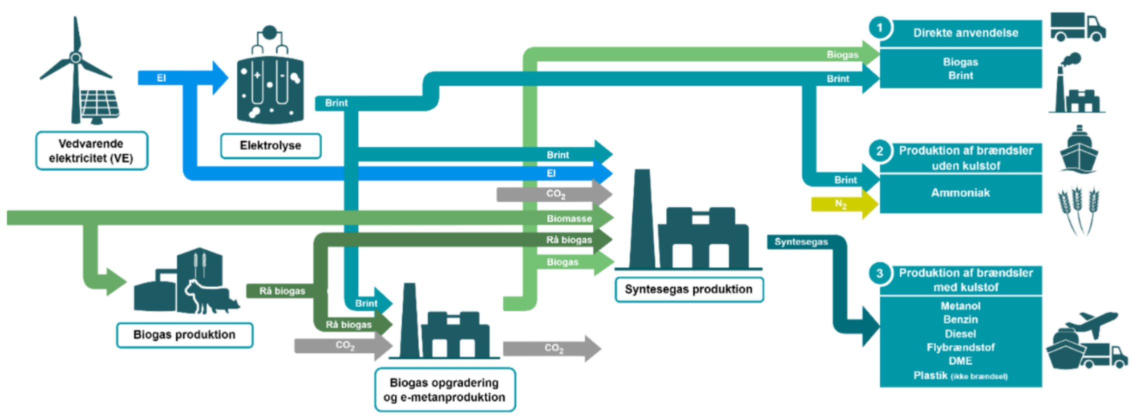
# Decarbonizing the Gas Grid:

## The Role of Renewable Fuels in Denmark's Path to Carbon Neutrality

**April 2022**



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**Note to Readers:**
The research for this paper was conducted primarily during the period from fall 2021 through March 2022. At that time, the underlying assumption in Denmark was that internal consumption of natural gas would steadily decrease, with renewable fuels meeting a rapidly increasing percentage of the remaining demand. However, the Russian invasion of Ukraine in late February 2022 is profoundly impacting global natural gas markets, and the desire of many nations to find new energy supplies. Initial discussions are now underway to explore the role that Denmark could play if it were to ramp up gas production and export to other European countries, rather than simply fulfilling its own internal needs. Should this become a reality, there could be a complete rethinking of the goals for renewable fuels production in Denmark, with even more aggressive growth of the industry than is described in this report.

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**Cover Illustration:**
Image by Danish Ministry of Climate, Energy and Utilities, from *Green Gas Strategy: The Role of Gas in the Green Transition* (2021), https://ens.dk/sites/ens.dk/files/Naturgas/groen_gasstrategi.pdf.

# 1 Executive Summary

Denmark is committed to being a frontrunner in global climate action that can inspire and encourage the rest of the world, and has established a goal of achieving climate neutrality economy-wide by 2050. Development of carbon-neutral renewable fuels is a critical strategy for achieving this goal. Their 2012 legislation introduced a subsidy scheme and established guidelines for injection of upgraded biogas into the natural gas distribution system, creating a replicable model and enviable growth in biofuel production. Renewable natural gas (RNG), which provided only 8% of the pipeline gas consumed by Denmark in 2018, rose to 25% by the end of 2021, and current projections anticipate RNG meeting 100% of the country's natural gas needs by 2034. This rapid growth of supply is due to supportive government policies, combined with close collaboration between the government and business, academic, and non-profit partners. Denmark has also benefited from a long-standing cultural and social cohesion, whereby different groups in society, in both rural and urban areas, have found common ground supporting and benefitting from the growth of the emerging biofuels sector. Biofuel production is a large and growing economic driver, particularly in rural portions of the country, and is projected to generate $2.4 billion in exports by 2035.

Circular economy principles, whereby raw materials and products are recycled and reused, have played an important role in support for biofuels. Production of biofuels is seen as a way to take materials previously considered as waste and use them to produce new and valuable products. The goal is to minimize waste and maximize the value of all outputs generated. Biogas plants are a tangible representation of this principle. In addition to biogas, many of these plants also produce products such as organic fertilizers, which have the potential to generate additional income and thereby make generation of biofuels more profitable. Wastewater treatment plants, which were previously regarded simply as expensive and energy-intensive plants needed to remove pollutants from domestic and industrial waste, are now being viewed as biorefineries that can produce biofuels, fertilizers, heat, and other products from the nutrient-rich waste streams they process.

Today, biofuels in Denmark are derived primarily from agricultural waste, particularly manure. Industrial biowaste is also a significant contributor, with dedicated energy crops playing a very minor role. Biogas plants often co-digest waste streams from multiple sources containing different materials, as they have found that having the ability to fine-tune the proportions of each input allows them to achieve economies of scale by drawing from a larger pool of resources, while also achieving higher yields of biogas and maintaining greater control and consistency of the products produced.

Denmark is now ramping up production of renewable fuels through Power-to-X technologies, utilizing green electricity from wind turbines to power electrolysis plants that will split water into hydrogen and oxygen. This renewable hydrogen can be stored or combined with other materials, including the carbon dioxide from carbon capture facilities and other sources, to produce a variety of synthetic, carbon-neutral fuels. Although still in its infancy, considerable funding is beginning to go into this area, with the expectation that the combination of biofuels and synthetic fuels could completely displace fossil fuels from the Danish economy.

Production of these fuels is necessary for Denmark to achieve reductions in greenhouse gas emissions within sectors of the economy – including industry and heavy transportation, such as aviation and maritime transport – that are going to be difficult to electrify. These represent as much as 40 to 60% of the energy needs projected for 2050.

Denmark's strong emphasis on carbon-neutral energy supplies, and the rapid growth of biofuels, has created both challenges and opportunities within the energy sector. Some traditional utilities have reinvented themselves as clean energy providers, and new companies are being formed to develop and commercialize the products and infrastructure needed to service this growing market. The role of the gas distribution system itself is changing as gas production becomes more decentralized. Massive grid connected storage of renewable fuels will be needed to provide the seasonal energy storage capacity that will allow Denmark to maintain the stability of its electrical system while it is serving peak winter heating demands. This role will become progressively more important as additional loads are electrified and demands on the electric grid increase. Strategic planning will be critical to help both government policy makers and industry navigate this transition successfully and take full advantage of the new opportunities it presents. Even though it is a small country, the lessons that can be taken from Denmark as it transitions to a carbon neutral energy sector – lessons that it is eager to share – will be invaluable for other global economies committed to doing the same.

