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf

[15] https://biogasassociation.ca/index.php/about_biogas/projects_canada

[16] www.irena.org/bioenergy

MEDIUM TO LARGE SCALE DIGESTERS UPGRADING TO BIOMETHANE

Upgrading of biogas to biomethane is relatively new but now a proven technology. While some plants upgrade biogas to be used as vehicle fuel, others inject it into the local or national grids. Plants are also beginning to capture CO_2 to be used in greenhouses and the food and drinks industry. There are over 540 upgrading plants operating in Europe with 195 in Germany, 92 in the UK, 70 in Sweden, 44 in France, and 34 in the Netherlands[17]. Outside of Europe, there are about 50 in the USA[18], 25 in China[19], 20 in Canada[20] and a few in Japan, South Korea, Brazil and India. Based on the data available, it is estimated that 700 plants upgrade biogas to biomethane globally.

The biogas sector employs an estimated 344,000 people directly or indirectly[21].

Having presented a high-level picture of where the industry stands at present, in the following chapters of the report, an analysis is presented of the potential contribution that the anaerobic digestion technology can give to energy and food security and greenhouse gas (GHG) abatement at a global level, first by feedstock and then collectively.

A sophisticated mathematical model has been developed to calculate the contributions of the various feedstocks and we can share this with researchers and academics upon specific request.

[17] http://biogas.org.rs/wp-content/uploads/2018/12/EBA_Statistical-Report-2018_European-Overview-Chapter.pdf

[18] http://task37.ieabioenergy.com/plant-list.html

[19] www.oav.de/fileadmin/user_upload/2_Termine/Allgemein/biogas_development_in_China.pdf

[20] https://biogasassociation.ca/index.php/about_biogas/projects_canada

[21] www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf

2. Livestock Manure

2.1 Key Findings

- If all 'available' livestock manure from cattle, buffaloes, pigs and chickens were to be collected and anaerobically digested, it has the potential to generate 2,600 to 3,800 TWh of energy globally, which can be used in the form of electricity and heat. It can meet the electricity demand of 330 to 490 million people globally[22].
- If upgraded to biomethane, there is a potential for 250 to 370 bcm biomethane to meet the natural gas demand of China and India combined[23].
- The energy generated from the treated livestock manure has the potential to meet 100% of the energy needs of world agriculture: 2,400 TWh including electricity, coal, fuel oil, liquefied petroleum gas, motor gasoline, gas-diesel oil, and energy for power irrigation[24]. It can contribute significantly to the energy security of farms which are often off the grid.
- If all 'available' livestock manure from cattle, buffaloes, pigs and chickens were to be collected and anaerobically digested, it has the potential to reduce global GHG emissions by 930 to 1,260 Mt CO_2 eq. per year, which is about 13 to 18% of the current emissions related to livestock[25].
- From the available and treated manure, 10 billion tonnes of nutrient-rich digestate can be produced to be used as organic fertiliser or soil amendment for the production of crops or feed for the livestock. Nutrients in digestate are more readily available to the crops making it a better fertiliser than untreated manures.

2.2 Introduction

Livestock is part of our farming industry: providing food such as dairy, meat, eggs for our consumption, organic fertiliser for growing crops and as draught animals in some countries.

The farm animals whose manure may be treated via anaerobic digestion include 1.5 billion cattle, 1 billion pigs, 22 billion chickens and 0.2 billion buffaloes[26]. Other farm animals are often fully grazed and hence their manure is not available for digestion, such as sheep, goats and horses, or are relatively few in numbers, such as other fowl, donkeys or camels.

Livestock animals under consideration: cattle and buffaloes may be grazed on pastures of grass and clover with concentrates such as corn and wheat; chickens and pigs may be fed grains such as corn, wheat with oilseed meals such as soybean and canola meal as concentrates. In the case of pigs, small amounts of meat or fish meal, fresh fruits and vegetables may be added for extra nutrition.

It is common agricultural practice to house these animals for some part of the day or year to protect them from adverse weather and potential predators. They may also be brought indoors for milking, feeding concentrates and health screening. While the rearing regime of cattle often allows for grazing during the day, pigs and poultry are reared primarily indoors. The manure excreted by the animals when they are indoors may be collected and managed through a variety of processes including anaerobic digestion. It is common for animals to be bedded on straw, wood chips or sand for their comfort and health, which gets mixed with the manure before being collected from the barn, pen or broiler.

[22] https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

[23] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

[24] FAO Stat www.fao.org/faostat/en/#data

[25] www.fao.org/news/story/en/item/197623/icode/

[26] FAO Stat www.fao.org/faostat/en/#data

2.3 Manure management

In developing countries, collected manure may be applied to agricultural land or formed into cakes, dried in the sun and then burnt as fuel for domestic cooking. Often, they are then sold into cities for cooking uses as this photo shows. The burning of these dung cakes leads to high particulate and greenhouse gas emissions and is detrimental for the health of the people, primarily women and children, inhaling this air[27].

Source: The Times (2005)[28]

In developed countries, livestock manure may be collected and stored in open or covered ponds, lagoons or tanks for some time before being applied to agricultural land. It can be safely assumed that the application of undigested manure to agricultural land is a common practice across the globe.

Manure is a source of nutrients as well as greenhouse gases. The volume of greenhouse gases emitted, primarily methane and nitrous oxide, depends on a number of factors including method of management, temperature, soil type and diet of the animals. Moreover, the application of manure to the soil that is wet or near watercourses can lead to nitrate run-off into the water with consequent damage to water quality; manure application requires careful management.

2.4 Digesting manure

Collecting manure and digesting it in an anaerobic digester significantly reduces the greenhouse gas emissions originating from the manure, provides energy that may be used on-site or exported to generate additional revenue, reduces odour produced from the manure and also provides a nutrient-rich digestate that may be used as organic fertiliser for crop production.

Most manure is digested under mesophilic, wet digestion conditions. If the animals are bedded on sand, then an additional sedimentation process is essential to remove it. Similar pre-treatment processes may be needed for other bedding materials such as wood chips and straw. The decomposition of cattle and pig manure starts soon after excretion, making it important to minimise the time from housing to digester in order to get the full corresponding energy and GHG abatement benefits.

Source: Manure Manager[29]

Livestock manure may be digested on its own, with other feedstocks and at varied scales:

DAIRY FARMS, BEEF LOTS AND PIG FARMS: Digestion of cattle/pig manure is an established technology and has been implemented widely all around the globe on varied scales. The electricity generated from the biogas may be used on site in farm buildings and running operations, heating water for washing milking areas and the digestate is applied to crops grown to feed the cattle.

POULTRY FARMS: Digestion of poultry manure is tricky and its mono-digestion uncommon. Poultry manure has high nitrogen content which causes the production of ammonia which inhibits the production of biogas. This can be avoided by storing pre-digestion, diluting the manure and stripping ammonia from the liquid or semi-solid state or by co-digesting poultry manure with other feedstocks to obtain a more favourable carbon to nitrogen ratio[30]. The technology to stabilise the digestion process has been recently developed. There are some biogas plants now operating, with large potential for further deployment.

[27] www.ccacoalition.org/es/initiatives/household-energy

[28] www.thetimes.co.uk/article/city-dwellers-fuel-online-demand-for-cow-dung-3gcj525wc6f

[29] www.manuremanager.com/beef/canadas-largest-biogas-plant-15093

[30] www.biosurf.eu/wordpress/wp-content/uploads/2015/06/Pre-treatment_of_poultry_manure_B%C3%B6jti-Tam%C3%A1s-Anaeobe.pdf

CO-DIGESTION WITH OTHER FEEDSTOCKS: The biogas potential of manure is lower when compared to some of the other feedstocks such as crop residues, food waste or energy crops. It is not uncommon for farm-based digesters to co-digest manure with other feedstocks to increase the amount of biogas produced for improved profitability.

MICRO-SCALE DIGESTERS: There are about 50 million rural household digesters operating in China, India and the rest of Asia, Africa and South America[31]. These primarily run on livestock manure with night soil and farm waste added when available. The biogas is used domestically for cooking and heating; substituting firewood, charcoal and other solid biomass, which adversely affect air quality; health and quality of living; and may also result in deforestation.

2.5 Potential benefits

2.5.1 Model

Based on the generalisation of livestock husbandry practices around the globe, it has been assumed in the model that cattle graze during the day and are housed at night, milking time and during adverse weather conditions. Pigs and poultry are primarily housed with variable access to pasture.

On small farms, micro-digesters can be installed to capture emissions from manure. On large farms, full-scale mono- or co-digesters may be installed to take advantage of the scale. Mid-size farms may struggle from not having the scale for a profitable large digester or being too big for a micro-digester using biogas directly. They may, however, form cooperatives for centralised digestion. We, therefore, assume that of the housing manure collected, a maximum 70% may be treated via anaerobic digestion (assumption) and is referred to as 'all available manure' in the report.

The key inputs used for calculating:

		Cattle and Buffalo	Pig	Poultry
Livestock population (2017)[32]	billion head	1.69	0.97	22.84
Manure production[33]	tonnes per head per year	16	1.6	0.112
Livestock housing[34]	%	50	90	75
Biogas yield[35]	m^3 per tonne fresh matter	40-60	25-35	60-80
Growth rate of livestock population[36]	%	0.6	0.5	1.5

2.5.2 Energy

If available manure from all the 1.5 billion cattle, 1 billion pigs, 22 billion chickens and 0.2 billion buffaloes living today were to be anaerobically digested, there is a potential to generate 250 to 370 bcm of biomethane or 2,600 to 3,800 TWh. The energy generated can meet the electricity demand of 330 to 490 million people globally[37]. If upgraded to biomethane, there is a potential to meet the natural gas demand of India and China combined[38].

[31] www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Dec/IRENA_Biogas_for_domestic_cooking_2017.pdf

[32] www.fao.org/faostat/en/#data

[33] http://agrienvarchive.ca/bioenergy/download/barker_ncsu_manure_02.pdf

[34] Assumption based on global practices and editorial board input

[35] ADBA Practical guide to AD Chapter 3 and editorial board input. Assumed BMP for buffalo based on the IPCC which shows a number of characteristics of cattle and buffaloes to be the same and this study which shows BMP of dairy cattle and buffaloes to be similar www.ncbi.nlm.nih.gov/pmc/articles/PMC4283175/

[36] www.fao.org/fileadmin/templates/esa/Global_persepctives/world_ag_2030_50_2012_rev.pdf

[37] https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

[38] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

The energy generated from the treated livestock manure has the potential to meet 100% energy needs of world agriculture; 2,400 TWh including electricity, coal, fuel oil, liquefied petroleum gas, motor gasoline, gas-diesel oil, and energy for power irrigation[39]. It can be used on-farm in many ways including for lighting, dairy operations, preparation of feed, heating farm buildings and as vehicle fuel in tractors. It can contribute significantly to the energy security of farms which are often off the grid. In addition, the energy can be exported to diversify farm incomes bringing prosperity and resilience.

2.5.3 Emissions

Livestock is responsible for 7.1 Gt of CO_2 eq. or 14.5% of all anthropogenic greenhouse gas emissions[40]. These originate from enteric emissions, emissions from manure management, production of animal fodder, energy used on farms, manure spread on soils and emissions from fertilisers used for the production of feed.

Emissions from livestock arise in the form of carbon dioxide, methane and nitrous oxide. The single biggest source of emissions from livestock is enteric fermentation, which is gas produced from the gut of the animals and released into the atmosphere. This gas is primarily made up of methane. Research is being conducted to decrease enteric emissions by modifying the diet of the animals, diet additives, genetic engineering and selective breeding[41]. These are yet to be adopted as common practices in animal husbandry.

GHG emissions from manure management are smaller than enteric emissions but can be significantly reduced by treating manure in an anaerobic digester. The most volatile carbon is captured as biogas, eliminating methane emissions. By reducing exposure to oxygen, nitrous oxide emissions from manure storage are also significantly reduced. In addition, the energy produced from the captured biogas offsets carbon dioxide emissions from fossil fuels that are used in farming activities and/or exported to other users via grid connections.

There are methane and nitrous oxide emissions corresponding to the application of manure and digestate to soils. Since there is a lack of robust data on the difference between manure and digestate application to land in terms of GHG emissions and savings, these have been assumed to be equal and not included in modelling of GHG abatement benefits of anaerobic digestion of livestock manure.

By collecting and anaerobically digesting manure from livestock, there is a potential to offset 930 to 1260 Mt CO_2 eq. per year of greenhouse gas emissions or 13 to 18% of the current livestock-related emissions[42]. This offset comes in the form of avoided emissions from manure management and energy produced from the captured biogas generated from manure in a digester and using it to generate energy that can be used on the farm or exported.

2.5.4 Nutrient recovery

Once livestock manure has been digested, and energy recovered, the nutrient-rich digestate obtained can be used as organic fertiliser to agricultural land. Empirical evidence shows that anaerobic digestion of manure makes the nutrients, nitrogen, phosphorus and potassium, more readily available to the crops and hence, improves the yield of crops as compared to undigested manure. However, the availability of nutrients depends on the soil type, moisture content, the health of the soil, crops grown and a number of other factors. There is a lack of robust global data on the difference between manure and digestate application to land in terms of nutrients available to crops. These have been assumed to be equal and not included in the modelling of nutrient recovery benefits of digesting livestock manure.

10 billion tonnes of digestate can replace the raw animal manure slurry that is currently being applied to agricultural soils as soil amendment.

[39] FAO Stat www.fao.org/faostat/en/#data

[40] www.fao.org/news/story/en/item/197623/icode/

[41] http://ccacoalition.org/sites/default/files/resources/2009-Enteric-Fermentation-Mitigation_C2ES_0.pdf

[42] www.fao.org/news/story/en/item/197623/icode/

2.6 Realising the potential

The energy generation, GHG emission abatement and nutrient recovery potential from the digestion of livestock manure are based on the assumption of capturing all available manure from all livestock animals around the globe while they are housed. It is important to understand where we are now and how we need to increase the capture rates to achieve our full potential. We give the year 2050 as a target date.

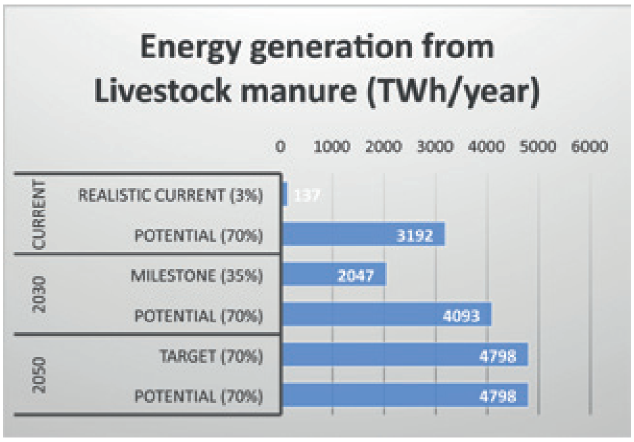
Taking the example of the USA, which we can use because it has all the climatic, industrial, agricultural and technological means needed to achieve growth, an estimate shows that the 248 currently operating digesters in the USA on livestock farms and digestion represent approximately 3% of the 8000 dairy and hog (pig) farms[43] on which such installations could be up taken. This uptake rate varies significantly by the type and size of farm and country:

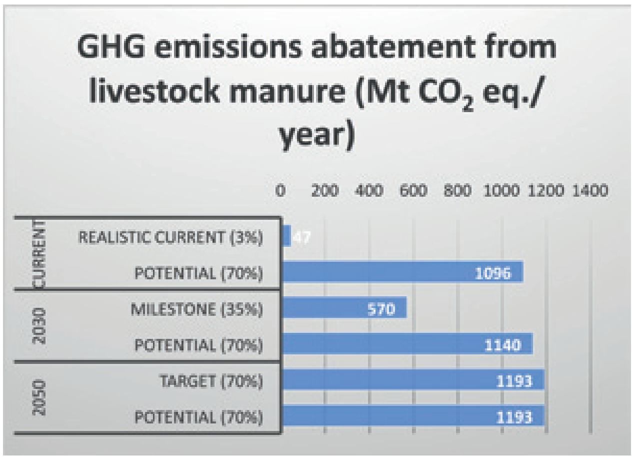
- higher adoption rate for dairy and cattle farms;
- AD on large farms is more economically viable;
- farms that are connected to the electricity grid;
- farms in countries where grid supply is erratic and unreliable;
- farms that grow feed for animals and can expand into crop residues and energy crops;
- farms in countries with supporting policies like Germany with a special tariff for energy generated from manure digestion; and
- farms in developing countries like India, China and Bangladesh where specific schemes exist for implementation of micro-scale digestion in rural communities.

