Chapter 8. Bioenergy

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Chapter outline

1. **Motivate the chapter** by watching a video and discussing the main points that we will address in the chapter
2. Study the **current status** of bioenergy in the energy mix focusing in the role of bioenergy in the industry sector, the transport sector, the building sector and the power sector
3. Study the **technology outlook** and the future trends of bioenergy
4. Complement the chapter by studying important topics as types of **bioenergy**, **biogas** or **bioethanol**

Discussion

To motivate the chapter, we start by watching the video How Gasification Turns Waste Into Energy

Based on that video, we discuss the next questions:

1. The video claims that bioenergy could have several **advantages for the environment**. Could you enumerate some of those advantages?
2. The video proposes different ways to obtain **energy from waste**. Could you enumerate them?
3. Can you explain briefly the **gasification process**?
4. Do you know **other ways** to generate biodiesel, biogas or methanol?
5. Can you explain the **business model** used during the gasification process?
6. Can you enumerate some of the **main challenges** that could face the implementation of gasification by using waste?

Bioenergy

The **greenhouse gas emissions** derived from agriculture, forestry, land use and waste suppose the 21.6% of the total greenhouse gas emissions (figure below).

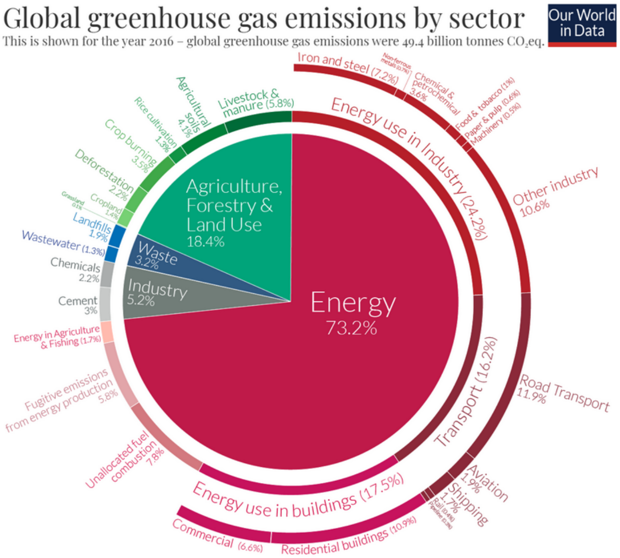
Moreover, The agricultural sector is responsible for more than 40% **of anthropogenic methane (**CH_4**) emissions** and more than 50% **of nitrous oxide (**N_2O**) emissions**. The waste sector also contributes to methane and nitrous oxide emissions.

Both methane and nitrous oxide are potent greenhouse gases with global warming potentials (for a 100-year time horizon) that are, respectively, **21 and 310 times greater than that of** CO_2. .

To avoid methane and nitrous oxide emissions, the residuals from agriculture and waste can be transformed into **bioenergy**.

There are two processes to produce bioenergy: **Gasification**, and **anaerobic fermentation**.

Bioenergy


Global greenhouse gas emissions by sector
This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2eq.
Our World in Data
Energy 73.2%
Agriculture, Forestry & Land Use 18.4%
Waste 3.2%
Industry 5.2%
Energy use in Industry (24.2%)
Transport (16.2%)
Energy use in buildings (17.5%)
Iron and steel (7.2%)
Chemical & petrochemical 3.6%
Other industry 10.6%
Road Transport 11.9%
Aviation 1.9%
Shipping 1.7%
Residential buildings (10.9%)
Commercial (6.6%)
Unallocated fuel combustion 7.8%
Fugitive emissions from energy production 5.8%
Energy in Agriculture & Fishing (1.7%)
Cement 3%
Chemicals 2.2%
Wastewater (1.3%)
Landfills 1.9%
Cropland 1.4%
Deforestation 2.2%
Crop burning 3.5%
Rice cultivation 1.3%
Agricultural soils 4.1%
Livestock & manure (5.8%)