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# 2 Introduction

Denmark has long been a global leader in introducing and successfully implementing strategic changes to its energy supply and distribution systems, which have allowed it to take full advantage of its limited resources in ways that also address its climate change concerns. When it faced the devastating economic impacts of the international oil embargo in the 1970s, Denmark embarked on a path of energy independence, and has since demonstrated its ability to grow its economy while reducing its energy needs and carbon emissions. Much of the country's early progress can be attributed to the construction of wide-scale district heating systems, development of a robust wind energy industry, increased reliance on solid biomass to produce heat and electricity, and improvements in the energy efficiency of its building stock. More recently, Denmark has begun to shift its focus to the sectors that have been more challenging to address: agriculture, transportation, and heavy industry.

Many policy makers and environmental groups in the United States believe that greenhouse gas (GHG) emissions can be largely eliminated by a combination of:

- Greening the electric grid – retiring fossil fuel-based power plants and replacing them with renewables such as wind and solar power
- Electrification – migrating all possible loads onto the electric grid
- Energy efficiency – improving the performance of buildings, transportation, and energy intensive industrial and commercial activities

While these are seen as important strategies in Denmark, they are not considered to be sufficient. The government and experts in the field have determined the country will be unable to achieve its climate change goals, especially within those sectors that will be difficult to electrify, without also dramatically increasing the production and use of renewable fuels – including both liquid biofuels and gaseous fuels such as biogas, renewable natural gas (RNG) and hydrogen.

RNG can be an attractive solution to reducing GHG emissions. Since consuming natural gas produces much lower carbon emissions than burning coal or oil, converting fossil fuel power plants to natural gas has been an important transitional step in global efforts to reduce carbon emissions over the past 20 years. However, while natural gas provides incremental emissions reductions, RNG is a net zero carbon solution with the same convenience and flexibility. It can serve as a one-for-one replacement for fossil fuel based natural gas in all uses. When purified and upgraded it can be blended with the natural gas supply, and thus be moved easily or stored for long periods using the existing natural gas infrastructure.

Producing RNG can also help to reduce emissions of methane, which is generated by the decay of organic materials, seepage of gas from underground deposits, and the digestion of food. Methane is a powerful greenhouse gas — 25 times more potent than carbon dioxide over 100 years[1] – and accounts for 16 percent of global emissions. According to the International Energy Agency the largest source of anthropogenic methane emissions globally is agriculture, responsible for around a quarter of the total, closely followed by the energy sector and then waste processing.[2] Rather than allowing it to leak into

[1] "Global Greenhouse Gas Emissions Data," United States Environmental Protection Agency, accessed November 3, 2021, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.
[2] "Methane Tracker 2020," International Energy Agency, March 2021, https://www.iea.org/reports/methane-tracker-2020.

the atmosphere, capturing methane from sources such as livestock, landfills, and wastewater processing and then upgrading it to RNG, to be used as an energy source, helps avoid these impacts.

Recently, Denmark has also begun to look at producing carbon-neutral fuels that don't rely on biological feedstocks. Under the concept of Power-to-X, low-cost renewable power will be used to split water into oxygen and "green" hydrogen through electrolysis. This hydrogen provides a foundation for producing a variety of synthetic fuels or other products with zero carbon footprint; it can be used directly to heat buildings or power fuel cells for trucks and ships, or it can be combined with carbon dioxide (CO2) to produce synthetic methane, methanol, and a variety of other chemicals.

As it has charted its energy future over the past 50 years, facing one challenge after another, Denmark has demonstrated repeated success in crafting a bold vision, establishing long-term and intermediate targets, and then successfully implementing measures to reach those goals. This success has been achieved by taking into account all of the different sectors of society and understanding what they require to get on-board to support that vision. Sometimes this has meant that people have had to change what they do; sometimes companies or entire business sectors have had to transform.

In this paper we will examine the assumptions that lie beneath Denmark's aggressive development of renewable fuels to understand its vision and roadmap, look at the progress that has been achieved to date, and consider the implications for the energy supply and distribution ecosystem of the future.

# 3 Denmark Background

## 3.1 Danish Climate Goals

Denmark's GHG reduction goals are among the most ambitious in the world. The Danish Climate Act of 2020 established a legally binding target of reducing all GHGs 70% by 2030, compared to the 1990 baseline level, with a goal of climate-neutrality by 2050.[3,4] The 2030 goal equates to a GHG emission target of 23.2 million tons of CO2e.

In a recent assessment, the Danish Energy Agency found that total nationwide GHG emissions were 46.7 million tons of CO2e in 2019, a reduction of 40% relative to total emissions in 1990. With the policies adopted at the time, emissions were expected to fall to 35.0 million tons of CO2e by 2030, a reduction of 55% from 1990 levels.[5] Though this would be a significant achievement,[6] these projections indicated that Denmark would still fall 15% short of reaching the Climate Act's 70% GHG emissions reduction target. As a result, in September 2020 the government announced that it was considering using new technologies such as carbon capture and power from wind turbines to produce hydrogen, for use by

[3] *Denmark's Climate and Energy Outlook 2020*, (Danish Energy Agency, August 2020), https://ens.dk/sites/ens.dk/files/Basisfremskrivning/deco_2020_27082020.pdf

[4] GHG emissions from all Danish territories are included, including emissions from consumption of fossil fuels, industrial processes, waste treatment, agriculture, and from removal stemming from forestry and other land use activities. GHG emissions from consumption of biomass is considered GHG neutral and is therefore not included.

[5] *Klimastatus og Fremskrivning 2021*, (Danish Energy Agency, June 2021), https://ens.dk/sites/ens.dk/files/Basisfremskrivning/kf21_hovedrapport.pdf.

[6] For comparison, this roughly corresponds to the current United States goal of cutting its greenhouse gas emissions by 50 to 52% by 2030 compared with 2005 levels.

heavy industry, shipping and air travel. These strategies could generate an additional 9 to 16.5 million tons in GHG emissions savings[7] and enable Denmark to achieve its 2030 target.