Lower adoption rates can be expected on poultry farms, mid-size farms which are too big for micro-digestion but too small to benefit from the scale of bigger biogas plants, farms that are off-grid, farms in countries with no or not well-implemented incentive schemes.

Assuming a current 3% uptake implies an untapped potential of 97% for energy generation and GHG emission mitigation. With the human population growing by about 1.1%[44] every year and increasing incomes resulting in higher consumption of meat and dairy per capita, more food may need to be made available either from reduced food waste or from increased yields or both, to meet the increasing demand. The growth rate of livestock population to meet the increased food demand is expected to be 0.6% for cattle and buffaloes, 0.5% for pigs and 1.5% for poultry[45]. In order to reach our full potential by 2050, we assume that the industry will need to increase the available manure capture rate to 35% by 2030.

If these capture rates are achieved, it may be possible to generate 2,047 TWh energy and mitigate 570 Mt CO_2 eq. emissions by 2030 and 4798 TWh energy and 1193 Mt CO_2 eq. emissions by 2050 as shown in the charts below. While most energy generation benefits increase with time, they are countered by the falling global emission factors for electricity and heat generation from the generation of cleaner energy resulting from the deployment of renewable energy technologies.





[43] www.epa.gov/agstar/agstar-data-and-trends

[44] https://esa.un.org/unpd/wpp/publications/files/wpp2017_keyfindings.pdf

[45] www.fao.org/fileadmin/templates/esa/Global_persepctives/world_ag_2030_50_2012_rev.pdf

2.7 What is needed to achieve this potential

- Acknowledge and incentivise GHG abatement resulting from anaerobic digestion of manure
- Mandate digestion of slurry for farms over a certain size
- Incentivise energy generation and use from livestock manure via targeted policies such as specific rural schemes in developing countries for micro-scale digestion that result in energy security and independence, reduced use of solid fuels for domestic cooking and heating, reduced deforestation. Include operation and maintenance training, health and safety training, regular maintenance and safety checks, and specifically include women in the economy of managing animal manures.

3. Sewage

3.1 Key Findings

- 61% of the global population live without access to safely managed sanitation facilities and 892 million people practice open defecation[46].
- If all available sewage generated by the entire world population is collected and treated via anaerobic digestion, there is a potential to generate 210 to 300 TWh of energy which can be utilised as heat and electricity or 22 to 32 bcm biomethane. The electricity can meet the needs of 27 to 38 million people around the globe[47] or the natural gas needs of Ukraine[48].
- Anaerobic digestion of sewage generated by people can mitigate 75 to 100 Mt CO_2 eq. of greenhouse gases per annum, equivalent to the emissions of Israel[49].
- If all sewage is collected and all sludge digested it would produce 0.23 billion tonnes of digestate containing 2.6 Mt nitrogen, 1.3 Mt phosphate, 0.12 Mt potash, 0.37 Mt magnesium and 1.9 Mt sulphur. This is enough to provide fertilisers for 30 million hectares of arable land[50] replacing about 0.4 - 3% of global inorganic fertiliser used[51].

3.2 Introduction

Whatever we eat and drink our body absorbs as energy and nutrients and excretes the rest as waste. This waste or sewage is generated by every person, every day in different quantities based on diet and water usage. While in most urban and developed areas of the world sanitation facilities and infrastructure available for the collection, treatment and disposal of this sewage have been built, rural areas of low- and middle-income countries do not have access to these facilities. 61% of the global population live without access to safely managed sanitation facilities and 892 million people practice open defecation[52].

Untreated sewage and poorly managed sewage contaminate the soil, surface and groundwater bodies. It poses a threat to people's health (from diseases such as diarrhoea, hepatitis A, gastroenteritis, and worm infections[53]) both through direct contact and from animals such as flies and cockroaches, dogs and cats. The high biological oxygen demand of sewage starves the water bodies of oxygen, adversely affecting the number of fishes and other aquatic life. It also causes eutrophication or the increased concentrations of nitrogen, potassium, and phosphorus in water leading to excessive growth of algae. Chemicals commonly used in cleaning products used in toilets such as chlorine, formaldehyde, ammonia and zinc compounds are toxic to aquatic flora and fauna.

The United Nations' target is to end open defecation and achieve access to adequate and equitable sanitation for all by 2030. It also aims to halve the proportion of untreated wastewater discharged to watercourses and the open environment, improving water quality[54].

3.3 Sewage treatment

In an urban setting or where infrastructure is available, sewage is collected from households via sewers. Through sewer pipes, it is transported to a wastewater treatment facility. While in some countries, the domestic sewage is mixed with partially treated or untreated industrial wastewater, in others these are kept separate. The analysis in this report includes only household sewage.

Source: New Civil Engineer[55]

[46] https://sustainabledevelopment.un.org/sdg6

[47] Per capita electric consumption of 3127.48 KWh per year https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

[48] www.eia.gov/beta/

[49] https://data.worldbank.org/indicator/en.atm.ghgt.kt.ce?most_recent_value_desc=true

[50] Per hectare fertiliser (NPK) consumption of 140.553 kg https://data.worldbank.org/indicator/ag.con.fert.zs

[51] World fertilizer trends and outlook to 2020 www.fao.org/3/a-i6895e.pdf

[52] https://sustainabledevelopment.un.org/sdg6

[53] https://bit.ly/2KUfKnj

[54] https://sustainabledevelopment.un.org/sdg6

[55] www.newcivilengineer.com/pictures/1240x826/7/3/4/3070734_Mogden-sewage-treatment-works.jpg

Coarse solids, grit and other large materials are first removed from the sewage. The sewage then undergoes primary treatment in a sedimentation tank where solids (faecal matter) settle to the bottom. The liquid (urine and other grey water) and suspended solids may undergo further secondary treatment such as aeration in lagoons or stabilisation ponds, activated sludge treatment, trickling filtration, or bio-contactors. This is followed by disinfection and advanced treatment and finally discharged into rivers, ponds, other surface water body or applied to agricultural land.

The settled solids from primary and secondary treatment, known as sewage sludge, is thickened after which it may be stabilised via anaerobic digestion, composted, used in cement production, incinerated after drying or send to landfill[56].

Homes that are not connected to this centralised infrastructure may have a septic tank for simple on-site sewage treatment. In some rural areas, the population may be served by toilets that are linked to a collection pit/tank that may have to be emptied on a regular basis to be treated. The toilet may directly be linked to a composting pit or to a digester. Many variations of these have been designed and implemented in different parts of the world, such as Ecosan and Loowatt.

Source: Western Pacific[57]

Building the London Super Sewer

In some instances, sewage treatment facilities that are built are not able to cope with the increased flow of sewage due to increased population or due to weather phenomenon such as heavy rainfall. In such cases, untreated sewage is released into water bodies, polluting them. This occurs in highly developed cities too, such as London, which is building a new sewage system to cope with increased population and discharges during heavy rainfall.

3.4 Digesting sewage

Anaerobic digestion of sewage sludge stabilises it by reducing biological activity, pathogens and weed seeds in it. It also significantly reduces odour[58]. Digestion of sewage can be centralised, as in an urban setting, or decentralised, as in rural areas where infrastructure is not available.

CENTRALISED DIGESTION: In most urban areas, sewage is collected from households and transported to wastewater or sewage treatment plant. After the settling, sieving and thickening process, the sludge may be digested on its own or co-digested with food waste. The energy content of sewage sludge is low as compared to other feedstocks. It is therefore sometimes co-digested with food waste in urban settings when there is an established food waste collection process. Sewage sludge is digested in a wet, mesophilic process to produce biogas and digestate. Digestate is dewatered and used while the water extracted is reintroduced into the treatment process.

Treating sewage and producing biogas in Jordan[59]

[56] www.fao.org/3/t0551e/t0551e05.htm

[57] www.westpeng.com/publicaciones/bulletin/maintenance-of-septic-tanks-type-1

[58] IEA Task 37 (2015) Sustainable biogas production in municipal wastewater treatment plants
http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/Wastewater_biogas_grey_web-1.pdf

[59] www.suezwaterhandbook.com/case-studies/wastewater-treatment/As-Samra-wastewater-treatment-plant-Jordan

Such sewage collection systems require an upfront investment but, once set up, they provide a reliable steady stream of feedstock and very little further active intervention is required. Sewage treatment is an energy-intensive process and is one of the big expenses for local government. By digesting the sludge, it is possible to partially or fully meet the energy requirement of the waste treatment process. The biogas may be upgraded to biomethane to be injected into the gas grid or used as vehicle fuel, based on the local requirement.

DECENTRALISED DIGESTION: In rural and remote areas, which are not served by a centralised sewage collection system, digestion of sewage sludge may take place in a small tank or pit connected directly to toilets. It may be an individual digester; a community digester serving multiple households; or a farm digester, co-digesting other feedstocks generated on-farm such as crop residues and livestock manure. The biogas generated from such micro- and small-scale digesters is likely to be used directly for domestic cooking or heating and the digestate spread on the farm.

DIGESTATE: Digestate produced from sewage sludge is high in nitrogen and phosphorus content when compared with digestate from other feedstocks. Phosphorus is available in limited quantity elsewhere in the natural world which makes sewage sludge digestate highly desirable as a soil amendment. Extraction of phosphorus from digestate is also possible for use as a targeted fertiliser[60].

Digested sludge is safer to apply to land than raw sludge as the digestion process reduces the pathogens and weeds in it. Industrial sewage that can possibly contain heavy metals and other chemicals may need further treatment and is not considered in the report.

3.5 Potential benefits

3.5.1 Model

Based on sewage treatment processes commonly used in wastewater treatment plants around the globe, the report assumes two separate treatment processes for the solid and liquid parts of domestic sewage. The sewage sludge or the solid part of the sewage, made up of faecal wet mass, is stabilised via anaerobic digestion and discussed here. The urine or the liquid part of the sewage is diluted by greywater and is treated aerobically in the wastewater treatment plant and then discharged into water courses.

Since 55% of the world population lives in urban areas[61], we assume that sewage from them can be fully captured for anaerobic digestion. People who live in rural areas and are not connected to centralised sewers can be connected to bio-toilets with septic tanks or digesters. The percentage of those that can be connected to digesters is assumed to 50%. Hence, the maximum capture of sewage for anaerobic digestion has been assumed to be 77.5%.

The assumption is based on the premise that energy recovery and nutrient recirculation make anaerobic digestion the most favoured methods of stabilising sludge.

The key inputs for calculating the potential of sewage for energy generation, GHG abatement and nutrient recovery are:

Population[62]		
2017	billion	7.6
2030	billion	8.6
2050	billion	9.8
Biogas potential[63]	litre per person per day	18 – 26
Methane in biogas[64]	%	65
Faecal wet weight[65]	grams per person per day	128

[60] https://phosphorusplatform.eu/success-stories

[61] https://data.worldbank.org/indicator/sp.urb.totl.in.zs

[62] www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html

[63] http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/Wastewater_biogas_grey_web-1.pdf

[64] http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/Wastewater_biogas_grey_web-1.pdf

[65] Critical Reviews in Environmental Science and Technology, 45:1827–1879, 2015

Sludge digestate typical nutrient content[66]:

Total Nitrogen (N)	kg/t fw	11
Total Phosphate (P_2O_5)	kg/t fw	5.5
Total Potash (K_2O)	kg/t fw	0.5
Total Magnesium (MgO)	kg/t fw	1.6
Total Sulphur (SO_3)	kg/t fw	8.2

3.5.2 Energy

If all available sewage generated by the entire world population were to be collected and treated via anaerobic digestion, there is a potential to generate 210 to 300 TWh energy which is available for use and export after meeting energy requirement of the digester in the form of heat and electricity or 22 to 32 bcm biomethane. The electricity can meet the needs of 27 to 38 million[67] people around the globe or the natural gas needs of Ukraine[68].

3.5.3 Emissions

Digestion of human sewage can mitigate 75 to 100 Mt CO_2 eq. per annum of greenhouse gases by displacing fossil fuel-based energy and by avoiding emissions from the manufacturing of mineral fertilisers displaced by digestate produced, equivalent to the emissions of Israel[69].

3.5.4 Nutrient recovery

When compared with other feedstocks such as food waste or crop residues, the energy generation and GHG emission abatement benefit of sewage is lower. However, sewage sludge is rich in nutrients and has an immense value from a nutrient recovery and circulation perspective. It is especially high in phosphorus, which is essential for the growth of plants and is available naturally in limited quantity. These nutrients, when discharged into water bodies, cause nutrient pollution or eutrophication, adversely affecting the quality of water as it leads to excessive growth of algae.

If all sewage is collected and all sludge digested it would produce 0.23 billion tonnes of digestate containing 2.6 Mt nitrogen, 1.3 Mt phosphate, 0.12 Mt potash, 0.37 Mt magnesium and 1.9 Mt sulphur. This is equivalent to the amount of fertiliser used on 30 million hectares of arable land[70] replacing about 0.4-3% of global inorganic fertiliser used[71].

3.6 Realising the potential

Access to proper sanitation facilities is imperative for every human being, for dignity and for health[72]. Untreated or improperly managed sewage poses risk to people's health, causes pollution of soil and water bodies, adversely impact the aquatic flora and fauna and gives rise to odours which impact people's quality of life.

While 39% of the global population has access to safely managed sanitation services, which means the sewage is treated in wastewater treatment plants or septic tanks and safely discharged, there is no global data available for how much of the sludge is treated by anaerobic digestion. We assume that 25% of the sludge from sewage sludge is currently collected (from 39% of the population) is stabilised via anaerobic digestion, i.e. ~ 10% of all sewage sludge generated.

In order to achieve the maximum capture of sewage sludge for anaerobic digestion by 2050 (77.5%), the industry would have to capture 35% by 2030.

[66] RB209 Digested Cake 25% DM **https://ahdb.org.uk/knowledge-library/rb209-section-2-organic-materials**

[67] Per capita electric consumption of 3127.48 KWh per year **https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC**

[68] **www.eia.gov/beta/**

[69] **https://data.worldbank.org/indicator/en.atm.ghgt.kt.ce?most_recent_value_desc=true**

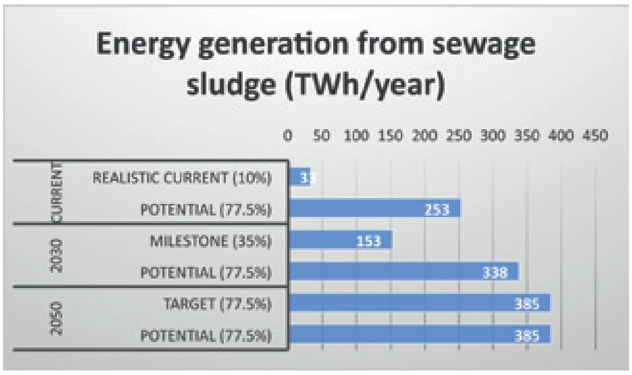
[70] Per hectare fertiliser (NPK) consumption of 140.553 kg **https://data.worldbank.org/indicator/ag.con.fert.zs**

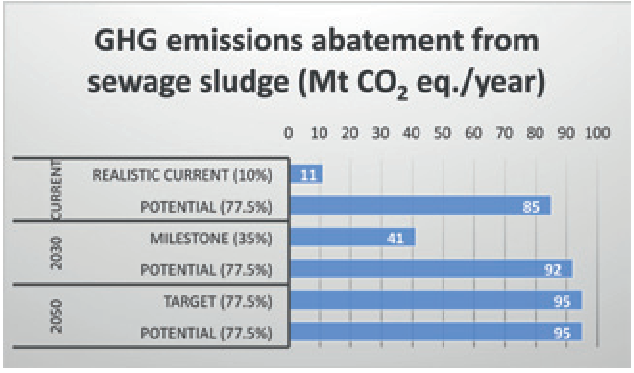
[71] World fertilizer trends and outlook to 2020 **www.fao.org/3/a-i6895e.pdf**

[72] **https://sustainabledevelopment.un.org/sdg6**

The advantage of sewage as feedstock is that it is a steady and reliable stream. The flow of this feedstock is guaranteed. Once the infrastructure has been set up, very little active intervention is required. As populations and incomes grow and diets become more nutrient dense, the nutrient recycling and energy generation potential of sewage sludge is expected to increase. However, the decrease in the emission factors of energy generation in the future may reduce the net GHG abatement that can be achieved.