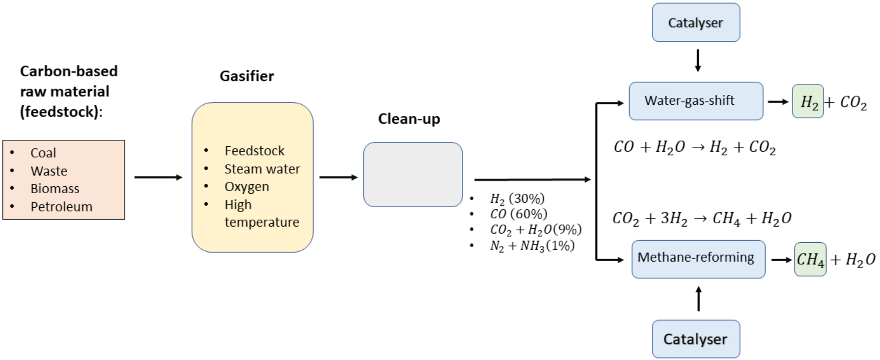
Gasification. The process

Gasification is a technological process that can convert any carbonaceous **(carbon-based) raw material** such as coal into fuel gas, also known as **synthesis gas (syngas)**.

Gasification occurs in a **gasifier**, generally a **high temperature vessel** where **oxygen** (or air) and **steam** are directly contacted with the coal or other feed material causing a series of chemical reactions to occur that convert the **feed** to **syngas** and **slag (mineral residues)**.

The products of gasification are **carbon monoxide (CO) (60%)**; **hydrogen (H_2) (30%)**; **carbon dioxide (CO_2) and water (H_2O) (9%)**; **nitrogen (N_2) and ammonia (NH_3) (1%)** (figure below).

Gasification. The process



(video)

Gasification. Catalysis

To accelerate the **water-gas-shift** and **methane-reforming** processes, **catalysts** can be employed.

Catalysis is the process of increasing the rate of a chemical reaction by adding a substance known as a **catalyst**.

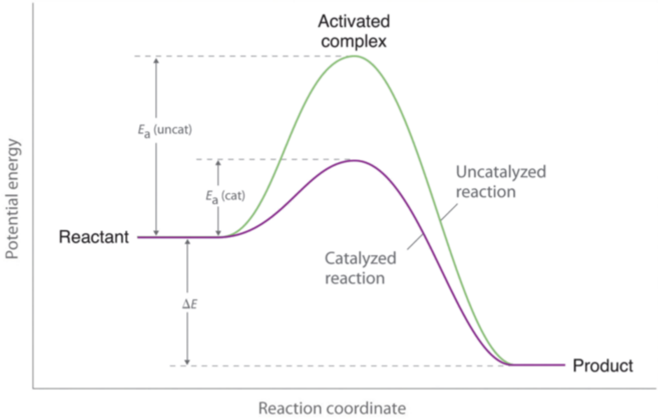
Catalysts work by providing an (alternative) mechanism involving a different transition state and lower **activation energy** (figure below).

Consequently, **more molecular collisions** have the energy needed to reach the transition state. Hence, catalysts can enable reactions that would otherwise be blocked or slowed by a kinetic barrier.

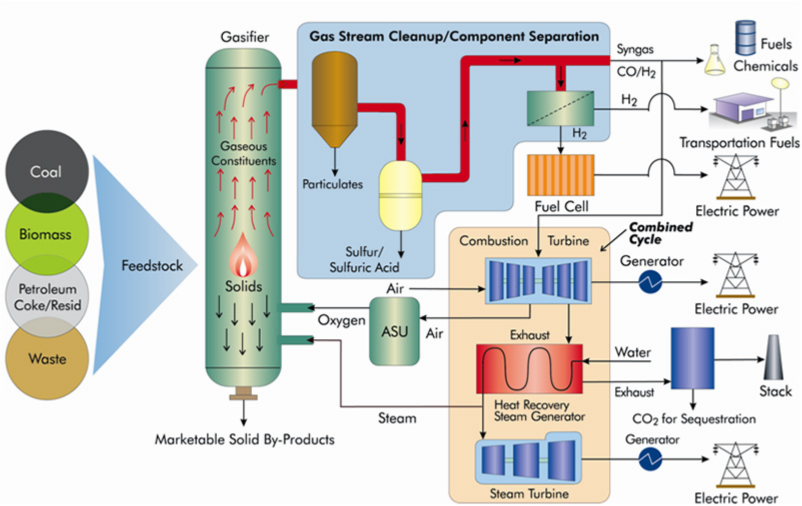
A video that illustrate the **catalysis process** is in this (link).

Gasification. Catalysis

Figure: Catalysis: Energy profile diagram



Gasification. The plant



Gasification

This section is based on the National Energy Lab webpage (link)

An useful video that summarize the chemical reactions within the gasification process is in this (link).

Anaerobic digestion

Anaerobic digestion is a sequence of processes by which **microorganisms break down biodegradable material in the absence of oxygen**. The process is used for industrial or domestic purposes to manage waste or to produce fuels.