If Denmark reaches its 70% target by 2030 it will be well-positioned to achieve climate-neutrality by 2050. However, in *Denmark's Climate and Energy Outlook 2020* the Danish Energy Agency emphasized that the final 30 percentage points of GHG reductions will be, by far, the most difficult to achieve. Denmark's entire transportation sector will have to transition to renewable energy, the agricultural sector will need to dramatically reduce its climate footprint, and industry will have to develop and rely on new, and potentially expensive, carbon capture technologies to provide the negative emissions needed to balance out any emission sources that may still exist in 2050.

| | 1990 | 2019 | 2025 (Projected) | 2030 (Projected) | 2030 (Goal) |
|---|---|---|---|---|---|
| **GHG Emissions (in million tons of CO2e)** | 77.4 | 46.7 | 40.8 | 35.0 | 23.2 |
| **GHG Emissions Reduction Relative to 1990 Baseline** | N/A | 40% | 47% | 55% | 70% |

*Table 1 - GHG Emissions Reductions Targets* [8]

## 3.2 Energy Supply in Denmark

As late as the 1990s Denmark's energy supply was based almost entirely on fossil fuels, including coal, oil, and natural gas. However, by 2019, 36% of the energy consumed, and 67% of the electricity supplied,[9] was produced with renewable energy – one of the highest levels in the world. Although it is well known that the country has been at the forefront of wind energy development, what is perhaps not as well recognized is that biofuels – including solid biomass, liquid biofuels, and biogas – have provided an even larger percentage of the energy used in the country (see Figure 1).

[7] Tim Barsoe, "Denmark's climate goal too reliant on unproven tech, government council says," Reuters, February 26, 2021, https://www.reuters.com/article/us-climate-change-denmark/denmarks-climate-goal-too-reliant-on-unproven-tech-government-council-says-idUSKBN2AQ1GA.

[8] *Klimastatus og Fremskrivning 2021*, (Danish Energy Agency, June 2021), https://ens.dk/sites/ens.dk/files/Basisfremskrivning/kf21_hovedrapport.pdf.

[9] "Danish key figures 2019," Danish Energy Agency, accessed November 26, 2021, https://ens.dk/service/statistik-data-noegletal-og-kort/noegletal-og-internationale-indberetninger.

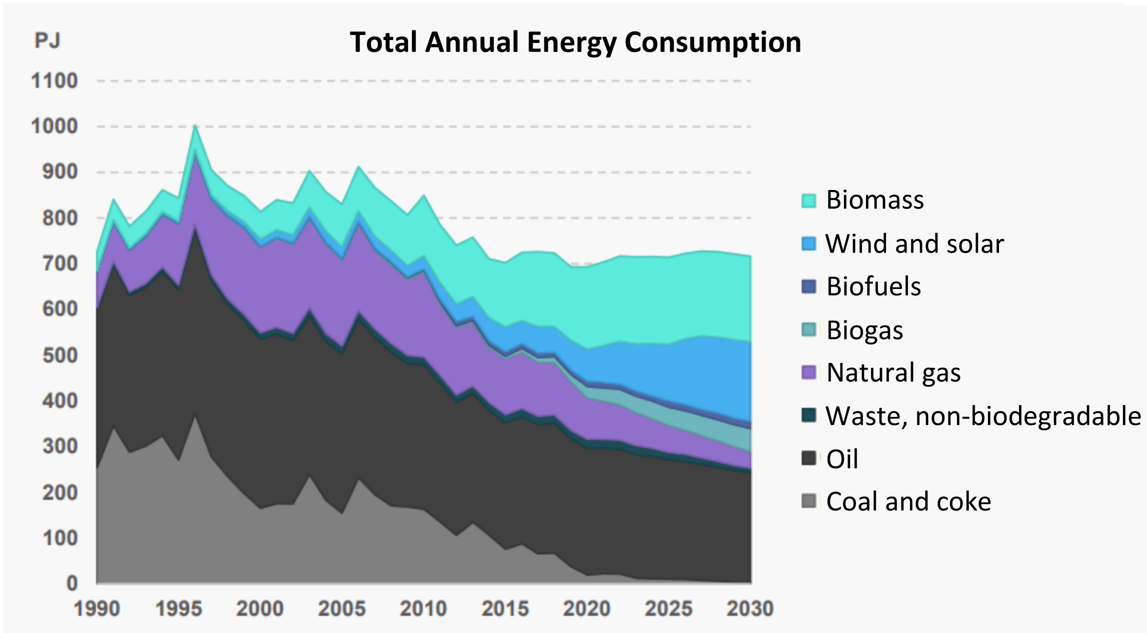


*Figure 1 - Total Danish Annual Energy Consumption by Fuel* [10]

Rather than relying on on-site boilers and furnaces, the heat for most homes and offices in Denmark is provided through an extensive district energy system, largely built out since the 1970s. Each building uses high temperature hot water that is supplied through the pipes that feed most urban areas. The hot water is produced by a combination of dedicated district heating plants, which use biomass boilers or heat pumps, and as part of the output from combined heat and power (CHP) plants that also produce electricity. The CHP plants rely on a variety of fuel sources including coal, oil, wood chips, straw, and municipal solid waste. The oil and coal fired plants still operating are rapidly being converted to lower carbon or fossil free fuels.

Today about 64% of Danish homes rely on district energy for heating.[11] Individual heating systems – typically using oil boilers, individual heat pumps, or biomass boilers – are less commonly used, and are more dominant in rural areas and small towns. The combination of more efficient district heating supply, use of combined heat and power production, and improvements in building energy efficiency has allowed the country to reduce average heating demand per sf by 45 percent since 1975.

[10] *Klimastatus og Fremskrivning 2021*, (Danish Energy Agency, June 2021), https://ens.dk/sites/ens.dk/files/Basisfremskrivning/kf21_hovedrapport.pdf.
[11] "Danish Experiences on District Heating," Danish Energy Agency, accessed March 24, 2022, https://ens.dk/en/our-responsibilities/global-cooperation/experiences-district-heating#:~:text=Denmark%20is%20one%20of%20the,Today%2C%20around%2064%20pct.