Assuming that sewage capture and digestion targets for 2030 and 2050 are met and sewage collection and digestion is increased to 35% and 77.5%, the energy generation potential is 153 TWh/year and 385 TWh/year and the GHG abatement potential is 41 Mt CO_2 eq./year and 95 Mt CO_2 eq./year as shown in figures 1 and 2.





3.7 What is needed to achieve this potential

In order to capture the potential of sewage sludge, a number of steps are required from policymakers.

- The Governments to ensure the availability of sanitation facilities for all.
- Building centralised sewage collection and treatment infrastructure for as many citizens as possible.
- Connecting decentralised sanitation facilities or community toilets to micro- or small- scale digesters.
- Governments, local, state and national, to include anaerobic digestion of sewage sludge as the preferred method of treatment.
- Governments to set consistent quality protocols and digestate standards for safe utilisation of sewage sludge-based digestate, e.g. limiting potential pollutants and pathogens
- Governments to ensure that the sewage treatment plants are upgraded to handle the increased sewage flow.

4. Food waste/loss

4.1 Key Findings

- Globally 1.6 billion tonnes of food is lost every year of which 1.3 billion tonnes is edible and 0.3 billion tonnes is inedible[73].
- Less than 2% of inedible food by-products are currently being collected for energy and nutrient recovery[74].
- If 'all available' food waste/loss was to be collected and recycled via anaerobic digestion, there is a potential to generate 880 to 1100 TWh of energy which can be utilised as electricity and heat. The electricity generated can meet the electricity need of 112 to 135 million people[75]. If upgraded into biomethane, the 85 to 100 bcm biomethane generated can replace the natural gas consumed by Germany[76].
- If 'all available' food waste/loss was to be collected and recycled via anaerobic digestion, it can mitigate greenhouse gas emissions equivalent to 510 to 560 Mt CO_2, emissions equivalent to those of the United Kingdom[77], in the form of avoided emissions from the production of fossil fuel-based electricity and heat, emissions from fertiliser production and also avoided landfill emissions attributed to food waste.
- The nutrient-rich digestate can provide organic fertiliser to replace 5.03 Mt nitrogen, 0.75 Mt phosphate, 1.8 Mt potash, 1.1 Mt calcium, 0.13 Mt magnesium and 0.58 Mt sulphur while also returning a part of the organic carbon to the soil. This would provide sufficient nutrients to fertilise 53 million hectares of arable land, equivalent to the arable land area of Australia[78] or 2-5% of the current global inorganic fertiliser consumption[79].

4.2 Introduction

The WBA has already published an extensive analysis of the management of food waste in its report, co-written with C40 Cities in 2018, *Global Food Waste management: An implementation guide for cities*[80]. The argument treated in this Chapter can be explored in that report in greater depth.

A third of all food produced in the world every year, 1.6 billion tonnes, is wasted or lost. The food wasted comes at a total cost of 2.6 trillion USD to the world in economic, environmental and social costs[81]. It accounts for 4.4 Gt CO_2 eq. greenhouse gas (GHG) emissions which represent 8% of all anthropogenic GHG emissions[82].

This is not only a waste of energy and resources but also ethically questionable when 800 million people around the globe suffer from hunger. The United Nations' Sustainable Development Goal 12 aims to halve the per capita food waste and loss by 2030[83].

While waste is undesirable, if it is unavoidable or has been generated and deemed inedible by humans or animals, the next best option is to treat it via anaerobic digestion to recover energy and nutrients.

[73] www.fao.org/news/story/en/item/196402/icode/

[74] www.ellenmacarthurfoundation.org/assets/downloads/Cities-and-Circular-Economy-for-Food_280119.pdf

[75] https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

[76] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

[77] www.europarl.europa.eu/news/en/headlines/society/20180301STO98928/greenhouse-gas-emissions-by-country-and-sector-infographic

[78] www.nationmaster.com/country-info/stats/Agriculture/Arable-land/Hectares

[79] World fertilizer trends and outlook to 2020 www.fao.org/3/a-i6895e.pdf

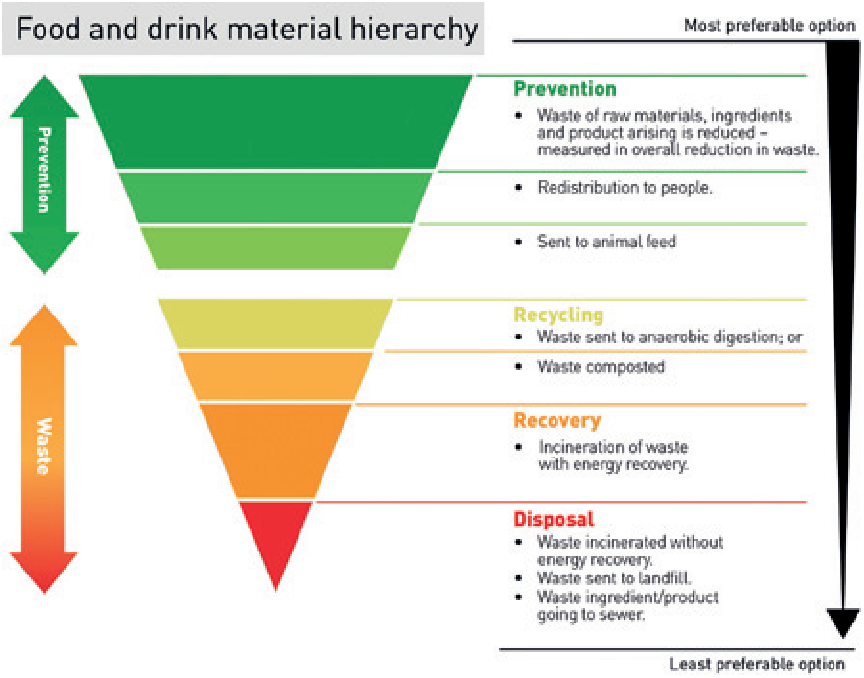
[80] www.worldbiogasassociation.org/food-waste-management-report/

[81] www.fao.org/3/a-i3991e.pdf

[82] www.fao.org/3/a-bb144e.pdf

[83] https://sustainabledevelopment.un.org/sdg12

Food waste, in this report, refers to food waste, food loss and inedible parts of food. Food waste is defined as any food and inedible parts of food, removed from the food supply chain that can be recovered or disposed of by any process including digesting, composting, combustion, incineration, and disposal to sewer, landfill, open dumps, or sea. This includes food that is wasted due to procedural and institutional failures such as overproduction, overstocking, appearance standards, poor planning, bad storage, confusion due to labelling and packaging defects. This also includes food loss which is food that unintentionally undergoes deterioration in quality or quantity as a result of food spills, spoils, bruising, wilting, or other such damage as a result of infrastructure limitations at the production, storage, processing and distribution stages of the food lifecycle. It also includes inedible parts of food such as stones, peels, shells and bones.



Source: WRAP[84]

4.3 Food waste management

Source: Future Agenda[85]

A very low proportion of food waste/loss is currently being digested for the production of energy. Food waste/loss is handled differently depending on the source of origin and stage of food lifecycle. In farms, food waste may be generated due to deterioration of quality (such as spoilage, bruising) or failure to meet the buyer's specification. At this stage of production, the handling and storage stage, fruits and vegetables that are spoilt or unwanted may be ploughed in, allowed to rot in the field, composted, fed to animals, may be used on site if the farm has its own anaerobic digester for the production of energy or sent to landfill.

On farms or food processing facilities, when large quantities of food loss are generated incidentally, lost food may be sent to the nearest biogas plant. However, where there is a steady stream of food waste such as from a fruit canning facility or brewery and which has energy consumption, food waste is often digested on-site.

Food waste generated during the distribution, market and consumption stages are more likely to be in urban settings and therefore likely to be dumped or sent to landfill. With over 50% of the world's population living in cities, increasing volumes of food waste and loss occur in these contexts.

[84] www.wrap.org.uk/sites/files/wrap/image/Food_and_Drink_hierarchy.jpg

[85] www.futureagenda.org/insight/food-waste

From households/businesses or at the post-consumption stage, food waste is likely to be mixed with residual waste ending up in dumps, incinerated or landfills, unless separately collected in which case it may be digested or composted. In lower-income nations, food waste often comprises more than 50% of the municipal waste stream[86]. The high concentration of water in food waste makes incinerating it an energy-intensive process along with a waste of nutrients. Digestion of urban food waste on its own or with wastewater is still implemented rarely although the practice is on the rise.

In developing countries, waste, including organic waste, is usually not managed properly and may end up in open dumps, landfills or littered. The unsanitary handling and disposal of waste causes odours and spread of diseases via vermin.

Food waste accounts for 44% of organic waste going to landfills[87]. Once in a landfill along with other organic waste, food waste biodegrades releasing greenhouse gases as emissions, primarily methane. Due to these greenhouse emissions and loss of nutrients from landfilling of organic waste, a number of countries around the world have set targets for reducing organics to landfills as well as capturing landfill gas. The landfill gas produced has about 50% methane content which can be captured to be flared, or cleaned and used for generation of electricity or biomethane.

In a number of countries, food waste, where appropriate, is processed into swill and fed to animals such as pigs. While it is the preferred method in some countries such as Japan, South Korea, Taiwan and Vietnam, the practice has been banned in Europe since 2002 after the outbreak of the foot-and-mouth disease in an epidemic (which is thought to have been started by the illegal feeding of uncooked food waste to pigs). Anaerobic digestion and subsequent pasteurisation of digestate render the waste safe for use on land.

4.4 Digesting food waste

Separate collection of food waste is necessary for the recovery of energy and nutrients via anaerobic digestion. Separate food waste collection from households and businesses is not yet a widespread practice but is expected to rise with the EU requiring separate food waste collections by end 2023[88].

Food waste generation is often incidental. It has high energy content and is a desirable feedstock for anaerobic digestion. The digestion of food waste can be complicated as very often one batch of food waste can vary significantly from the next. Although food waste can be and is often digested on its own, in order to stabilise the digestion process, it may be mixed with other substrates like livestock manure, sewage or crop residues. This reduces the energy generated per unit of feedstock but makes the variability of food waste feedstocks easier to handle. It also allows for continued generation of energy during periods when food waste is not or is less available. In rural areas, food waste may be co-digested with crop residues, energy crops or livestock manure. In urban settings, it may be co-digested with industrial wastewater or sewage.

Most food waste is digested in wet mesophilic conditions. Food waste digesters tend to have large capacities. The biogas produced from the digestion of food waste may be used for the generation of electricity and heat or upgraded to biomethane. It is common practice to use some of the energy generated from food waste onsite to meet digester requirements, pasteurise (or high-temperature treatment) digestate, meet process requirements (such as keeping a distillery warm, warming greenhouses, running food processing equipment).

Source: Waste Management World[89]

[86] https://openknowledge.worldbank.org/handle/10986/30317

[87] https://openknowledge.worldbank.org/handle/10986/30317

[88] http://europa.eu/rapid/press-release_IP-18-3846_en.htm

[89] https://waste-management-world.com/a/fixed-spec-food-waste-feedstock-for-biogas-plants-hits-market

Pasteurisation of digestate produced using food waste is essential to prevent the spread of potential pathogens in food waste to the agricultural land and crops that the digestate is applied to. Since the composition of food waste varies significantly, so does it's nutrient content and that of the digestate. This requires management when applying food waste digestate to land. However, testing of nutrient content and certification of its safety can help address issues and create a market for digestate. Creation of a market is important for smooth logistics and profitability of food waste generators and biogas operators in urban areas who do not have access to land to apply the digestate on. Certifications help them sell their product and receive a fair price for it.

A number of processes for upgrading digestate to higher value products such as the use of liquid digestate for algal growth, digestate recirculation for further energy recovery, bioethanol production and pyrochars are being currently studied for future implementation[90].

4.5 Potential benefits

4.5.1 Model

The model assumes that food waste reduction targets as set by the United Nations will be met. Based on collection rates achieved in Milan, we assume that the maximum food waste that can be collected in an urban setting is 87%. In a rural setting, where food is primarily lost incidentally in large quantities or due to spoilage, we assume that a maximum of 50% can be captured for anaerobic digestion. Rest may be fed to animals or ploughed in. We assume that since all separation of inedible parts of food is a result of food processing, 100% can be captured. Food waste and loss each make up 50% of the 1.6 billion tonne total of global food waste. Hence, the maximum capture of food waste has been assumed to be 68.5% and is referred to as 'all available' food waste in the report.

In calculating the benefits of collecting and treating food waste, emissions avoided from generating energy, displacing inorganic fertiliser and avoided landfill gas emissions have been taken into account. Based on increased per capita gross domestic product and increased waste generation linked to it, The World Bank has estimated that the current landfill gas emissions of 1,600 Mt of CO_2 eq. will rise to 2,600 Mt of CO_2 eq. by 2050[91]. Landfill gas constitutes a mix which is approximately 50% each of methane and carbon dioxide with trace amounts of volatile organic carbons. The report assumes that a proportion of these landfill gas emissions will be avoided due to food waste collection and that this proportion is the same as that of the collection of food waste. The remaining landfill gas emissions from non-food organics in landfills, such as cardboard and paper, which are not currently digested, are not included in this report. They can potentially be avoided by recycling or by capturing via landfill gas capture technology.

Key inputs used in the calculation of energy generation potential, GHG emissions abatement and nutrient recovery are listed below:

Food waste/loss (2015)[92]		Billion tonnes	1.6
Estimated food waste and loss based on population and targets to reduce food waste[93]			
	2017	Tonnes per capita per year	0.21
	2030	Tonnes per capita per year	0.11
	2050	Tonnes per capita per year	0.05
Biogas yield[94]		m^3 per tonne fresh weight	150 – 180
Landfill emissions[95]			
	2017	Mt CO_2 eq. per year	1,600
	2030	Mt CO_2 eq. per year	1,994
	2050	Mt CO_2 eq. per year	2,600
Percentage of food waste in landfill[96]	%	44	

[90] www.researchgate.net/publication/279516055_New_opportunities_for_agricultural_digestate_valorization_Current_situation_and_perspectives
[91] https://openknowledge.worldbank.org/handle/10986/30317
[92] www.fao.org/3/i3347e/i3347e.pdf
[93] www.fao.org/3/a-i3991e.pdf
[94] https://cordis.europa.eu/docs/results/241334/final1-valorgas-241334-final-publishable-summary-140110.pdf
[95] https://openknowledge.worldbank.org/handle/10986/30317
[96] https://openknowledge.worldbank.org/handle/10986/30317

Food waste typical nutrient content[97]:

Total Nitrogen (N)	kg/t fw	5.4
Total Phosphate (P_2O_5)	kg/t fw	0.8
Total Potash (K_2O)	kg/t fw	1.9
Total Calcium (Ca)	kg/t fw	1.2
Total Magnesium (MgO)	kg/t fw	0.14
Total Sulphur (SO_3)	kg/t fw	0.62

4.5.2 Energy

Today the world generates close to 1.6 billion tonnes of food waste every year. If 'all available' food waste/loss was to be collected and recycled via anaerobic digestion, there is a potential to generate 880 to 1100 TWh of energy which can be utilised as electricity and heat. The electricity generated can meet the electricity need of 112 to 135 million people[98]. If upgraded into biomethane, the 85 to 100 bcm biomethane generated can replace the natural gas consumed by Germany[99].