Anaerobic digestion is used as part of the process to treat **biodegradable waste**.

Anaerobic digestion is widely used as a source of **renewable energy**.

The process produces a **biogas**, consisting of methane, carbon dioxide, and traces of other 'contaminant' gases.

This biogas can be used directly as **fuel**, in combined heat and power gas engines or upgraded to natural gas-quality **biomethane**.

The nutrient-rich digestate also produced can be used as **fertilizer**.

Anaerobic digestion. The process

1. The **photosynthesis** process (figure below) uses light transform carbon dioxide (CO_2) and water (H_2O) into sugar ($C_6H_2O_6$) and oxygen (O_2) according with the equation:

$$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_2O_6 + 6O_2$$

Anaerobic digestion. The process

2. By following **four different steps** (figure below), the **anaerobic digestion** transforms the sugar ($C_6H_2O_6$) into methane (CH_4) and carbon dioxide (CO_2).

1. **Hydrolysis**: Through hydrolysis the complex organic molecules are **broken down** into simple sugars, amino acids, and fatty acids.
2. **Acidogenesis**: The biological process of acidogenesis results in **further breakdown of the remaining components** by acidogenic (fermentative) bacteria. Here, volatile fatty acids (VFAs) are created, along with ammonia, carbon dioxide, and hydrogen sulfide, as well as other byproducts.
3. **Acetogenesis**: The third stage of anaerobic digestion is acetogenesis. Here, simple molecules created through the acidogenesis phase are **further digested** by acetogens to produce largely acetic acid, as well as carbon dioxide and hydrogen.
4. **Methanogenesis**: Methanogens use the intermediate products of the preceding stages and **convert them** into methane, carbon dioxide, and water.

Anaerobic digestion. The process

3. **Clean and upgrade process** (figure below): Usually, the produced biogas must be **dried** and drained for condense water and biological or chemical **cleaned** for hydrogen sulphur H_2S, NH_3 and trace elements. **Further upgrading steps** to increase the CH_4 content, membrane separation of CO_2 and pressurising the biogas can be taken depending on the utilisation purpose.

The upgrade to bioethanol implies the removal of contaminants such as hydrogen sulphide or siloxanes, as well as the carbon dioxide. Bioethanol contains at least 90% of methanol CH_4.

Anaerobic digestion. The process

Depending on the **temperature**, the anaerobic digestion can be classified as:

- **Mesophilic** temperature from $25 - 35^{\circ}C$.
- **Thermophilic** temperature from $49 - 60^{\circ}C$.

The majority of the agricultural biogas plants are operated at **mesophilic temperatures**. Thermophilic temperatures are applied mainly in large-scale centralised biogas plants with co-digestion, where more stringent sanitation requirements are required.

Anaerobic digestion. The process

Photosynthesis

$$6CO_2 + 6H_2O + light \rightarrow 6O_2 + \boxed{C_6H_{12}O_6}$$

Anaerobic digestion

1. Hydrolysis
2. Acidogenesis
3. Acetogenesis
4. Methanogenesis

$$C_6H_{12}O_6 \rightarrow 3CO_2 + \boxed{3CH_4}$$

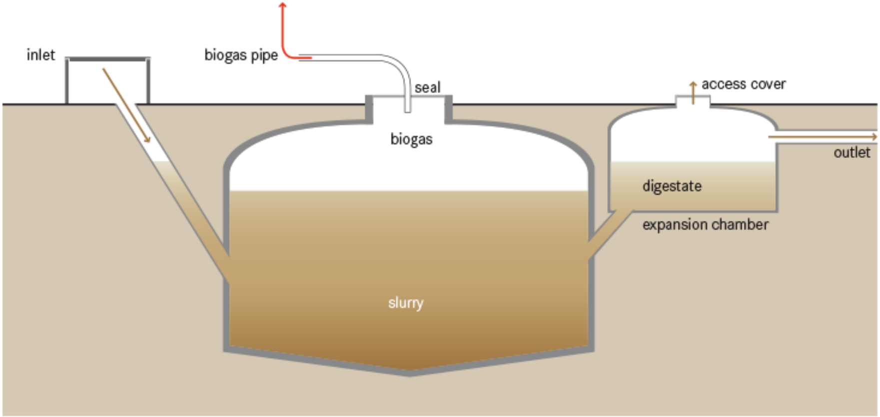
Temperature:

- Mesophilic $(25 - 35^0C)$
- Thermophilic $(49 - 60^0C)$

Clean + upgrade

$$bioethanol \boxed{(> 90\%\ CH_4)}$$

Anaerobic digestion. The plant



Anaerobic digestion. The plant

This section is based on the next two links: link 1, link 2.