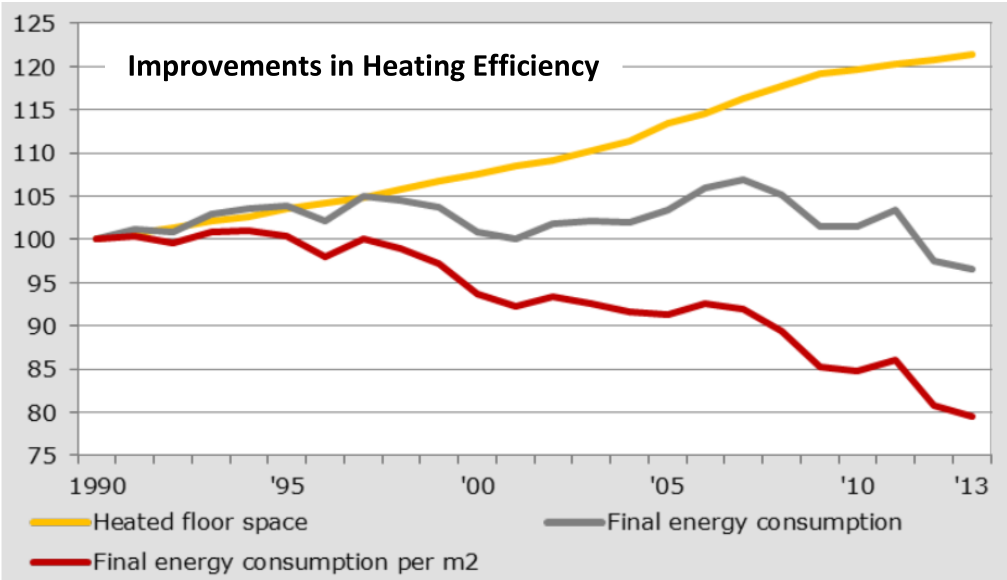

*Figure 2 – Improvements in Heating Efficiency in Denmark*

# 4 Current State of Renewable Fuels Development

Natural gas has been an important transition fuel in Denmark, helping to bridge the gap between a fossil fuel intensive past and a carbon-free future. The country's North Sea fields first began producing in 1985, with gas production peaking in 2005. Production is projected to gradually decline, with a temporary but significant dip in 2020 and 2021 due to rebuilding of the facilities on the Tyra North Sea field. As part of the country's efforts to become carbon neutral, Denmark has committed to end its North Sea oil and gas production by 2050.

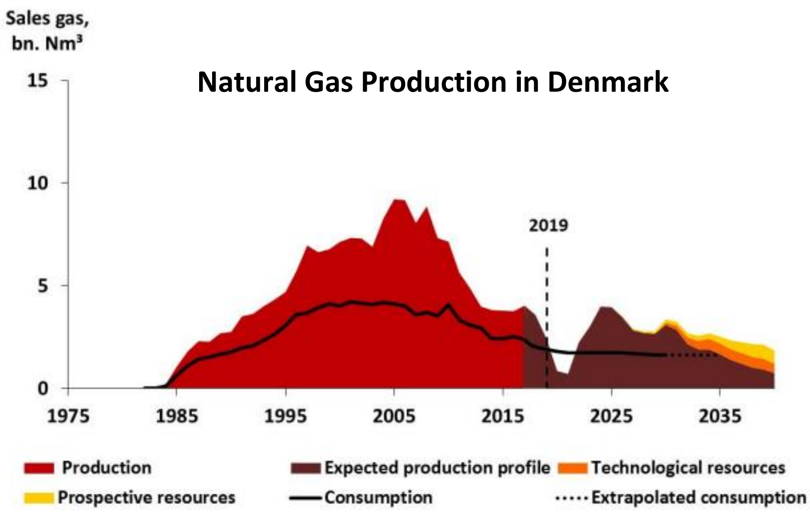

*Figure 3 - Natural Gas Production in Denmark* [12]

[12] *Resource Assessment and Production Forecasts* (Danish Energy Agency, August 2018), https://ens.dk/sites/ens.dk/files/OlieGas/ressourcer_og_prognoser_20180829_rev_en.pdf.

Denmark has been very deliberate and pragmatic in determining the best strategies to achieve its GHG reduction targets. The country acknowledges that strategic electrification – converting existing loads to electricity whenever possible while simultaneously greening the grid by producing more and more electricity from fossil free sources – is a key strategy for achieving carbon neutrality. **However, despite having one of the highest levels in the world of electricity produced with renewable energy, Denmark has determined that strategic electrification alone will not allow Denmark to achieve its GHG emissions reduction goals.**

Analyses show that approximately 40 to 60% of Denmark's energy needs projected for 2050 cannot be converted to direct electricity consumption, so these loads will have to be covered by other fuels.[13] With North Sea natural gas production dropping, and viewed primarily as a near-term energy source, renewable fuels will be particularly critical for decarbonizing energy-intensive industries and heavy transportation sectors, such as aviation and maritime, that cannot easily be served exclusively by electricity. Denmark has determined that to meet its climate goals it must leverage its existing natural gas infrastructure and greatly increase production of renewable fuels, including RNG.

Biofuels are already providing an increasing share of the energy generated in Denmark, and biogas production is widely seen as a significant success story in Denmark. Total production more than tripled between 2014, when the Climate Act subsidies were introduced, and 2020, reaching a total annual production of 14.2 MMBtu (15 PJ). Initially most of the biogas produced was used in electricity production, but since 2015 a growing portion of biogas has been upgraded to RNG and delivered to the natural gas system.

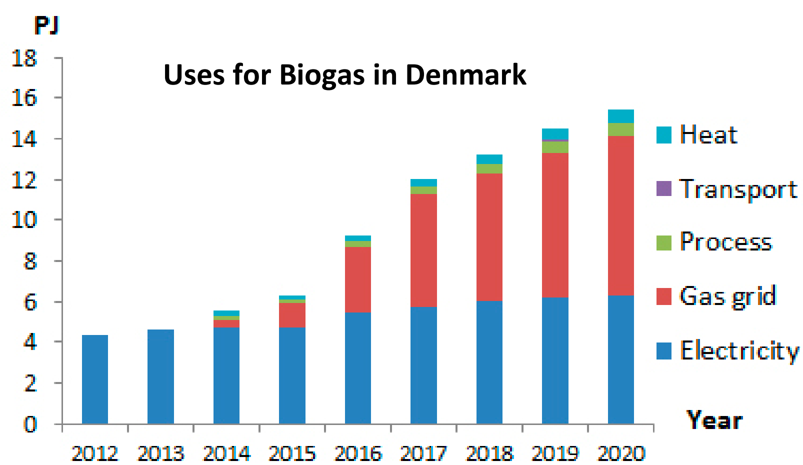

*Figure 4 - Historical End Uses of Biogas in Denmark* [14]

At the same time, overall dependence on natural gas is beginning to decrease. In the 2020 FutureGas Report, a consortium of 18 academic, industry, and government partners representing all major stakeholders of the Danish gas industry determined that by 2050 the overall level of gas consumption would be roughly 30% to 45% below the demand in 2020.[15] The decreasing reliance on natural gas,

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[13] Michael Støckler, Bodil Harder, Daniel Berman and Thomas Young Hwan Westring Jensen, *Biogas Production: Insights and Experiences from the Danish Biogas Sector* (Food & Bio Cluster Denmark and Danish Energy Agency, June 2020), https://biogasclean.com/wp-content/uploads/2021/02/biogas-in-denmark-june-2020.pdf.
[14] "Biogas in Denmark," Danish Energy Agency, accessed December 20, 2021, https://ens.dk/en/our-responsibilities/bioenergy/biogas-denmark.
[15] The complete list of participants is available at https://futuregas.dk/the-consortium/

combined with rapid growth in production of RNG, is leading to steep increases in penetration levels for RNG use. It took wind turbines more than 30 years of development to reach 5% of the Danish power production – a feat achieved in just four years (2014 to 2018) by the biogas industry.[16] RNG's share of Danish gas consumption rose to over 21% in 2020, and 25% by the end of 2021. The Danish Energy Agency now projects that biogas will account for 75% of Denmark's pipeline gas by 2030, and 100% by 2040.[17] Energinet, the country's state-owned system operator for electricity and natural gas, has an even more optimistic view. In 2022 they announced that if biogas production continues to grow, the fuel will meet all of Denmark's gas consumption as early as 2034.[18]

# 5 Additional Benefits of Renewable Fuels

In addition to playing an important role in serving sectors that will be difficult to electrify, renewable fuels provide several other strategic benefits, reinforcing Denmark's commitment to expanding their use and production.