4.5.3 Emissions

Food waste accounts for 4.4 Gt CO_2 eq. greenhouse gas (GHG) emissions which represent 8% of all anthropogenic GHG emissions[100]. These GHG emissions take place at all stages of food lifecycle and include emissions due to change in land use and deforestation, emissions from livestock slurries, burning of fossil fuels for the production of food, production and application of mineral fertilisers, heating farm buildings and greenhouses, processing food, refrigeration and transport of food, and decomposition of food in open dumps or landfills[101].

The best way to decrease these emissions is by wasting less food, which in turn will reduce the amount of food needed and the resources that go into producing it. If the waste is unavoidable and has been generated as a result of any of the above-discussed reasons, by collecting and anaerobically digesting the food waste, our modelling shows there is a potential to offset 510 to 560 Mt of greenhouse gas emissions, emissions equivalent to those of the United Kingdom[102]. This offset comes in the form of displacement of fossil fuel-based energy with the energy generated from the captured biogas, from displaced emissions from the production of mineral fertiliser by the production of digestate, an organic soil amendment, and avoided landfill emissions.

4.5.4 Nutrient recovery

Food waste that is not collected ends up in open dumps or landfills and the nutrients (primarily nitrogen, phosphorus, potassium, calcium, magnesium and sulphur) that have gone into its production are lost forever. However, collecting food waste and then composting or anaerobically digesting it, produces digestate, an organic fertiliser that can be applied to agricultural land for the production of crops. This keeps the nutrients in circulation.

If all food waste was to be collected and the remainder that could not be diverted to animal feed digested, we have calculated it has the potential to displace 5.03 Mt nitrogen, 0.75 Mt phosphate, 1.8 Mt potash, 1.1 Mt calcium, 0.13 Mt magnesium and 0.58 Mt sulphur while also returning part of the carbon to the soil. This would provide sufficient nutrients to fertilise 53 million hectares of arable land, equivalent to the arable land area of Australia[103] or 2-5% of the current global inorganic fertiliser consumption[104].

97 www.wrap.org.uk/sites/files/wrap/DC-Agri_Work_Package_2_-_Digestate_nitrogen_supply_and_environmental_emissions.pdf

98 https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

99 www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

100 www.fao.org/3/a-bb144e.pdf

101 www.worldbiogasassociation.org/food-waste-management-report/

102 www.europarl.europa.eu/news/en/headlines/society/20180301STO98928/greenhouse-gas-emissions-by-country-and-sector-infographic

103 www.nationmaster.com/country-info/stats/Agriculture/Arable-land/Hectares

104 World fertilizer trends and outlook to 2020 www.fao.org/3/a-i6895e.pdf

4.6 Realising the potential

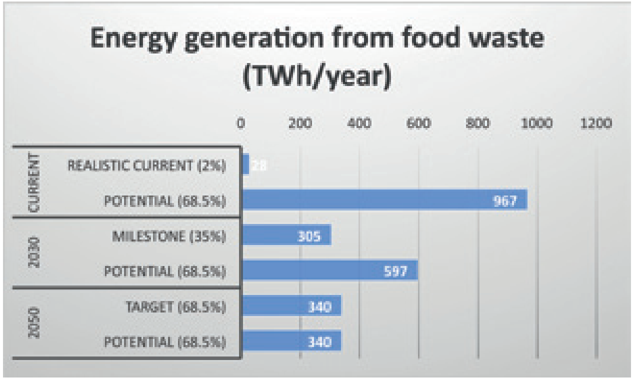
There are two important aspects to estimating the potential for food waste digestion: food waste generation and separate collection of food waste/loss.

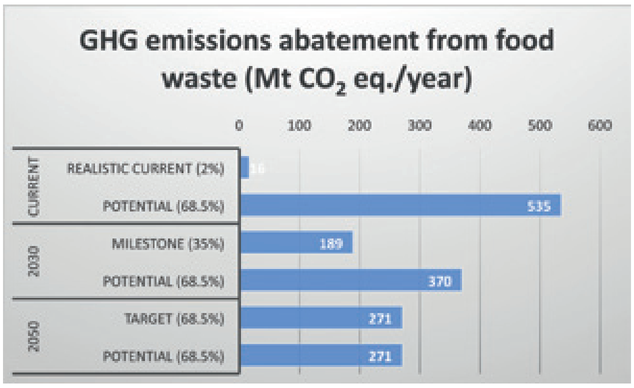
Food waste generation is undesirable; a waste of energy and resources; and, if avoidable, ethically not permissible. The United Nations have acknowledged this and the United Nations' Sustainable Development Goal 12 aims to halve the per capita food waste and loss by 2030. The United Nations estimates that the world population will increase to 9.8 billion by 2050[105]. The World Resources Institute indicates that the first step towards being able to feed the world's increased population is to cut down food waste to a quarter of current wastage by 2050[106].

Separate collection of food waste is the key to unlocking the potential of food waste in terms of energy generation, GHG emissions abatement and nutrient recovery. It also has an important role to play in modifying our current processes in favour of implementation of circular economy in the future. According to the Ellen Macarthur foundation, less than 2% of inedible food by-products are currently being collected for energy and nutrient recovery[107]. It is estimated that in a highly industrialised region as Europe 25% of bio-waste (includes food waste and garden waste) is composted or digested[108] while in some developing regions where the infrastructure is not available, this rate might be negligible.

Food losses from farms and rural areas need to be captured and treated locally. The scale of the farm, distance from the closest digester, frequency of loss, availability of knowledge and infrastructure are some of the factors that will play a role in the ability to capture and treat food waste in rural areas.

Looking into the future, we assume that food waste reduction targets for 2030 and 2050 are met. In order to capture all available food waste for anaerobic digestion (68.5%) by 2050, it is assumed that 35% must be captured by 2030. This also implies, that unlike most other feedstocks, the food waste available for anaerobic digestion will decrease, but will be countered by higher collection rates. The model assumes that collecting and digesting food waste will result in reduced GHG emissions from landfills. Based on these assumptions, we estimate that collection and digestion targets can achieve energy generation potential is 305 TWh/year and 340 TWh/year and GHG abatement potential is 189 Mt CO_2 eq./year and 271 Mt CO_2 eq./year.





With soil quality in many parts of the world shown to be at risk of depletion of organic carbon[109], replenishment of nutrients and carbon has become critical. Digestate contains both these key elements.

[105] www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html

[106] www.wri.org/blog/2018/12/how-sustainably-feed-10-billion-people-2050-21-charts

[107] www.ellenmacarthurfoundation.org/assets/downloads/Cities-and-Circular-Economy-for-Food_280119.pdf

[108] www.compostnetwork.info/policy/biowaste-in-europe/

[109] www.fao.org/3/a-i5199e.pdf

The European Union is leading in efforts to implement separate food waste collections by making it mandatory by 2023 under the Circular Economy Package. It is standard practice in some food processing industries such as distilleries and sugar processing to use their food waste, there is still much left to be done in order to tap into the vast potential of food waste a resource. Even as we work tirelessly to reduce its generation, food waste has great potential for energy generation, GHG abatement and nutrient recirculation.

4.7 What is needed to achieve this potential

- Raise awareness amongst individuals on the ill-effects of food wastage and how they can prevent it.
- Regulate the supply chain of food such that losses and wastage are minimised.
- Require local governments of cities over a certain population to provide separate food waste collection facilities to citizens.
- Mandate reporting and separate food waste collections and treatment from businesses and industries over a certain size.
- Acknowledge and incentivise GHG abatement resulting from anaerobic digestion of food waste.
- Implement regulations, standards and certifications for safe trading and use of digestate.

5. Crop Residues

5.1 Key Findings

- Crop residues are a waste stream with a high untapped potential for energy generation and greenhouse gas mitigation.
- Using all sustainably recoverable residues from the current global production of crops suitable for anaerobic digestion: rice, wheat, maize, rye, barley, oats, rapeseed, sugar beets, sugarcane, and sorghum, there is a potential to generate 3,080 to 3,920 TWh or 300 to 380 bcm biomethane per year. It takes into account ploughing in and diversion of a part of the residues to feeding animals.
- The biomethane could meet the combined natural gas consumption of China and Japan[110]. If the energy is converted into electricity instead, it can meet the needs of 393 to 500 million people or 5.2 to 6.5% of the world population[111].
- Anaerobic digestion of select crop residues can mitigate greenhouse gas emissions equivalent to 865 to 1,100 Mt CO_2 per year, equivalent to the emissions of Germany[112] in the form of avoided emissions from the production of fossil fuel-based electricity and heat and those from burning of crop residues in the field.

5.2 Introduction

Cereals have been a staple part of the human diet since it transitioned from being a hunter-gatherer to growing its own food. While some of these plants once sown can be harvested year on year, like apples from a tree, others, like cereal grains such as rice, wheat and maize, need to be harvested completely and freshly planted every year.

The stalks, leaves or roots of such plants that are normally not eaten by people are known as crop residues. Every part of the world has its own climate and crops that are grown best to feed its population and build its economy, making a variety of crop residues abundantly available all around the world. The sustainability of using crop residues and the possible competition of purpose-grown crops with food crops for land, have been widely recognised and have brought them to the forefront of the bioenergy debate.

5.3 Residue management

Crop residues are defined as the part of plants such as stalks, roots, and leaves that are not commonly used as food by people. These vary with the plant and its use. These may include parts of cereal plants such as stalks, leaves and chaff that are left after the cereal grain has been separated from the harvested plant or leaves of sugar beet once the beet has been harvested to be processed into sugar.

Retrieving the entire plant when harvesting to maximise residue is neither possible nor desirable. The roots of the plants hold the soil together. They give soil structure and upon degradation add humus or carbon content to the soil. This is important to prevent soil erosion and also increases the water holding capacity of the soil. It is estimated that 30-60% of crop residue can be sustainably recovered[113].

Crop residues are currently managed or utilised in a few different ways depending on the crop and agricultural practices of the region.

- **PLOUGHING IN:** Ploughing in is one of the most commonly used methods of managing the parts of the plant, such as the roots and stubble of the crops that are not harvested. Ploughing in the residues gives structure to the soil, returns some of the carbon and nutrient content to the soil and also increases its water holding capacity. As a sustainable farming practice, a part of the residue should usually be ploughed in and is the most commonly used method of residue management.

[110] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

[111] https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

[112] www.europarl.europa.eu/news/en/headlines/society/20180301STO98928/greenhouse-gas-emissions-by-country-and-sector-infographic

[113] Einarsson R, Persson UM (2017) Analysing key constraints to biogas production from crop residues and manure in the EUÐA spatially explicit model

- **LIVESTOCK FODDER AND BEDDING:** On farms with livestock, in addition to grass, crop residues are often collected and preserved to be fed to livestock in winter season when they are primarily housed and cannot be grazed. Straw may also be used as bedding for the comfort of the animals while they are housed. The spent bedding is treated along with the livestock manure.

- **BURNING:** After rice, wheat and other grains have been harvested, the stubble or the residue straw in the field is sometimes burnt to prepare the field for the next crop. Burning of crop residues has been banned in most parts of the world as it wastes nutrients, causes air pollution, and is a fire hazard. However, it continues to be practised illegally in parts of Asia and Africa as it a quick and cheap way of clearing the field and also kills weeds and insects.

- **BIOFUELS:** Crop residues such as wheat straw may be burnt in biomass boilers to generate energy or converted into biofuel such as cellulosic ethanol from corn stover. In rural areas, it may be used as domestic fuel for cooking or heating. While this captures energy from the residue, the nutrients in the residue are lost. Biomass boilers are also not energy efficient and cause particulate air pollution.

- **ANAEROBIC DIGESTION:** By digesting crop residues that are not ploughed in and not fed to livestock, energy can be captured via biogas and nutrients recycled via digestate application to agricultural land. Anaerobic digestion of crop residues, though not widely implemented yet, is a proven technology.

Source: Beef magazine[114]

5.4 Digesting crop residues

Once crop residues have been recovered and a suitable proportion diverted to feeding animals, they can be digested in stages:

- **STORAGE AND PRE-TREATMENT:** Unlike food waste or livestock manure, crop residues do not come in continuous supply. Crop residues are produced in the harvest season and need to be treated suitably and stored for a steady, continuous supply throughout the year. The crop residues are chopped finely and compacted to push out as much oxygen as possible. Roots crops like sugar beets need to be washed thoroughly before being chopped to get rid of any grit that may later accumulate in the digester. After compaction, the residues may be ensiled and stored in silos or clamps.

  Crop residues are high in lignin-cellulosic plant matter or the fibrous parts of the plant, which takes longer to breakdown compared to the starchy parts. Pre-treatment of crop residues creates an anaerobic environment that allows for faster digestion and higher biogas yields in a shorter period of time.

- **DIGESTION:** Crop residues may be digested on their own or co-digested with other feedstocks. The rotation of crops, time of harvest, soil quality, water availability and climate play a vital role in determining the biogas yield. Depending on the crop residue and if other feedstocks are being co-digested, the digestion process and configuration of digesters may vary.

  Mono-digestion – It is uncommon for single crop residues to be digested on their own. Different crop residues provide a variety of nutrients to keep the digestion process stable and also provide resilience against the failure of a crop due to disease or weather phenomenon. Digestion of crop residues is often done in dry digestion set up with retention time of 80-100 days if the process is mesophilic and 30-40 days if the process is thermophilic.

[114] www.beefmagazine.com/feeding-systems/cornstalk-grazing-offers-potential-winter-cattle-feed-savings

- **Co-digestion** – Crop residues are most often co-digested with livestock manure that is produced on-farm or industrial food waste. The process used for digestion in such a case is wet and the crop residues are macerated for better mixing.

Source: OWS[115]

- **DIGESTATE:** The nutrient content of crop-based digestate varies significantly based on the feedstocks used. Digestate is handled based on the process configuration employed for the digestion crop residues: If crop residues are digested on their own, the digestate is thick with up to 30% solid matter. The digestate may need to be dewatered and composted if it has been produced by co-digestion of feedstocks such as food waste or manure and the regulations require further treatment. Application of digestate produced from a variety of crop and feedstocks replenishes the soil with a variety of macro- and micro-nutrients and trace elements. Digestion makes the nutrients more available for plant absorption and also deactivates plant pathogens and weed seeds making use of digestate desirable.

5.5 Potential benefits

5.5.1 Model

The analysis in this chapter has been based on commonly available, digested and viable crop residues from around the globe: rice, wheat, maize, rye, barley, oats, rapeseed, sugar beets, sugarcane and sorghum. It has been assumed that 30-60% of crop residues can be captured sustainably[116,117], from which a portion is used to feed animals, resulting in a final residue recovery rate for digestion of 25-35% of crop residues. This includes straw that is used for animal bedding, which may enter the digestion process along with livestock manure.

After allowing for ploughing in and animal feed, of the 25-35% of crop residues that can be sustainably captured, we assume that the maximum capture percentage is 80%.