An useful video to understand the anaerobic digestions is in this (link).

Current status

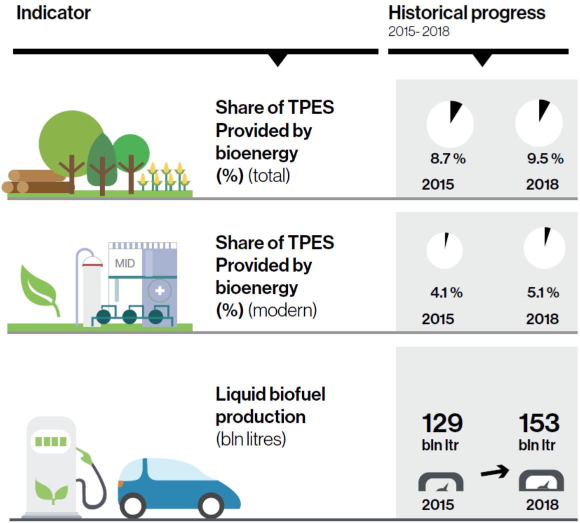
Bioenergy makes up a large share of renewable energy use today and plays a key role as a source of energy and as a fuel in the end-use sectors (**industry**, **transport** and **buildings**), as well as in the **power sector**

Bioenergy today accounts for 70% of the global renewable energy supply and 10% of the total primary energy supply

In terms of end **uses**, the largest share of total bioenergy use (modern and traditional) is in the **buildings sector**, which includes cooking and space heating (26%). The second largest share is in the **industry sector** (at 7%), followed by the **transport sector** (3%), mostly in the form of liquid biofuels from crops such as sugar cane and corn, and the **power sector** (2%)

Current status

Figure: Bioenergy. Total Primary Energy Supply (TPES)



Current status

Primary energy (PE).

Primary energy (PE) is an energy form found in nature that **has not been subjected to any human engineered conversion process**. It is energy contained in raw fuels, and other forms of energy received as input to a system. Primary energy can be non-renewable or renewable.

Total primary energy supply (TPES).

Total primary energy supply (TPES) is the sum of production and imports subtracting exports and storage changes.

Current status. Industry sector

- The industry sector uses energy for a **wide range of purposes**, such as for processing and assembly, steam generation, cogeneration, process heating and cooling, lighting, heating, and air conditioning
- **Most of the energy consumed in industry** is in the form of heat, especially in the most energy-intensive industrial sectors – iron and steel, chemical and petrochemical, nonmetallic minerals, pulp and paper, and the food industry
- Current direct renewable energy use in industry is predominantly in the form of **biofuels** and **energy from waste**
- Biomass is also used for carbon emissions reductions in the industry sector through the production of **natural synthetic fibres** based on cellulose, and **biomaterials to produce bioplastic**

Current status. Transport sector

- Globally, the share of renewable energy in this sector is very small at just 3% in 2017
- In **road** transport, the use of renewables is dominated by liquid biofuels, mostly **bioethanol** and **biodiesel**, which offer an alternative fuel for all types of internal combustion engines in both passenger vehicles and trucks
- Liquid biofuels could also help decarbonise the **shipping** and **aviation** sectors, which currently are entirely fueled by fossil sources
- Advanced biofuels offer significant **emissions reductions** compared to petrol and diesel
- They can be made from **non-food** and **non-feed biomass**, including waste materials (such as vegetable oils or animal fats) and energy-specific crops grown on marginal or degraded land

Current status. Building sector

There are two different ways of using biomass in the buildings sector: **space heating** and **cooking**.

1. **Buildings** can currently be heated using biomass through town-scale district heating systems or building-scale furnaces, both of which use feedstocks such as wood chips and pellets very efficiently.
2. **Cooking** with biomass is typically one of the traditional uses of biomass in developing countries.
   - Inefficient traditional cookstoves paired with solid fuels and kerosene emit indoor smoke that imperils the **health of mainly women and children** and causes nearly 4 million premature deaths every year.
   - Unsurprisingly, the largest share of biomass consumption in the buildings sector in 2017 was in **Sub- Saharan Africa** at 91% (entirely in the form of traditional uses).