## 5.1 Reducing Winter Peak Electrical Loads

In the United States many local jurisdictions have taken steps to prohibit natural gas infrastructure in certain new buildings and make electric appliances standard.[19] Although reducing reliance on natural gas produced through traditional extractive methods can be an important strategy for reducing carbon dioxide emissions, shifting heating loads to the electric grid places even more stress on electric distribution systems that may already be in need of substantial upgrades.

Denmark faces a similar dilemma. The country has a temperate climate marked by relatively cool summers and cloudy, moderately cold winters. As such, the peak energy demands are driven by winter heating loads. Converting existing heating loads to electricity, while simultaneously continuing to green the electric grid by retiring fossil fuel fired plants, could present a significant challenge to the electric system. Because of the variable nature of wind power, it will be necessary to build not only additional wind and solar generation capacity, but also more electric storage and distribution grid capacity. In an all-electric, renewable energy scenario, the cost to upgrade the electric grid and storage infrastructure is likely to significantly exceed the cost of the new renewable energy sources themselves.[20]

By continuing to meet a portion of heating loads with RNG, using direct heating, hybrid gas-electric heat pumps, or district energy systems powered by renewable fuels, rather than converting all heating loads to electricity, winter peak electric needs can be minimized, saving billions of dollars in avoided capital investments. This approach will ensure that carbon reduction goals can be met in the most cost-effective way.

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[16] Marc-Antoine Eyl-Mazzega and Carole Mathieu, *Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy* (ifri Centre for Energy, April 2019), https://www.ifri.org/sites/default/files/atoms/files/mathieu_eyl-mazzega_biomethane_2019.pdf.

[17] *Analysis prerequisites for Energinet 2021*, translated from *Analyseforudsætninger til Energinet 2021* (Danish Energy Agency, October 12, 2021), https://ens.dk/sites/ens.dk/files/Hoeringer/sammenfatningsnotat.pdf.

[18] Cristina Brooks, "Denmark predicts gas networks will use only biogas in 2034," IHS Markit, January 13, 2022, https://cleanenergynews.ihsmarkit.com/research-analysis/denmark-predicts-gas-networks-will-use-only-biogas-in-2034.html.

[19] Maria Rachal, "California takes a first-of-its-kind step on building decarbonization", SmartCities Dive, August 12, 2021, https://www.smartcitiesdive.com/news/california-energy-commission-adopts-building-decarbonization-changes/604762/.

[20] Henrik Lund, "Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach," *Energy* 151 (2018): 94-102.

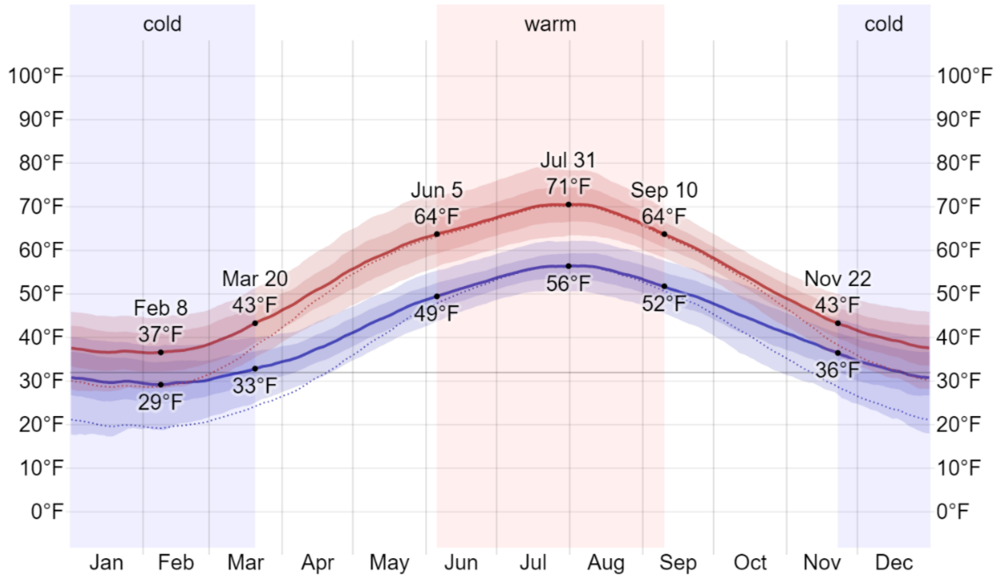

*Figure 5 - Average Temperatures in Copenhagen [21]*

## 5.2 Seasonal Energy Storage

The Danish energy system must not only be able to absorb surplus electricity, it must also maintain reserve capacity for times when energy consumption is high and solar and wind production is low. With Denmark's impressive wind energy generating capacity, the electricity supplied by wind farms frequently exceeds total system demand. When the wind farms produce more energy than can be consumed, stored, or sold into other markets, the turbine production must be curtailed, with the energy that could otherwise be produced essentially being thrown away. Through the Power-to-X initiative (see Section 8.1) Denmark is exploring the use of wind energy for hydrolysis, to convert water into "green" hydrogen and oxygen. This hydrogen can be stored in underground caverns or converted into synthetic natural gas and stored in tanks and pipelines, making it available to provide heat during the cold winter months.

Although electric battery storage capacity has improved tremendously over the past few years it is still relatively limited, making it more suitable for hourly or daily storage than for long term seasonal storage. The largest battery storage bank in the world is the 1,600 MWh Moss Landing Energy Storage Facility in California, which went on-line in July 2021. This system stores excess wind and solar power and makes it available during periods of high energy demand and intermittent production, thereby helping to stabilize California's electric grid as utilities statewide shed key baseload resources to meet the state's zero-carbon goal by 2045.[22]

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[21] "Climate and Average Weather Year Round in Copenhagen," Weatherspark, accessed January 19, 2022, https://weatherspark.com/y/74001/Average-Weather-in-Copenhagen-Denmark-Year-Round.