The key inputs for modelling the benefits of digesting crop residues are:

Crop residues (million tonnes)	Rice	Wheat	Maize	Rye	Barley	Oats	Rape seed	Sugar Beets	Sugar cane	Sorghum
Global Crop Yield estimate[118]	770	772	1,135	14	147	26	76	301	1,842	58
Harvesting residue coefficient[119]	1.33	1.33	1.5	1.86	1.5	1.5	3	0	0.28	2.33
Processing residue coefficient[120]	0.23	0.21	0.18	0.2	0.27	0.2	0.3	0.25	0.2	0.1
Recovery factor[121]	90	90	90	90	90	90	90	90	0	90
Total solids	96	90.15	89.6	86	86	86	80	11.6	76.7	94.5
Volatile Solids	79.4	93.55	93.2	94.4	93.7	93.5	94.3	85	86.3	94.2
Methane yield[122.123.124.125.126]	335.6	213.43	360	179	195	320	240	340	252	360

115 www.ows.be/organic_feedstock/dranco-farm/

116 IRENA (2014) Global bioenergy supply and demand projections for the year 2030

117 Einarsson R, Persson UM (2017) Analysing key constraints to biogas production from crop residues and manure in the EUĐA spatially explicit model

118 www.fao.org/faostat/en/#data

119 www.irena.org/publications/2014/Sep/Global-Bioenergy-Supply-and-Demand-Projections-A-working-paper-for-REmap-2030

120 www.irena.org/publications/2014/Sep/Global-Bioenergy-Supply-and-Demand-Projections-A-working-paper-for-REmap-2030

121 www.irena.org/publications/2014/Sep/Global-Bioenergy-Supply-and-Demand-Projections-A-working-paper-for-REmap-2030

122 CROPGEN Database www.cropgen.soton.ac.uk/deliverables.htm

123 BOORG Database www.bioenergy.soton.ac.uk/BMP_database.htm

124 Zealand (2017) Effect of feeding frequency and organic loading rate on biomethane production in the anaerobic digestion of rice straw https://doi.org/10.1016/j.apenergy.2017.05.170

125 Sharma (1988) Effect of particle size on biogas generation from biomass residues https://doi.org/10.1016/0144-4565(88)90107-2

126 Janke (2015) Biogas Production from Sugarcane Waste: Assessment on Kinetic Challenges for Process Designing https://doi.org/10.3390/ijms160920685

5.5.2 Energy

If all of the sustainably available residues (25-35%) from select crops were to be collected and anaerobically digested, they have the potential to 3,080 to 3,920 TWh that can be used on-farm or exported in the form of electricity and heat or as 300 to 380 bcm biomethane. The biomethane could meet the combined natural gas consumption of China and Japan[127]. If converted into electricity, it can meet the needs of 393 to 500 million people or 5.2-6.5% of the world population[128].

5.5.3 Emissions

Burning of crops, though illegal in most countries, continues to be practised as it is a cheap and quick way of clearing the field for the next planting. However, it causes greenhouse gas and particulate emissions, adversely affecting the air quality of neighbouring areas. This phenomenon has been observed on an annual basis in parts of Asia and Africa, notably India and China. The challenges to collect crop residues remain.

Digestion of residues of select crops can mitigate 865 to 1,100 Mt CO_2 eq. GHG emissions per year, equivalent to the emissions of Germany[129], by displacing fossil fuel-based energy and by avoiding emissions from the burning of crops.

5.5.4 Nutrient recovery

The nutrients from crop residues, which otherwise would have been lost to burning in biomass boilers or domestically for heating or cooking, can be recovered by anaerobic digestion. However, robust data on nutrient content and its availability in crop-based digestate are not available. Hence, the nutrient recovery advantage of crop residues has not been taken into account in the current analysis.

5.6 Realising the potential

Both ploughing in of residues and feeding them to animals are a desirable way of using crop residues. Those retrieved sustainably, in excess of these needs should be prioritised to be recycled via anaerobic digestion for energy and nutrient recovery. Currently, only a small proportion of crop residues is being utilised to its full potential. Some residues such as sugarcane are utilised for ethanol production in the US and Brazil. A part of rice and wheat straw is burnt domestically for fuel or in biomass boilers. Burning residues domestically causes significant air pollution and has an adverse effect on the health of women[130].

We assume that currently 5% of the currently sustainably recoverable residues of rice, wheat, maize, rye, barley, oats, rapeseed, sugar beets, sugarcane, and sorghum, that are not fed to animals (25-35%) are utilised for anaerobic digestion. We assume that this will increase to 25% by 2030 and 50% by 2050, keeping in mind the challenges in recovering residues from small farm holdings.

With increasing population, increased availability of calories per person and shift in diets, it is estimated that crop production will need to increase annually by 1.3% till 2030 and 0.8% till 2050 to meet the increased demand for food[131].

[127] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

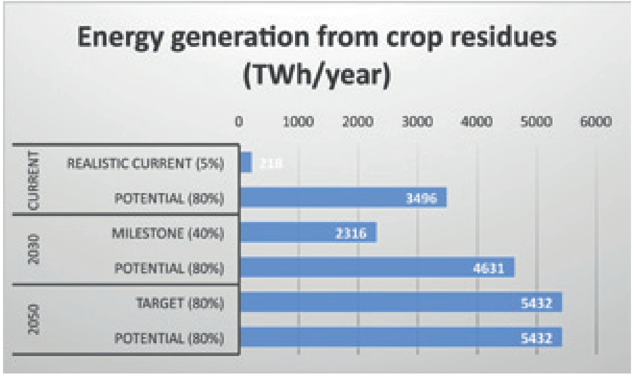
[128] https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC

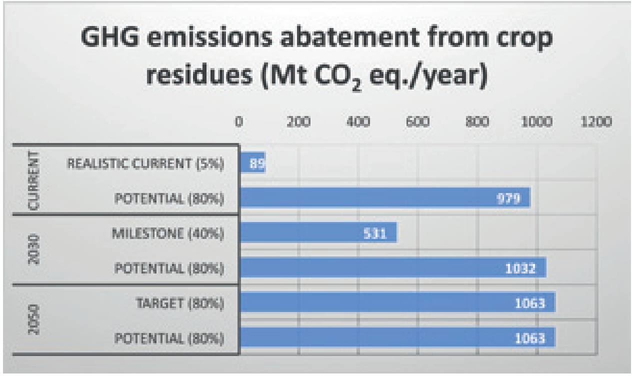
[129] http://cait.wri.org/

[130] www.ccacoalition.org/es/initiatives/household-energy

[131] www.fao.org/fileadmin/templates/esa/Global_persepctives/world_ag_2030_50_2012_rev.pdf

Assuming that crop production targets for 2030 and 2050 are met, in order to fully realise the potential of crop residues by 2050, the crop residue collection and digestion will need to be increased to 40% by 2030 and 80% by 2050. If this is achieved, the energy generation potential is 2,316 TWh/year and 5,432 TWh/year and GHG abatement potential is 531 Mt CO_2 eq./year and 1,063 Mt CO_2 eq./year as shown in figures 1 and 2.





5.7 What is needed to achieve this potential

- Enforcing the ban on burning of crop residues in the field.
- Giving rural households access to digesters, biogas and biogas stoves.
- For small farms: setting up cooperatives to collect and digest crop residues at scale.
- For large farms: Requiring farms above a certain size to have nutrient management plans that include crop residues.
- Making information on crop-based digestate available to farmers, both to support use on farm and also to get fair value for their export.

6. Energy Crops

6.1 Key Findings

- If energy crops were grown effectively and sustainably on 7% of agricultural land[132], as a part of annual, double, cover and rotational cropping schemes, there is a potential to generate 3,350 to 5,000 TWh of energy which can be utilised as heat and electricity, equivalent to the electricity consumed in India[133] or 330 to 490 bcm biomethane, equivalent to the natural gas consumed in the Russian Federation[134].
- These can mitigate greenhouse gas emissions equivalent to 910 to 1,350 Mt CO_2 per year, equivalent to emissions from Germany[135], in the form of avoided emissions from the production of fossil fuel-based electricity and heat.

6.2 Introduction

Crops that are grown for the sole purpose of producing energy are known as energy crops. Plants capture carbon dioxide from the atmosphere, photosynthesize it and convert it into biomass. This biomass, such as cereal crop silage, oilseeds and grasses, are harvested and used to produce energy by various methods such as anaerobic digestion to produce biogas, burning in biomass boilers to generate heat, converting it into bioethanol or biodiesel to be used as vehicle fuel. When biomass is digested in an anaerobic digester the methane from this process is captured and is known as biogas – its subsequent release occurs when the biogas is used as a fuel for heating, producing electricity, or for transport. When the biomass is burnt to produce energy, carbon dioxide is returned directly to the atmosphere. Energy crops are generally considered to be low carbon, renewable sources of energy. They substitute the energy that would have otherwise been produced from fossil fuels and can repeatedly be renewed through growing new crops.

Energy crops, however, need land to be grown upon and agricultural land is also used to grow food for people and animals. Any allocation to energy crops beyond a certain point takes away the availability of land for food, potentially leading to shortages or increased prices of food, both of which are undesirable. If land that is currently not under cultivation is used to grow energy crops, these could detract from the forests, grasslands, peatlands or other ecologically and environmentally essential land uses and result in greenhouse gas emissions from a change in land use- thus to a certain extent neutralising the benefits of renewable and low carbon energy. Further, the use of water and fertilisers for the growth of energy crops is a resource issue where previously fallow land is converted to this use. These concerns are addressed by implementing sustainability and greenhouse gas emissions criteria[136] for biofuels, limiting the use of agricultural land to meet renewable energy targets[137] and by encouraging sustainable agricultural practices such as crop rotation, cover cropping, and double cropping.

6.3 Energy crop management

Depending on geography, climate and type of fuel needed, a number of different varieties of crops can be grown and energy derived in different forms such as sugarcane and corn for bioethanol, rapeseed, palm and soybeans for biodiesel. For biogas production, maize silage and other cereal silages, grass silages, oilseed crops and root crops like potatoes and beets may be used.

[132] www.ieabioenergy.com/wp-content/uploads/2018/10/CountryReport2018_EU_final.pdf
[133] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf
[134] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf
[135] www.europarl.europa.eu/news/en/headlines/society/20180301STO98928/greenhouse-gas-emissions-by-country-and-sector-infographic
[136] https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/sustainability-criteria
[137] www.ieabioenergy.com/wp-content/uploads/2018/10/CountryReport2018_EU_final.pdf

Energy crops may be grown as dedicated, annual crops (harvested once a year on the same land), part of double cropping (harvesting twice in a year), part of rotational cropping (different crops grown on the same piece of land in rotation) or as cover crops (crops grown when land would normally be left fallow between 2 harvests). Mono-cropping or dedicated energy crops are not advised since they have an adverse effect on soil fertility, disease prevention and biodiversity. Cover crops or double crops, on the other hand, help in avoiding the food and fuel conflict, prevent land use change and also soil erosion. Digesting the crops and applying digestate contributes towards maintaining the soil carbon content and fertility[138]. Cover crops or double cropping can also be part of a rotation of crops tailored towards replenishment of soil nutrients, disease protection and supporting biodiversity.

6.4 Digesting energy crops

The digestion process of energy crops is similar to the digestion of crop residues discussed previously. Since energy crops are harvested seasonally, they are processed and preserved in order to maintain a continuous supply all through the year. The crop is chopped during harvesting and then dried to achieve optimal dry solids content. It is then compressed and covered to push out the air, following which it is fermented anaerobically to produce acidic conditions which prevent the spoilage of crop during storage. This process is called ensiling. The silage is then stored in silos to be used as feedstock when needed[139].

Energy crops are most often digested in a dry digestion process. It is lower in cost than wet digestion and also allows for longer retention times required by crops to achieve high biogas yields. The liquid digestate collected during the digestion process is recycled to seed the next batch of feedstock with micro-organisms. The solid part of the digestate is applied to land as soil amendment returning some of the carbon and nutrients.

Energy crops have high biogas and hence energy potential. They are often grown and added to manure digesters to make them financially viable since the energy generation potential of manure is quite low, but manure management and GHG abatement benefits which are not monetised are high. Relative biogas yields of feedstocks are shown in the figure (right)[140]:

WASTE	BIOGAS YIELD RANGE (M^3/WET TONNE)
Manure	
Chicken fresh	90-150
Chicken broiler	50-100
Pig slurry 6-9% TS	18-26
Pig manure (dung) 25% TS	40-80
Cattle slurry 8-12% TS	18-25
Cattle manure 25%	40-80
Raw materials	
Maize silage 33% TS	180-220
Whole crop (wheat)	180-210
Grain (oats, rye, barley, wheat)	300-550
Whole crop (oats, rye, barley Maize)	80-332
Grass Silage (cut to 6mm)	120-215
Beet leaves, fresh grass	39-70
Rapeseed	550-650
Sugar beet	235-380
Maize grain	270
Organics	
Potatoes 18%-20%	100-120
Bread	400-500
Mixed food (eg supermarket)	75-140
Cheese	>600
Vegetables	50-80
Molasses 80-90% TS	450-579
Brewery draff 20%TS	60-100
Misc	
Thick sewage sludge 10%	45
Glycerine	500-700

[138] www.researchgate.net/publication/305371248_Biogasdoneright_An_innovative_new_system_is_commercialized_in_Italy

[139] www.fao.org/3/x8486e/x8486e09.htm

[140] ADBA Practical guide to AD

6.5 Potential benefits

6.5.1 Model

Based on methane yield per hectare and the ease of growing and handling, the following energy crops have been chosen in the report: Corn silage, grass, ryegrass and alfalfa. Potatoes, sugar beets and Jerusalem artichokes have high yields but are trickier to digest due to them being root crops and needing to be washed thoroughly in order to avoid the build-up of grit in digesters and pipes, hence not included in the study.

There is no clear evidence on how much land can be sustainably allocated for the cultivation of energy crops as dedicated crop, cover or double cropped or rotationally cropped. Guided by the 7% limit that the European Union has established for the share of biofuels from crops grown on agricultural land that can be counted towards meeting renewable energy goals[141], we assume that area of land to be the maximum available for biogas energy crops. We assume that this land is equally divided to grow corn silage, grass, ryegrass and alfalfa.

Key inputs used for the modelling the benefits of digesting energy crops are:

Land currently used for the production of food crops that is suitable for agriculture[142]	Billion hectares	1.3
Percentage of land for energy crops	%	7

		Maize whole crop	Grass	Ryegrass	Alfalfa
Yield[143]	t DS per hectare	19.5	12.5	11.2	12
Methane yield (low)[144]	m^3 methane per hectare	5,000	4,000	3,500	4,000
Methane yield (high)[145]	m^3 methane per hectare	9,000	5,000	4,500	6,000
Dry matter content[146]	%	33	28	13	20

6.5.2 Energy

If 7% of global agricultural land were to be cultivated for energy crops as a part of the annual, double, cover and rotational cropping schemes and the harvest anaerobically digested, there is a potential to generate 3,350 to 5,000 TWh of energy. This energy can be utilised as heat and electricity, equivalent to the electricity consumed in India[147] or 330 to 490 bcm biomethane, equivalent to the natural gas consumed in the Russian Federation[148].

6.5.3 Emissions

The greenhouse gas emission mitigation benefit of energy crops has come under close scrutiny as it can lead to direct or indirect land use change, which has been pronounced in many parts of the world including Brazil and Indonesia[149]. Land use change takes away land forests, peatlands, grasslands and releases carbon stored in the land into the atmosphere.

However, sustainably grown energy crops have the potential to mitigate 910 to 1,350 Mt CO_2 eq. of greenhouse gases by displacing fossil fuel-based energy, equivalent to emissions from Germany[150].

[141] www.ieabioenergy.com/wp-content/uploads/2018/10/CountryReport2018_EU_final.pdf

[142] www.irena.org/publications/2014/Sep/Global-Bioenergy-Supply-and-Demand-Projections-A-working-paper-for-REmap-2030

[143] http://task37.ieabioenergy.com/files/daten-redaktion/download/publi-task37/Update_Energy_crop_2011.pdf

[144] http://task37.ieabioenergy.com/files/daten-redaktion/download/publi-task37/Update_Energy_crop_2011.pdf

[145] http://task37.ieabioenergy.com/files/daten-redaktion/download/publi-task37/Update_Energy_crop_2011.pdf

[146] CROPGEN database www.cropgen.soton.ac.uk/deliverables.htm

[147] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

[148] www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

[149] https://ec.europa.eu/energy/sites/ener/files/20190212_draft_report_-_post-isc_final.pdf

[150] www.europarl.europa.eu/news/en/headlines/society/20180301STO98928/greenhouse-gas-emissions-by-country-and-sector-infographic

6.5.4 Nutrient recovery

Energy crops require nutrients for their growth. However, unlike crops grown for human consumption of food, the nutrients are not diverted towards the production of cereal grains or vegetables. All the nutrients stay within the silage and after digestion, returned to the soil via digestate in a more available form.