Current status. Power sector

- Biomass and waste fuels in solid, liquid and gaseous forms are currently used to **generate electricity**
- The feedstocks and technologies range from mature, **low-cost options**, like the combustion of agricultural and forestry residues, to less mature and/or **expensive options**, like biomass gasification or municipal solid waste generators with stringent emissions controls
- Electricity generation from biomass is most often provided through **combined heat and power (CHP) systems**

Future projections. Industry sector

The **versatility of biomass** and its **finite supply** result in competition for its use within and between industry sectors, and other sectors of the economy

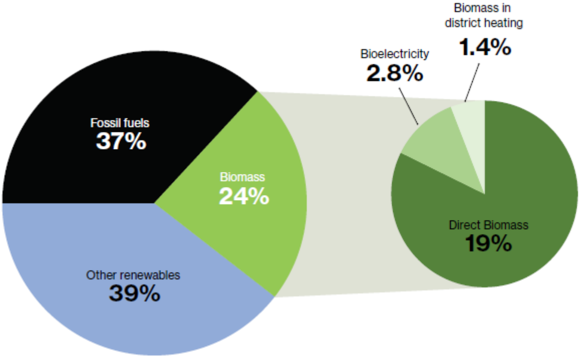
Renewable energy (including renewable electricity and district heating) could contribute 63% of **industry's total final energy consumption** by 2050.

Of that total energy, 24% would be sourced **from biomass** (direct, bioelectricity and biomass in district heating) and the remaining 39% from **other renewable sources** (figure below)

Other potential industrial applications include the use of biomass residues generated in biomass based industries such as pulp and paper, lumber and timber, food and biofuels.

Future projections. Industry sector

Figure: Renewables in industry



Future projections. Industry sector

Bioenergy in some industrial sectors that are hard to decarbonise

1. **Iron and Steel**. A significant share (about 78%) of the **total energy consumed for iron and steel production** comes from the use of coal and coke as chemical reducing agents for iron production.

   Using biomass instead of coal and coke more widely could **cut emissions** by almost 50%, but it remains costly and its use on a larger scale is only at the research stage

2. **Cement**. The manufacture of clinker is responsible for the bulk of the CO2 emissions associated with cement production. **Biomass could be considered as a clinker substitute** (however, its role and potential are still quite limited)

Future projections. Industry sector

3. **Aluminium**. Most energy consumed in the aluminium industry is in the form of electricity used for smelting. The use of **biofuels and solar heat** are among several new technologies emerging in this industry to reduce the electricity needed for smelting
4. **Chemicals and Petrochemicals**. Biomass is one of the prime alternatives to fossil fuel use in the sector, either through **biomaterials** or using biomass building blocks

   Key **bio-based feedstocks**, which can be used to produce conventional products such as plastics, are bio-ethylene and biomethanol; others include also biogas or bio-naphtha.

Future projections. Transport sector

- Biofuels and **biogas consumption would grow** to nearly five times 2017 levels by 2050 and provide 20% of total transport final energy demand
- Biofuels would play a particularly important role for the **decarbonisation of long-haul transport** (aviation, marine and long-haul road freight)
- Transport will become much more electrified, **but not everywhere**, **not in all sectors** and **not all at once**

  While **EVs** powered by renewable electricity will dominate light vehicle fleets, they can only enter markets with well-developed power grids

  Long-haul transport is unlikely to be fully electrified due to the higher energy density it requires

  Hence, a **mix of oil-based**, and **carbohydrate-based biofuels** has to be developed and used

Future projections. Transport sector

Bioenergy in some transport sectors that are hard to decarbonise

1. **Aviation**. Aviation, and in particular jet fuel use, is one of the fastest-growing sources of greenhouse gas emissions

   Biofuel for jet aircraft, known as bio-jet, is the **only currently available option** for achieving significant reductions in aviation emissions

   Despite the large potential, the **current market for bio-jet is quite limited**, due to high costs and lack of supportive regulatory framework and/or carbon pricing.

2. **Shipping**. From a **technological perspective**, liquid biofuels are mature, require few adjustments to existing ship engines or port infrastructure, and can significantly reduce emissions

   However, there are **three main barriers** to wider use: economics, availability and sustainability concerns.

Future projections. Transport sector

Bioenergy in some transport sectors that are hard to decarbonise

3. **Heavy-duty trucks.** Biomethane, biodiesel and renewable diesel can be used in **heavy-duty natural-gas-powered or diesel-powered vehicles** (as well as in light-duty vehicles) without any specific adaptation

   Some truck manufacturers are trying to develop biogas-fueled trucks for heavy and long-haul transport, while biodiesels are already being blended with conventional diesel and used in existing vehicles without any modification

Future projections. Building sector

Bioenergy in the district heating.