[22] "Burns & McDonnell Completes Construction at Largest Battery Storage Facility in the World", accessed November 21, 2021, https://www.burnsmcd.com/insightsnews/in-the-news/2021/08/largest-battery-storage-facility-in-world#:~:text=The%20Moss%20Landing%20battery%20energy,storage%20facility%20in%20the%20world.

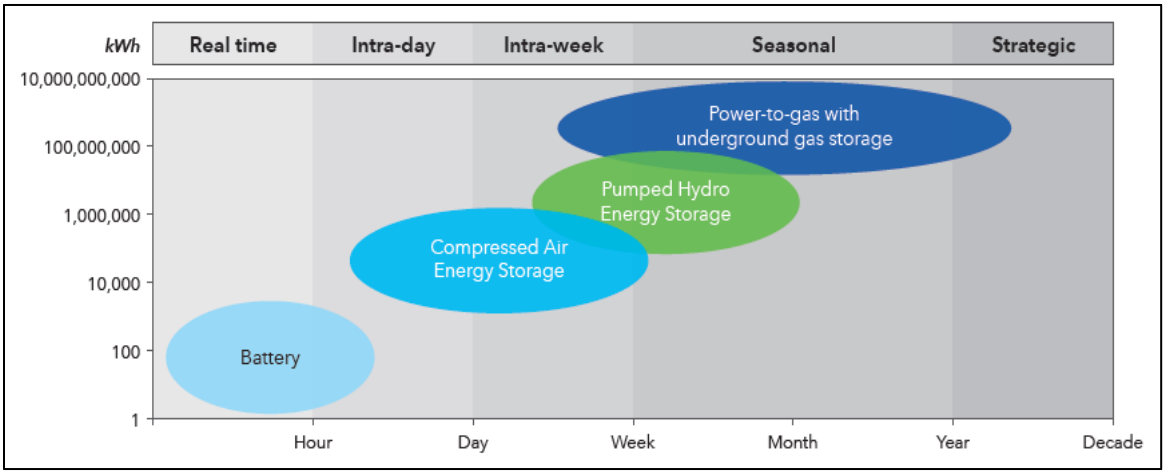


*Figure 6 - Seasonal Energy Storage (Source: European Power to Gas [23])*

By comparison, Gas Storage Denmark operates two underground storage facilities that are connected to the national gas delivery system and serve to mitigate the risk of supply shortages: an aquifer storage facility with a capacity of 5,855 GWh and a salt cavern facility with a capacity of 4,965 GWh. Their total combined capacity of almost 11,000 GWh is about one-third of the total annual energy consumption in Denmark and almost 6,800 times the size of the Moss Landing Energy Storage Facility. [24,25] Historically, these gas storage facilities are charged during summer and discharged during winter. Filling these storage facilities with renewable fuels such as RNG or green hydrogen during the months of lower demand would provide sufficient capacity to meet much of the winter heating load of the country, whether it be through direct gas heating, feeding hybrid heat pumps, powering district heating plants, or providing a zero-carbon fuel to run electricity generation plants as production from wind and solar fluctuates. It is unlikely that this level of seasonal capacity will be achievable with battery storage technology for many more years.

Figure 7, below, illustrates the relative magnitude of energy storage in Denmark, comparing the current gas storage (11,000 GWh) to the thermal storage currently connected to district heating systems (2,600 GWh), and the estimated potential for electrical storage if electric cars with a battery capacity of 30 kWh replaced all 2.5 million vehicles in the country (75 GWh), which would provide far more electrical storage than the 1.6 GWh capacity of the Moss Landing Energy Storage Facility.[26]

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[23] Paula Schulze (lead author), Johan Holstein, Albert van den Noort and Johan Knijp, DNV GL, *Power-to-Gas in a Decarbonized European Energy System Based on Renewable Energy Sources*, European Power to Gas.

[24] Denmark's annual electric consumption is about 32 TWh. See annual energy statistics at https://www.enerdata.net/estore/energy-market/denmark/#:~:text=Total%20Energy%20Consumption,cap%20of%20electricity%20in%202019.

[25] "What We Do", Gas Storage Denmark, accessed November 21, 2021, https://gasstorage.dk/Our-storage.

[26] Henrik Lund, "Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach," *Energy* 151 (2018): 94-102.

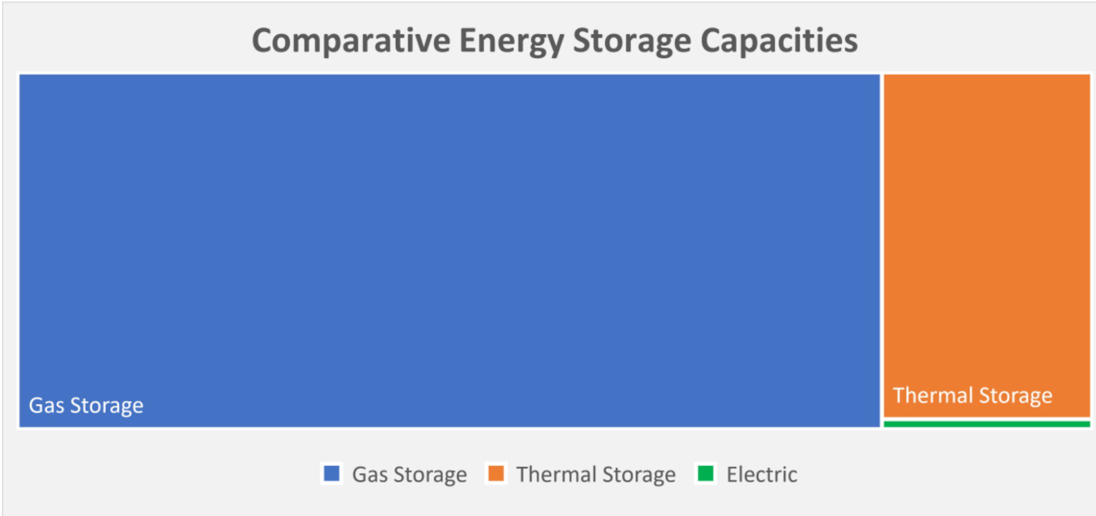


*Figure 7 - Comparative Energy Storage Capacities*

## 5.3 Economic Development

Developing RNG and other biofuels is seen as a key strategy for Denmark to maintain its global leadership in green energy, which has already provided job growth, new market opportunities, and increased opportunities for exports. According to Green Gas Denmark, replacing all of the natural gas used in Denmark with RNG would help to create a strong and vibrant Danish green gas industry with potentially up to 20,000 new jobs and $2.3 billion in exports by 2035.[27] Because biofuels are often derived from rural fuel supplies such as agricultural waste, RNG production provides a way for these often economically challenged rural areas to benefit directly from development of new green energy sources and the local jobs they create. Throughout Denmark new businesses are being created to take advantage of the economic opportunities, and traditional utilities are reinventing themselves to thrive in a future fossil free economy.