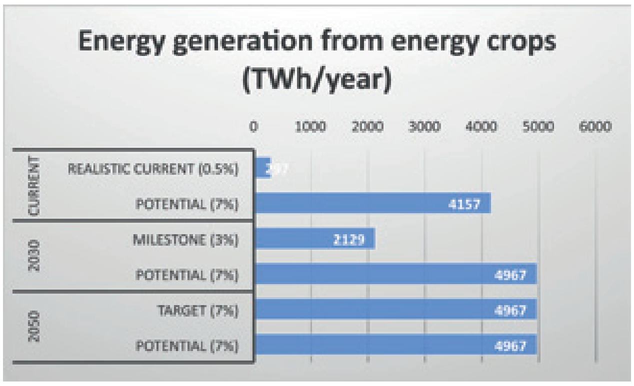
Thus, it is assumed that the fertilisers required to produce the energy crops are offset by the digestate applied to the farmland subsequently and that there is no net benefit in terms of nutrient recovery.

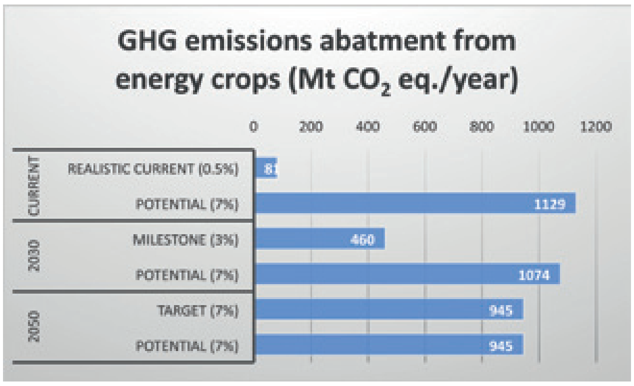
6.6 Realising the potential

The potential of deriving energy from crops is immense, not just from dedicated energy crops but also from cover, double and rotational cropping. While the cultivation of cover, double and rotational cropping of energy crops is being promoted in many parts of the world such as Italy and the UK, it is not a common practice still and little pertinent data is available. Dedicated cultivation of energy crops is the current norm. 2.2% of the total arable land in the UK is used to grow crops for the production of bioenergy and 1% for the production of biogas[151]. In Brazil, 1% of cultivable land in Brazil is used to grow energy crops, but the production of biogas is low as compared with the production of other bioenergy fuels such as bioethanol[152].

Based on these examples, it has been assumed that 0.5% of the current agricultural land globally is under the production of energy crops for biogas production. Based on the EU regulations, we assume that the maximum land that can be sustainably used for growing energy crops is 7% of total agricultural land. We also assume that moving forward, annual, dedicated energy crop production will give way to cover and rotational energy crops, allowing for effectively 7% of agricultural land be under energy crop cultivation at different times in the year.

In order to realise the full potential of energy crops to produce biogas via anaerobic digestion by 2050, 3% of arable land may be used for their cultivation by 2030 to reach 7% by 2050. If this is done, 2,129 TWh/year and 4,967 TWh/year of energy may be produced and 460 Mt CO_2 eq./year and 945 Mt CO_2 eq./year of GHG emissions may be abated, by 2030 and 2050 respectively. This is shown in figures 1 and 2. The increase in energy production potential from the same amount of land can be attributed to increased biogas yields that can be expected with the improvement in technology. The decrease in GHG mitigation potential from the same amount of land from 2017 to 2050 is due to reduced energy emission factors resulting from the deployment of renewable energy technologies.





[151] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664991/nonfood-statsnotice2016-6dec17b.pdf

[152] Bordonal, R..O., Carvalho, J.L.N., Lal, R. et al. Agron. Sustain. Dev. (2018) 38: 13. https://doi.org/10.1007/s13593-018-0490-x

7. Results and Conclusions

7.1 Key Findings

- The key finding of this report is that AD has the potential to reduce GHG emissions by 3,290 to 4,360 Mt CO_2 eq., which is equivalent to 10-13% of the current greenhouse gas emissions, through renewable energy generation, avoided emissions management, crop burning, deforestation, landfill gas and fertiliser manufacture emissions[153].
- There are currently about 50 million micro-digesters, 132,000 small, medium and large- scale digesters and 700 upgrading plants operating globally.
- Based on the current estimate of 87 TWh electricity generation, we are tapping into 1.6-2.2% of the potential of AD[154]. The potential for the growth of the biogas industry is therefore extraordinary and involves every country.
- The potential to generate energy from currently available and sustainably grown/recovered major feedstocks in the world is 10,100 to 14,000 TWh. This energy can meet close to 6-9% of the world's primary energy consumption or 23-32% of the world's coal consumption[155].
- When used as electricity, it has the potential to meet 16-22 % of the electricity consumed in the world[156].
- If the energy is utilised as biomethane, it can substitute 993 to 1,380 bcm of natural gas, equivalent to 26-37% of the current natural gas consumed[157].
- Use of digestate as soil amendment can replace 5-7% of inorganic fertiliser currently in use. It can fertilise 82 million hectares of land[158], equivalent to the combined arable land in Brazil and Indonesia[159].

7.2 Introduction

The combined benefits of anaerobically digesting food waste, livestock manure, crop residues, energy crops and sewage and capturing landfill gas are significant in terms of energy generation, greenhouse gas abatement and nutrient recovery. The report now details the combined impact that anaerobic digestion of these feedstocks can have and how they can help in enabling energy security, climate change mitigation and soil replenishment. We assume that all conditions of sustainable recovery and growth discussed with regards to each feedstock are met and all feedstock then made available is utilised via anaerobic digestion.

In addition to the feedstocks discussed in the earlier chapters, there are waste streams from the food and drinks industry, such as palm oil mill effluent, breweries, dairies, slaughterhouses that can utilize their waste via anaerobic digestion. While some of these such as breweries widely treat their waste, others like the palm oil mills are now beginning to implement treatment while digestion of slaughterhouse waste is not common. Similarly, the digestion of seaweed, algae and cacti is being undertaken on a pilot scale and the technology is on the horizon. The potential of these waste streams varies widely with geography and is not included in this report.

7.3 Energy generation

The potential to generate energy from currently available major feedstocks in the world is 10,100 to 14,000 TWh. This energy can meet 6-9% of the world's primary energy consumption or 23-32% of the world's coal consumption[160]. This energy can be used in the form of heat and electricity or upgraded to biomethane to be used as heat or vehicle fuel. When used as electricity, it has the potential to meet 16-22% of the electricity consumed in the world. This has the benefit of displacing fossil fuel-based energy with low carbon, renewable energy and also abatement of greenhouse gas emissions.

[153] Data IEA/OECD (2018), World Energy Outlook, Paris

[154] www.irena.org/bioenergy

[155] Data IEA/OECD (2018), World Energy Outlook, Paris

[156] Data IEA/OECD (2018), World Energy Outlook, Paris

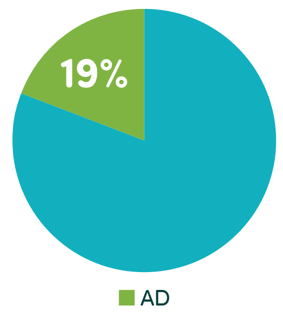
[157] Data IEA/OECD (2018), World Energy Outlook, Paris

[158] https://data.worldbank.org/indicator/ag.con.fert.zs

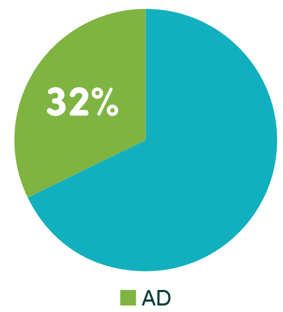
[159] www.nationmaster.com/country-info/stats/Agriculture/Arable-land/Hectares

[160] Data IEA/OECD (2018), World Energy Outlook, Paris

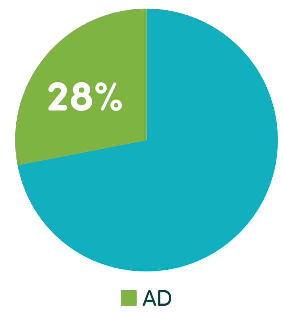
If the energy is utilised as biomethane, it can substitute 993 to 1380 bcm of natural gas, equivalent to 26-37% of the current natural gas consumed. While natural gas has lower emissions than its solid fuel counterparts, it is still a fossil fuel which on burning adds carbon dioxide to the atmosphere.



AD potential to meet Global electricity demand
Mid point case



AD potential to meet Global natural gas demand
Mid point case



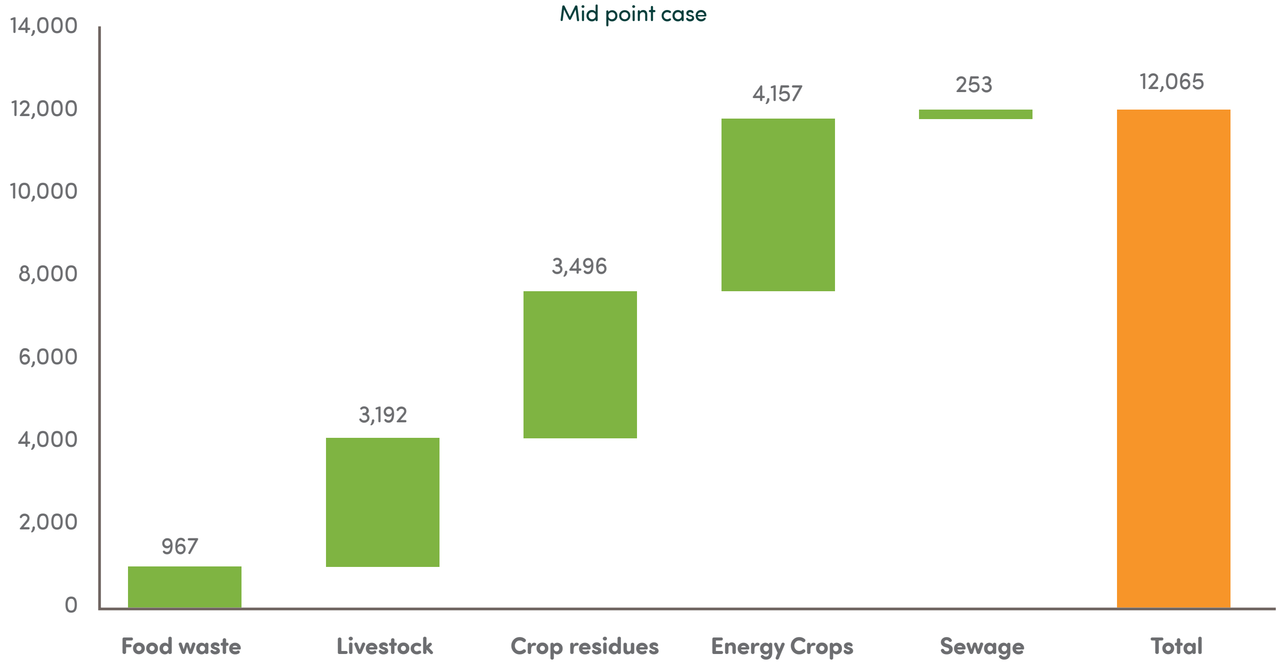
AD potential to meet displace primary energy from coal
Mid point case

Livestock manure and crop residues have the greatest energy generation potential, followed by energy crops. The figure below shows the relative contribution of each feedstock to the total potential to generate energy via anaerobic digestion. The high potential contribution from livestock manure is a result of the sheer volume of manure generated as the unit energy potential of livestock is relatively low. Crop residues have both high energy potential per tonne and also can be available in high volume. In an urban setting, food waste has the most significant contribution towards energy generation.

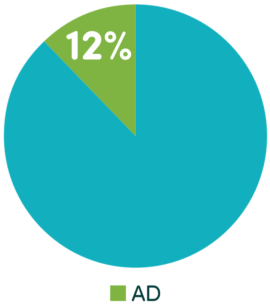
7.4 GHG abatement

Greenhouse gas abatement from anaerobic digestion of organic waste streams comes in a number of forms: avoided emissions from fossil fuel burning, avoided emissions from inorganic fertiliser manufacture, avoided landfill emissions from food waste digestion, avoided emissions from manure management and avoided emissions from burning of crops.

Potential energy generation from various feedstocks (TWh)
Mid point case



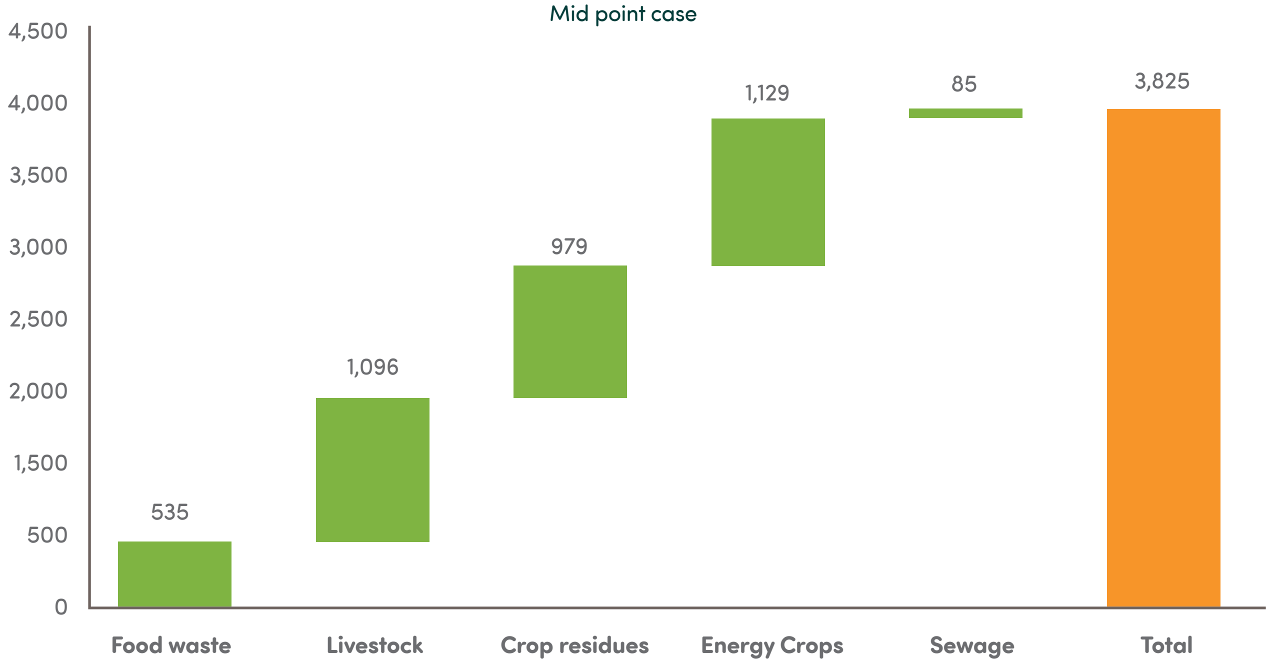
The key finding of the report is that if all streams of feedstock are sustainably captured as discussed in the previous chapters, there is a potential to reduce GHG emissions by 3290 to 4360 Mt CO_2 eq. which is equivalent to 10-13% of the current greenhouse gas emissions.



AD potential to abate GHG emissions
Mid point case

The figure below shows the potential contribution of various feedstocks of AD for GHG abatement. The collection and digestion of livestock manure has the highest potential contribution, followed by crop residues and energy crops. While the potential contribution of food waste is not relatively high, it has the highest impact in an urban setting. Sewage and landfill gas capture offer the easiest implementation pathways, since no collection and transport of feedstock is required.