- Modern bioenergy use also is expected to play an increasing role in the decarbonisation of the buildings sector, particularly in areas with high demand for space heating.
- Buildings can be heated through **town-scale district heating systems** or building-scale furnaces, both of which use feedstocks like wood chips and pellets very efficiently.
- It is important, therefore, to **replace existing low-efficiency heating systems** by high efficiency district heating and cooling (DHC) or buildingscale furnaces fueled by renewable sources as much as possible.

Future projections. Building sector

Combined-heat and power (CHP) plants.

- Using **biomass solely for electricity generation** is not seen as a good choice because of its low efficiency, at about 30%.
- The **overall efficiency of biomass-based CHP plants** for industry or district heating can be 70% – 90%.
- As a result, sustainable bioenergy used to provide heat and power can **reduce emissions considerably** compared to coal, oil and natural gas-generated heat and power.

Future projections. Power sector

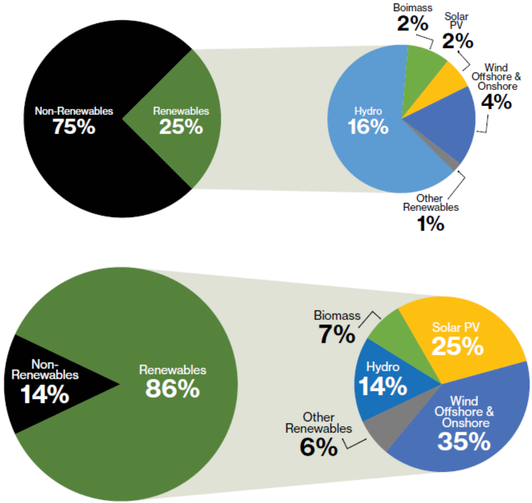
The **share of electricity in total final energy** use would increase from just 20% today to 49% by 2050, and 86% of that electricity would be generated by renewable sources, mostly wind (35% of renewable electricity), solar PV (25%) and some hydro (14%). Biomass would be the fourth largest renewable power source, generating 7% of electricity (figure below)

To produce that much power, bioenergy **installed capacity** would increase six-fold from 108 GW in 2017 to 685 GW in 2050

Asia would lead in bioenergy installed capacity, with 318 GW, followed by the **European Union** with 107 GW and **Latin America** and the **Caribbean** with 94 GW. In addition, biomass can be used for co-firing coal power plants as an intermediate measure to reduce CO2 emissions

Future projections. Power sector

Figure: Energy mix 2017-2050



Future projections. Power sector

Bioenergy-based electricity can play a particularly important role when:

1. Its **generation costs** are lower than other sources (i.e. where biomass feedstock costs are low or where heat can be used in co-generation systems).
2. It helps to **balance output** over time on electricity grids with high shares of variable wind and solar power.
3. It is possible to use **Bioenergy with carbon Capture and Storage** (BECCS).

Biogas applications

- Biogas can be burned directly for **cooking and lighting** or indirectly in **combustion engines** to generate electricity or motive power
- **Biogas for cooking** is particularly relevant for many developing countries, where it can reduce traditional use of solid biomass, offering a sustainable way to meet community energy needs, especially in areas without good grid access or where heat requirements cannot be met only by electricity

In 2019, the **World Biomass Association** estimated that there were about 700 biogas upgrading plants, with more than 75% of them in Europe

Germany is the world's largest producer of biomethane with 220 plants, nearly half of the global installations

As of 2019, Denmark injects 10% biogas into its natural gas network, and the Danish gas industry has set a goal of reaching 100% by 2035

Biomethane applications

- Biomethane is a **versatile energy carrier** produced from biomass via gasification or upgraded from biogas
- It is sometimes also known as **renewable natural gas**, as it possesses compatible properties to natural gas
- In the **transport sector**, biomethane can be used as a drop-in substitute for natural gas in existing light- and heavy-duty natural-gas-powered vehicles, such as commercial vehicles, city buses and urban service fleets for delivery and refuse collection
- Biogas and biomethane can also be used for **greening the gas system**
- Biomethane production via anaerobic digestion (AD, biogas), thermal gasification of biomass, or power-to-gas from hydrogen and carbon dioxide represents a clean and feasible solution for **cleaning the gas system**