### 5.3.1 Case Study: Nature Energy

Nature Energy began operations in 1979 as Naturgas Fyn, one of the five regional gas distribution companies in Denmark. In 2014 the name was changed to Nature Energy, and they completed their first biogas plant supplying biogas to the Danish gas network. In 2018 it divested its distribution and gas sales business to focus exclusively on the production of climate-friendly biogas. Today Nature Energy views itself as a “fully integrated renewable gas company”[28] with 11 plants designed to produce biofuels from agricultural waste produced by Danish farmers, industry, and households. Nature Energy’s biogas plants will treat more than 4.4 million tons of biomass in 2022, converting it into more than 181 million $m^3$ (63 million therms) of carbon neutral biogas, enough to heat 57,000 homes. The company is now one of the leading producers of biogas globally and is actively exploring opportunities to expand into the United States and other international markets.[29]

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[27] *Greening the Gas Grid in Denmark* (IEA Bioenergy Task 37, February 2019), https://www.ieabioenergy.com/wp-content/uploads/2019/03/IEA_Greening-the-Gas-Grid_end.pdf.
[28] “From grey to green – the story of Nature Energy” [PowerPoint presentation from in-person meeting with the author], September 19, 2019.
[29] “About Nature Energy,” Nature Energy, accessed February 18, 2022, https://nature-energy.com/about-nature-energy.

*Figure 8 - Nature Energy's Vaarst Plant*

## 5.4 Circular Economy Orientation

A circular economy employs closed loops in which raw materials, components and products lose their value as little as possible, and renewable energy sources are used. This systems-oriented approach is at the core of Denmark's success in growing their economy. By using the circular economy lens, decision makers in Denmark attempt to evaluate the total potential revenue stream of a waste recovery process, as well as the avoided cost of waste treatment and disposal, which can make an opportunity more attractive than it might otherwise appear. Production of biofuels is rarely viewed as the exclusive end goal of a process; biofuels are but one of several outputs generated when all materials in a waste stream are utilized as efficiently as possible. For example, organic farmers have a special interest in biogas plants but, for them, the main incentive is not the biogas production itself, but the production of organic fertilizers.

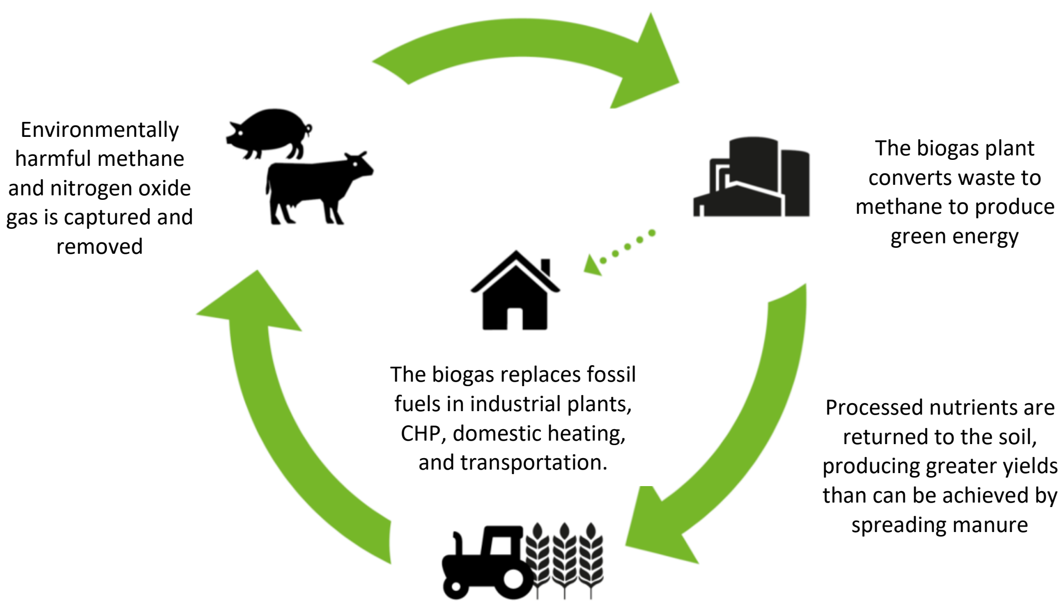


*Figure 9 - Circular Economy Concepts Applied to Biogas Production from Agricultural Waste*

One of the greatest barriers to increased reliance on RNG in the United States has been the perception that there are insufficient supplies of economically viable feedstock for RNG to play a major role in reducing carbon emissions. For example, the State of Oregon produced a report showing that biogas will only be a minor contributor to reducing GHG emissions, with the potential to displace between 4.6% to 17.5% of their total annual natural gas use.[30]

However, most studies in the United States that have evaluated the potential contribution of biofuels have not used the lens of the circular economy, nor considered the impacts of co-production of products. For example, the most recent study of biomass potential in Washington State stated:

> *Electrical energy production was the calculated product for this study, however numerous other products such as fuels and chemical bioproducts are possible, and even more likely as valuable and viable products. Thus, any future studies and business plans building upon this study should emphasize the need for a well-researched biorefinery approach which leads to multiple coproducts, increased distributed business opportunity, expanded market access and strives to achieve 'zero waste'.* [31]

In Denmark, companies looking to make investments in biogas plants cannot afford to ignore the economic potential for these co-products, which can make biofuel production more competitive and increase the size of feedstock inventories. A systemic analysis based on circular economy principles allows biofuels to be viewed as but one element in a mix of valuable products, rather than forcing these fuels to stand alone on their individual economic merits.

[30] *Biogas and Renewable Natural Gas Inventory SB 334 (2017): 2018 Report to the Oregon Legislature* (Oregon Department of Energy, September 2018), https://digital.osl.state.or.us/islandora/object/osl%3A501771/datastream/OBJ/download/2018.pdf.

[31] *Biomass Inventory and Bioenergy Assessment: An Evaluation of Organic Material Resources for Bioenergy Production in Washington State* (Washington State Department of Ecology and Washington State University, December 2005); https://apps.ecology.wa.gov/publications/documents/0507047.pdf.