Potential GHG abatement from various feedstocks (Mt CO_2 eq. per year)
Mid point case



7.5 Nutrient recovery

Once the feedstocks have been treated and energy recovered from them, what is leftover is called digestate or natural fertiliser.. This nutrient-rich digestate can be applied to land for the recirculation of nutrients and carbon to the soil. There is empirical evidence that anaerobic digestion makes the nutrients in feedstock more available for plant absorption. From a lifecycle perspective, anaerobic digestion of food waste and sewage recovers nutrients that otherwise would have been lost to landfills or water bodies. It is common practice to apply raw livestock slurry to land or crop residues to be ploughed into the soil, hence the benefit of digestate is from higher availability of nutrients. This benefit also varies significantly on external factors including feedstock type, soil type and climatic conditions. The nutrient recycling benefit of AD has, therefore, potentially been underestimated in the report.

Application of digestate also returns a part of the carbon in the feedstock to the soil. With soil quality in many parts of the world shown to be at risk of depletion of organic carbon[161], replenishment of nutrients and carbon has become critical.

Use of digestate as soil amendment can replace 5-7% of inorganic fertiliser currently in use[162]. It can fertilise 82 million hectares of land[163], equivalent to the combined arable land in Brazil and Indonesia[164].

7.6 Realising the potential

As we have seen in this report, anaerobic digestion has tremendous potential to meet our energy needs, abate GHG emissions and recover nutrients and carbon. Based on the current estimate of 87 TWh electricity generation, we are tapping into 1.6-2.2% of the potential of AD[165]. The technology is proven and established. The feedstocks are there. In order to realise the full potential of AD, the right policies need to be implemented now, to increase the capture of feedstocks and to attract investment to the sector.

As we look to the future, there are three high-level trends that we foresee:

- With increased capture, of all feedstocks except food waste, the energy generation potential of AD is likely to increase from the current 12,065 to 14,627 TWh in 2030 and 15,922 TWh in 2050. The higher capture rate of wastes and their treatment via anaerobic digestion will decrease emissions to the atmosphere.
- With increased deployment of other renewable energy technologies and the shift away from coal in energy generation, the emission factors of the grid energy are likely to improve. This will counterbalance the unit GHG abatement benefit from energy generation via anaerobic digestion.
- The projections of development of AD, 2030 and 2050 discussed in the respective feedstock chapter, are based on the technology and yields from feedstocks that we can achieve today. We know that some ruminant animals' digestive system biologically undertakes the same process at 30 times the efficiency. With further deployment of technology, investment in research, better yields and efficiencies are likely to be achieved, improving the environmental credentials of anaerobic digestion further.

7.7 Policy Recommendations

To achieve this potential, policy and regulatory support is required because the ability to decarbonise energy production is dependent upon being able to operate at least on a level playing field as entrenched and existing operators. The multiple contributions from biogas (treating waste as well as producing energy and fertilisers) are often not accounted for as a value so operators do not receive payment for these. Therefore biogas is considered often to be more expensive than fossil fuels and policymakers have difficulty in understanding the full intrinsic value- especially where fossil fuels receive substantial incentives and tax breaks.

[161] www.fao.org/3/a-i5199e.pdf

[162] World fertilizer trends and outlook to 2020 www.fao.org/3/a-i6895e.pdf

[163] https://data.worldbank.org/indicator/ag.con.fert.zs

[164] www.nationmaster.com/country-info/stats/Agriculture/Arable-land/Hectares

[165] www.irena.org/bioenergy

The types of support required will vary depending on the particular geography in question, but at the high level the global industry needs:

- The removal of all fossil fuel subsidies to create a level playing field. This includes the gradual removal of subsidies to lower the retail price of fuels to consumers as well as eliminating tax breaks for exploration and exploitation of fossil fuel reserves. According to the IMF current fossil fuel subsidies represent 6.5% of global GDP, the highest externality ever recorded[166].
- Making a national commitment to reduce greenhouse gas emissions to nett zero by 2050. The United Kingdom has announced this commitment and put binding legislation before Parliament to ensure it is enforced long term[167].
- The drafting of national energy plans to raise the level of renewable energy production and consumption over a future period (a decade is normal) and incorporating into this targets for the production of biogas by anaerobic digestion[168].
- Anaerobic digestion to be urgently included in all government strategies for meeting greenhouse gas abatement targets recognising the GHG abatement benefits of anaerobic digestion and incentivised via carbon markets[169].
- Anaerobic digestion to be included in all renewable energy generation incentives[170].
- To develop knowledge, raise awareness and implement regulations, standards and certifications for safe trading and use of digestate[171].
- The implementation of circular economy strategies with AD at their core; and, anaerobic digestion to be nominated as the preferred method of treatment of all biodegradable wastes (human – sewage and food; agricultural; commercial; industrial) accompanied by policies to increase capture[172].

All policies should consider the circular nature of the AD industry, and consider the full potential for energy generation, nutrient recovery and recycling, use as waste treatment and the potential to fuel buses and fleet transport:

- Improved sanitation infrastructure around the globe will significantly improve health and environmental outcomes, as well as increase collection of sewage for wastewater treatment. This should be accompanied by the connection of centralised wastewater treatment plants to anaerobic digesters and decentralised sanitation facilities or community toilets to micro- or small- scale digesters.
- Local governments should provide separate food waste collection to all citizens of towns and cities, and to rural communities where feasible. This increase in food waste collection should be met with increased anaerobic digestion capacity to process the new waste stream and convert it into biomethane to fuel the boilers, cookers and buses of the localities.
- Businesses above a certain size should be mandated to report and separately collect food waste for treatment. The biogas generated can then be upgraded to power their business and fuel their delivery fleets. Businesses powered by biogas can be certified with the biogas mark to signal their support for the AD industry.
- Large farms should have nutrient recovery plans that recycle organic material through AD, including crop residues and manure. Agreements should be arranged in rural communities to collect and digest livestock manure and crop residues from small farms. Rural communities in more isolated geographies should be provided access to digesters to recycle their organic waste and provided with biogas stoves to use the biogas produced. Digestate produced can be applied as fertiliser, or upgraded, to recycle valuable nutrients back to the soil and displace inorganic fertilisers.
- Sustainability and greenhouse gas emissions criteria for all agricultural production to ensure land is managed with due diligence to the environmental impact and energy crops can be integrated into production in the most sustainable way.
- Governments should incentivise widespread investment in refuelling network for biomethane as a transport fuel and infrastructure for injection of biomethane into the gas grid. Developing the infrastructure network will encourage growth in anaerobic digestion and biomethane upgrading.

[169] www.worldbank.org/en/programs/pricing-carbon

[170] www.ofgem.gov.uk/environmental-programmes/fit/fit-tariff-rates

[171] www.iea-biogas.net/files/daten-redaktion/download/publi-task37/digestate_quality_web_new.pdf

[172] www.gov.uk/government/publications/resources-and-waste-strategy-for-england/resources-and-waste-strategy-at-a-glance

Policies from around the globe:

- South Korea increased food waste collection from 2% in 1995 to 95% in 2019 by banning food waste to landfill; introducing compulsory food waste recycling; charging for biodegradable bags; using smart bins that weigh food waste as you deposit it and charge residents accordingly; and introducing schemes to establish urban farms and community gardens.
- The European Commission has introduced legislation in 2018 to oblige member states to introduce source segregated food waste collection on households and businesses from 2023. This can be counted towards recycling targets only if treated in AD or composting.
- Specific policies that provide financial incentives have been effective in stimulating increased AD capacity in the UK and Germany. Long term security over incentives helps create a low-risk environment for the growth of the AD sector, as seen in Germany
- Effective policies regarding the management of agricultural waste streams can incentivise appropriate treatment through anaerobic digestion, for example, Canada's Agricultural Waste Control Regulation in its Environment Act
- Nutrient management policies can help protect surface water bodies from contamination, eutrophication, growth of algae and decreased oxygen level. India's National Biogas and Manure Management Program promotes the use of small-scale AD plants that use manure as feedstock and fuel domestic cookers, reducing deforestation for firewood and improving sanitation. Sweden has an advanced digestate quality standards programme.
- Germany, in its Biofuels Quota Act, has set a minimum share of biofuels to be sold in the energy market, and Chile has set a minimum requirement for the proportion of energy sourced from renewables, which has been increased to 20% by 2025.
- Feed in Tariffs have been introduced in Malaysia for the treatment of palm oil residues; South Africa's 2019 national energy plan foresees incentives for renewable energy production
- In Finland, biomethane is exempt from production and excise tax;in the Dominican Republic, equipment and accessories related to the installation of biodigesters are exempt from tax under the Renewable Energy Development Act; in the UK a Climate Change Levy taxes businesses for energy use but they are exempt for energy sourced from renewables.
- Credits for renewable transport fuel are applied in Belgium; UK; USA; Italy; Sweden; Norway among others.

Abbreviations

- **AD** – Anaerobic digestion
- **CO_2** – Carbon dioxide
- **Bcm** – Billion cubic metre
- **GHG** – Greenhouse gas emissions
- **Gt** – Gigatonnes / Billion tonnes
- **Mt** – Megatonnes / Million tonnes
- **TWh** – Terra Watt-hour

Inputs to the model common to all feedstocks

- 2017 has been used as the base year where possible with future analysis for 2030 and 2050.
- The low and high ranges of potentials (energy generation and GHG abatement) are based on low and high values of the assumed range of biogas yields for all feedstocks except for crop residues, which are based on the potential to sustainably capture residues.
- In 'Realising the potential' analysis, 2017 energy production and GHG abatement values are calculated based on the midpoint of the assumed range of biogas yields, while 2030 and 2050 values are based on the high values of the assumed range. The biogas yields for 2030 and 2050 have been the same due to lack of robust data on what might be expected. This is assumption is applicable for all feedstock future

Energy calculations[173]:

1	Watt	1	Joule per second
1	Watt Hour	3,600	Joules
1	kilowatt hour	3,600,000	Joules
		3.6	MJ
1	m^3 of biogas	22	MJ
		6.11	kilowatt hour total energy
1	m^3 of methane	10.19	kilowatt hour total energy

Methane content of biogas[174]	60	%
Digestate to feedstock ratio[175]	0.85	Assumed
Electrical Energy conversion efficiency[176]	40	%
Thermal Energy conversion efficiency[177]	50	%
Parasitic load[178]	10	%
Fugitive emissions[179]	2.5	%

	2017	**2030**	**2050**	
Electricity emission factor[180]	0.53	0.402	0.343	Mt CO_2/TWh
Heat emission factor[181]	0.12	0.111	0.106	Mt CO_2/TWh

[173] www.valorgas.soton.ac.uk/Pub_docs/JyU%20SS%202011/CB%204.pdf

[174] 50-75% ADBA Practical Guide to AD Chapter 5

[175] 80-90% https://bit.ly/2FiutVC

[176] www.clarke-energy.com/2013/chp-cogen-efficiency-biogas/

[177] www.clarke-energy.com/2013/chp-cogen-efficiency-biogas/

[178] www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf

[179] www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf

[180] Data IEA/OECD (2018), World Energy Outlook, Paris

[181] Data IEA/OECD (2018), World Energy Outlook, Paris

Emissions in production of fertiliser[182]

N-fertiliser	5,881	g CO_2eq/kg N
P_2O_5-fertiliser	1,011	g CO_2eq/kg P_2O_5
K_2O-fertiliser	576	g CO_2eq/kg K_2O
CaO-fertiliser	130	g CO_2eq/kg CaO

World population forecast[183]

2017	7.6	billion
2030	8.6	billion
2050	9.8	billion

[182] www.biograce.net/content/ghgcalculationtools/standardvalues

[183] www.un.org/development/desa/publications/world-population-prospects-the-2017-revision.html

Sponsors

When it comes to biogas upgrading there is no doubt that DMT should be your choice. For the key biogas contaminants, our team of biogas specialists can offer one or a combination of proven, reliable technologies to economically manage them. DMT is your partner, a reliable total solutions provider.

Our team is there for you, every step of the way from funding to lifetime service. Our technology is simple, no high columns or complicated technologies using a lot of heat and electricity. DMT's biogas upgrading system, using membrane technology, is the most efficient and reliable on the market to date.
www.dmt-et.com

IES BIOGAS is an Italian company specialised in the design, construction and management of biogas and biomethane plants. Founded in 2008, IES BIOGAS immediately began playing a key role in the agricultural and industrial sector through the construction of nearly 200 plants in just a few years.

IES BIOGAS' goal has always been to build installations that fully meet the needs of the market in terms of construction and safety but also of management and automation. Since July 2018, IES BIOGAS has become part of the Snam Group, the European leader in natural gas infrastructure management.
www.iesbiogas.it

WANGEN PUMPEN: The market leader for progressive cavity pumps to the anaerobic digestion industry. Convincing high quality and flexibility.
www.wangen.com

The rise of membrane biogas upgrading technology globally

Upgrading biogas to biomethane, for injection into the gas grid or for use as a vehicle fuel, has long been touted as one of the most efficient uses of biogas – it boasts efficiency levels of almost 100%, in comparison to just 40 per cent when the gas is converted into electrical energy.

What is upgrading?

Natural gas is typically composed of more than 90 per cent methane, plus carbon dioxide (CO_2), hydrocarbons and other contaminants. Biogas is only suitable for heat and electricity generation, but when it is upgraded to a higher standard of purity, it can be injected into the gas grid and used for the same purposes as natural gas. The upgrading process removes CO2 and any contaminants, thereby increasing the methane content to more than 97 per cent. This upgraded biogas is called biomethane.

Upgrading options

There are a number of different upgrading technologies on the market. The main solutions are:

- Water wash technology, which uses high pressure water to 'scrub' impurities such as CO_2, and H_2S from raw biogas;
- Chemical wash, which uses absorber liquids such as glycol ethers or amines to remove the contaminants;
- Pressure swing adsorption (PSA), which uses adsorbent beds to remove impurities;
- Cryogenic upgrading, which involves compressing, cooling and then expanding the biogas until the CO_2 is condensed and can then be removed as a liquid;
- And membrane technology, which uses gas permeation to separate CO_2, O_2 and H_2 from CH_4 and N_2.

All of these solutions are in use at biomethane facilities around the world. But in recent years, membrane technology has become the preferred upgrading solution at more than 50% of all upgrading plants globally, see figure 1. It was also the technology adopted by the UK's first commercial biogas to biomethane plant, at Poundbury in Dorset. The plant builder chose the Carborex®MS system, a highly selective membrane technology from DMT Environmental Technology, to upgrade its biogas to biomethane.

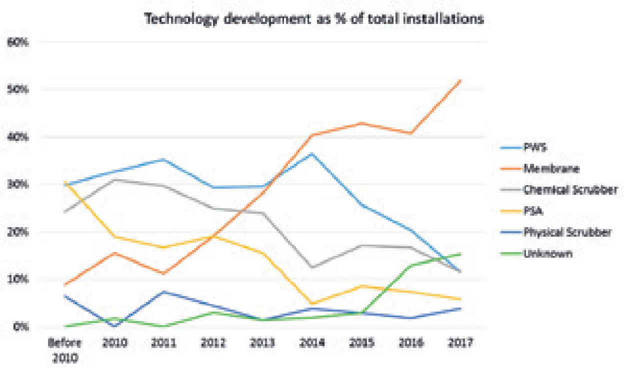


Figure 1 -Annual market share of upgrading techniques worldwide (source: DMT market data)

Understanding the pros and cons

As well as their respective advantages, most of the upgrading solutions listed above also have their disadvantages. Historically, the first commercial biogas upgraders in Europe were water scrubbers. Despite a strong heritage and being known for its reliability, the technology is not without its limitations: the tall columns needed for the solution to work are unsightly and can cause issues with planning permission; its optimisation potential is not particularly high; and it has a high-water consumption, as well as producing lots of wastewater.

Chemical scrubbers also have a visual impact, requiring the same tall columns as water scrubbers. This technology has its limitations because the availability to freely regenerate chemicals to suppress the operational cost is very limited. The technology can achieve extreme low methane slip, however the work with chemicals can be a disadvantage for planning permission and operation.

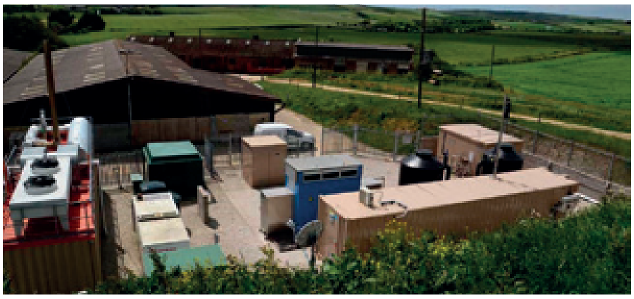
PSA has a smaller footprint but is liable to leak small quantities of methane, known as a 'methane slip'; methane is a 23-times stronger greenhouse gas than carbon dioxide, so keeping the amount that leaks into the atmosphere from your biogas upgrading system under at least two per cent is essential for any responsible developer. And while cryogenic upgraders generate excess heat which can be recovered for use elsewhere in the process, they also require a considerable amount of energy, are complex operations and have high maintenance requirements.

Membrane upgraders have a small footprint, a low methane slip, require little maintenance, achieve high quality and gas production; all of which has helped to become the most popular biogas upgrading technology in the world today.

Advantages of membrane

One of the most efficient membrane solutions on the market is the Carborex®MS, a compact, modular unit built into containers. It upgrades biogas to biomethane via a unique, advanced multi-stage system in combination with highly selective membranes. It has the highest energy recovery available at 96-98 per cent and the upgraded gas has a methane concentration of 97-99 per cent CH_4. It is also an environmentally-friendly solution – at just 0.5 per cent, the methane slip level of the Carborex®MS is among the lowest on the market, and it has the lowest electrical requirement of all the upgrading solutions.

Carborex® MS



DMT Delivers first commercial biogas upgrading plant using membrane technology

It has been five years since HRH The Prince of Wales officially opened the UK's first commercial biomethane-to-grid plant at Poundbury, Dorset, back in November 2012. Such was the confidence in the market following Poundbury that it inspired nothing short of a green gas revolution; in just five years, 87 biomethane plants have been built across the UK, injecting a total of 3.8 TWh of green gas into the grid each year – enough to heat a city the size of Sheffield.

The membrane upgrading technology for the 650 m^3/hr Poundbury project was supplied by DMT Environmental Technology and it has since been installed at over 50 biomethane plants worldwide generating over ½ billion m^3/hr of biomethane in 2019.

As it was first unknown what the capabilities of the membrane technology were, DMT's portfolio has proven that both in flow rate (ranging from 40Nm^3/h – 6500 Nm^3/h) and biogas quality (ranging from complex landfill gas to biogas from MSW or agriculture) membrane upgrading is capable of achieving the necessary quality and output.

DMT has stays as such on the forefront of the development and also includes the multi-award-winning biomethane plant at Somerset cheese producer Wyke Farms.

DMT Environmental Technology has now been prompted to take its UK offering to the next level by the pace of activity in the UK biomethane sector. With increased RHI tariffs and guarantees about to be rubber-stamped in Parliament, the company has confidence in the strength of the market and has invested in a dedicated sales force; UK Business Director Stephen McCulloch, who has led work on numerous UK gas-to-grid projects throughout his career. "As well as expanding the UK market, we will be increasing the scope of our supply, including offering finance options," says Stephen. "In addition, we have fine-tuned our offering and are issuing a five-year equipment guarantee on our Carborex®MS technology. With this new, improved strategy we look forward to helping to take the already thriving UK biomethane sector to the next level."

For media enquiries about DMT Environmental Technology please contact:

Marjolein Overbosch, DMT Environmental Technology
Yndustrywei 3,8501 SN, Joure, The Netherlands
Tel: +31 513 636789
Email: **info@dmt-et.nl**
www.dmt-et.com

Guaranteed performance

For many users of the Carborex®MS membrane technology, one of the key benefits is its ease of operation. From start-up to grid injection takes just 3-4 minutes and is activated with the touch of a button. Its compact size and ease of use make it highly flexible and suitable for AD plants of any size, treating any type of feedstock. It has low maintenance requirements too, boasting an uptime of 98 per cent.

Thanks in part to the impending changes to the RHI, we see a robust future for the UK biomethane sector. As a result, as well as expanding the UK market, we are increasing the scope of our supply of membrane upgrading solutions, including offering finance options. In addition, we have fine-tuned our offering and are issuing a five-year membrane guarantee on our Carborex MS upgrading technology.

Already in use at almost 50 UK plants, modern membrane systems offer users a high quality, environmentally-friendly and flexible upgrading experience, compared to other traditional high-rise, complicated or energy-intensive techniques. Compact, efficient and simple to use, membrane upgrading technology is perfectly placed to take the UK towards a green gas revolution

About DMT Environmental Technology

DMT Environmental Technology is the market leader in biogas upgrading with membrane technology and innovations for desulphurization, water treatment and resource recovery - these technologies and products help companies to make a contribution to the environment in a profitable way. A reliable partner with 30 years' experience, DMT-ET was the first to build a commercial upgrading plant in Europe. In 2016 we sold the biggest upgrading plant in the world, acquired a company to add resource recovery technology to our products and developed the Sulfurex BR for better desulphurization. DMT-ET has offices in Europe, the United States, Canada and Asia.

www.iesbiogas.it

1410 kW

CASE HISTORY
ADECOAGRO CHRISTOPHERSEN

SANTA FE - ARGENTINA

An innovative and efficient biogas plant Made in Italy, perfectly integrated into the production cycle, created by IES BIOGAS, able to enter into the national grid up to 1410 kW per hour and meet the needs of 3,500 families, without waste, without odor, to the benefit of the environment and the community. An investment that has successfully completed the cycle of self-sufficiency of the farm AdecoAgro. At the same are produced thermal energy for district heating and natural fertilizer quality. So the cycle is perpetuated over time, with a high level of efficiency.

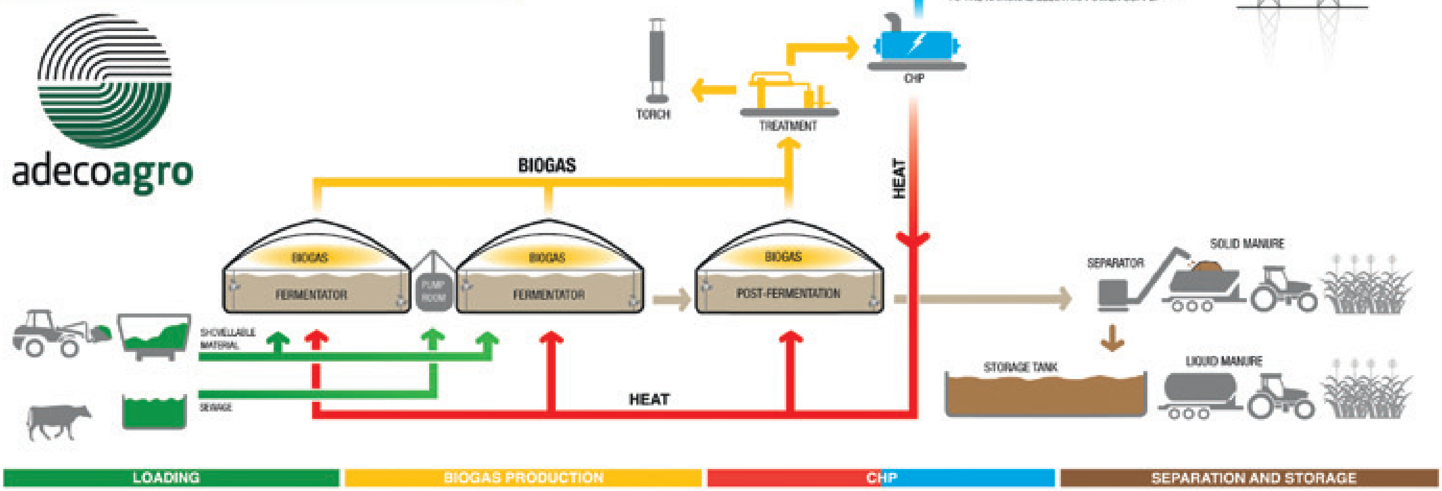
IES AGRO & INDUSTRY is the division of **IES BIOGAS** entirely dedicated to the provision of design, implementation, management and assistance services for biogas/biomethane plant facilities for the agricultural and agro-industrial sectors Our watchword is "elasticity and measure", adopting a professional approach and objective.
Through careful analysis of the area and the business environment, **IES AGRO & INDUSTRY** offers each customer the best technical solution. The aim of **IES BIOGAS** has always been to create a system that fully meets the needs of the market in terms of construction and safety, but also the management and automation. For this reason, projects, civil works, piping, electrical and plumbing, software, technical assistance and biological, are developed in Italy, guaranteeing the customer a product "made to measure".

Our verifiable reliability and experience are the guarantee that a plant signed **IES BIOGAS** is a safe investment for the future, with a high, constant and programmable gain.

IESAGRO&INDUSTRY
New Energy from Nature

DATASHEET CHRISTOPHERSEN

adecoagro



INSTALLED ELECTRIC POWER				1410 kW

A TWO-STAGE PROCESS MESOPHILIC

Pre tank mixing:	n.1	Ø 10 m		h=4m
Fermenters:	n.2	Ø 30 m		h=6m
Post-fermenter:	n.1	Ø 30 m		h=6m
Biomass Load:	n.2 hopper			60mc

DAILY FEED TABLE

Bovine manure:	140,0 ton
Feed Discard:	10,0 ton

ENERGY YIELD

Annual production of electricity:	11.886.000 kWh
Annual production of biogas:	5.058.000 mc
Average concentration of methane (CH_4) in biogas:	52-54%

ALTERNATOR TECHNICAL DATA

Manufacturer:	Stamford
Modello:	HCI 734

ENGINE

Manufacturer:	GE Jenbacher
Model:	JGS 420 GS SL B33

THE BIOGAS IS ONE OF THE ALTERNATIVE SOURCES MORE USED FOR THE PRODUCTION OF RENEWABLE ENERGY.

The biogas is the product of the microbial degradation of organic substances in the absence of oxygen, a process commonly called anaerobic digestion. It is a mixture of gases, composed mainly of methane (CH_4) and carbon dioxide (CO_2).

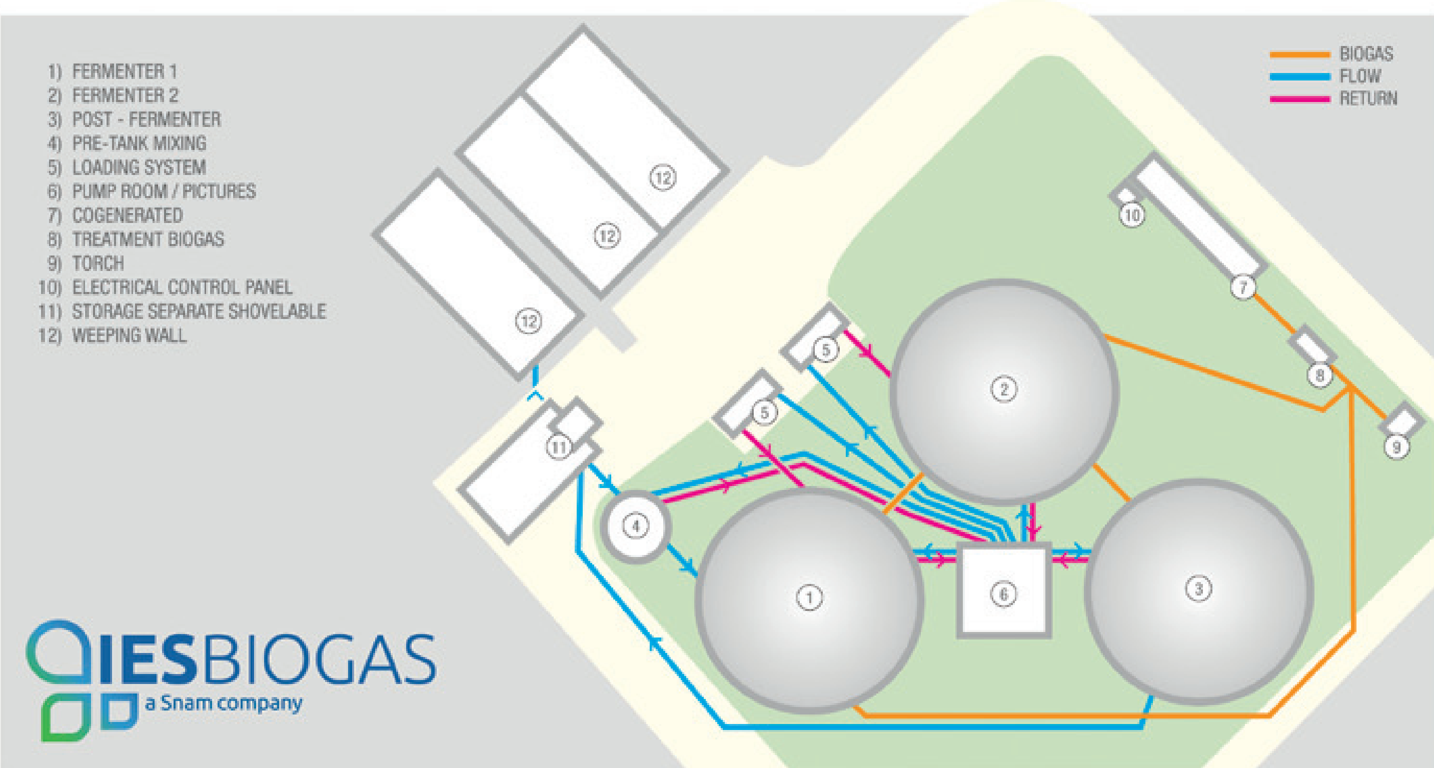
Corn silage, Milking cow scurry and Cow manure, are inserted daily into the two primary digesters. Here they remain for about 100 days and then go in the storage tank covered. The process and then type a "dual-stage" and occurs at a temperature of 38-42 degrees (mesophily conditions). The technology to "double-stage" allows you to have a fermentation process secure and resilient but especially ensures retention times appropriate.

The coverage of storage in addition to ensuring a complete degradation and therefore an effective exploitation of biomass used, allows a greater reserve of biogas and allows for better desulfurization (removal of the H_2S). Desulphurisation and of biological type for injection of very small amounts of oxygen. The internal structure and a network desolforatrice offer a good surface for the colonization of bacteria desolforatori. The biogas produced is conveyed to the cogenerator that produces electricity and thermal energy. The first is transferred to the public network, the heat instead is reused in part for the fermentation process, in part because of the district heating of the stables and offices. At the end of the fermentation process is obtained the digestate, a liquid material, completely odourless, high value for cultivation, with improved features with respect to the starting material.

The digestate undergoes a process of solid/liquid separation: the solid that has the consistency, the appearance and smell of a "humus", is distributed in the fields with a wagon manure spreaders or sold to specific users as the gardens-florists.

Biogas is an opportunity to produce energy locally and in a sustainable way, improve the impact of the herds, diversify the income of farms, giving the farmer with the possibility to gain a secure. Biogas can also be tool in order to ennoble the role of "resource" by-products of the asset farm difficult to reuse otherwise, which are converted into opportunities for further income and lever for a healthier environment.

FOR THE BENEFIT OF WATER QUALITY, AIR AND SOIL.



WORLD BIOGAS
ASSOCIATION

The World Biogas Association

The WBA is a non-profit association dedicated to the development of biogas globally. We are available to offer services to countries, cities and industries wanting to know more about biogas, its technologies, the policies and incentives needed to ensure biogas is made a core solution to resolving global challenges around sustainable development, climate change and public health.

The future of biogas is now
Join us in realising our mission

E: **info@worldbiogasassociation.org**
T: +44 (0) 20 3735 8116