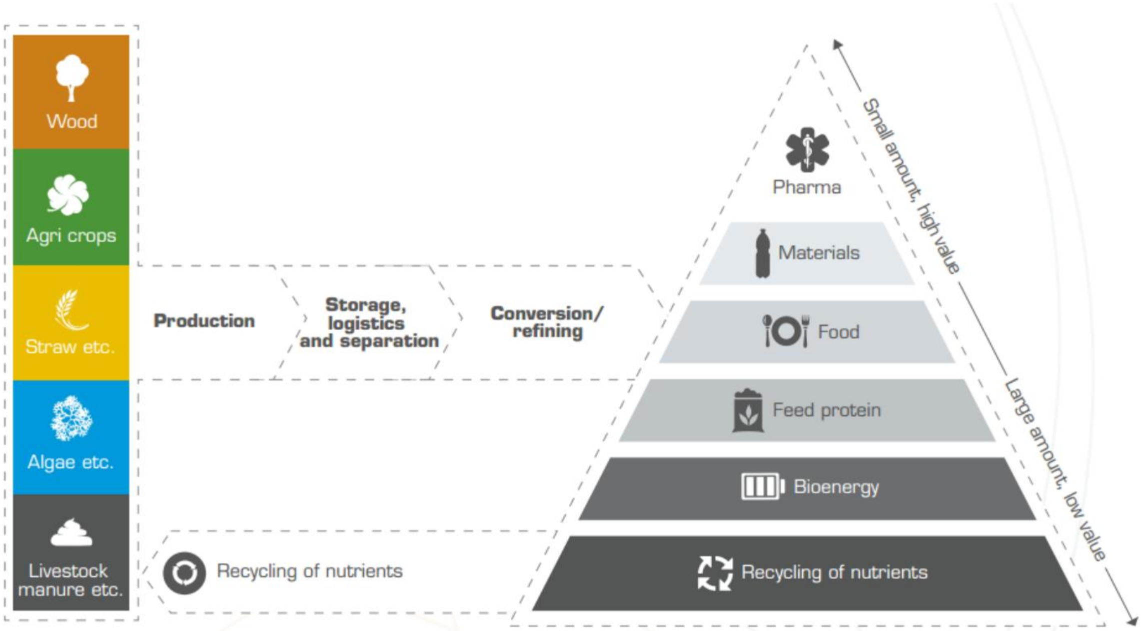


*Figure 10 – Value Stack for Potential Co-products from Biogas Production*

# 6 How is Denmark Doing This?

Biofuel production in Denmark has been catalyzed by strong government leadership, together with support from industry and academic partners. The Danish government has historically incentivized the production of renewable fuels through a number of carrot and stick approaches, including:

- Government subsidies for designated uses
- Taxes on consumption of fossil fuels (energy and carbon taxes)
- Agricultural regulations
- Creation of a Biogas Taskforce
- Support for research, development, and demonstration of new technologies

Denmark is currently co-chairing the Beyond Oil & Gas Alliance (BOGA), which was launched at the 2021 United Nations Climate Change Conference (COP26) in Glasgow. The mission of BOGA is to create an international community of practice to support governments in achieving a managed phase-out of oil and gas production. This announcement demonstrates Denmark's ongoing commitment to maintaining a leadership position in policies that support the transition from fossil fuels to biofuels and other renewable energy sources.

## 6.1 Government Subsidy Programs

Production of biogas expanded rapidly after the Danish government enacted a new subsidy package under the Danish Energy Agreement 2012, which was in effect until 2020. Different levels of support were available, depending on how the biogas was to be used. Financial support was provided in the form of adjustable feed-in premiums on top of the natural gas prices, using a base subsidy and two price supplements: [32,33]

- General Subsidy: The fixed settlement price provided a varying level of support in proportion to the market price. The settlement price was calculated by deducting the electricity market price from a fixed settlement price.
- Price supplement 1: *increased* in case of a *reduction* in the price of natural gas and *decreased* in case of an *increase* in the price of natural gas. This subsidy ensured that the biogas producer would continue to receive income even if natural gas prices plummeted, while protecting the government from overcompensating biogas plant owners if natural gas prices increased.
- Price supplement 2: was set to a fixed, gradual reduction from 2016, sunsetting in 2020. It was intended to spur the development of biogas projects as quickly as possible.

The following table shows the subsides that were available when these schemes took full effect, in 2014:

| Biogas Use | General Subsidy | Bonus Regulated in Relation to Natural Gas Prices (Supplement 1) | Temporary Bonus Phased Out in 2020 (Supplement 2) | Total Subsidy |
|---|---|---|---|---|
| | **USD/therm** | **USD/therm** | **USD/therm** | **USD/therm** |
| Upgrading Biogas for Injection into the Natural Gas System | $ 1.28 | $ 0.42 | $ 0.16 | $ 1.86 |
| Industrial Process Loads | $ 0.63 | $ 0.42 | $ 0.16 | $ 1.21 |
| Transportation | $ 0.63 | $ 0.42 | $ 0.16 | $ 1.21 |
| Heating | $ 0.00 | $ 0.42 | $ 0.16 | $ 0.58 |
| | **USD/kWh** | **USD/kWh** | **USD/kWh** | **USD/kWh** |
| Electricity Generation | $0.122 | $0.040 | $0.015 | $0.177 |

*Table 2 - Biogas Subsidy Scheme Effective 2014* [34, 35]

Growth in biogas production and demand for subsidies was so high under these support schemes that in early 2020 the Danish government projected there would be approximately 40 million MMBtu (42PJ) of biogas production by 2030, one third more than had been planned.[36] As a result, in 2018 Parliament chose to end the 2012 support scheme. The program was replaced with a new scheme under the Energy Agreement 2018. Under this new agreement the government set aside funding for the support of biogas

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[32] *Memo on the Danish support scheme for electricity generation based on renewables and other environmentally benign electricity production* (Danish Energy Agency, March 2017), https://ens.dk/sites/ens.dk/files/contents/service/file/memo_on_the_danish_support_scheme_for_electricity_generation_based_on_re.pdf.

[33] Marc-Antoine Eyl-Mazzega and Carole Mathieu, *Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy* (ifri Centre for Energy, April 2019), https://www.ifri.org/sites/default/files/atoms/files/mathieu_eyl-mazzega_biomethane_2019.pdf.

[34] Adapted from "Prosperity from Sustainable Infrastructure and Energy Sustainable energy - Biogas", presentation by Michael Støckler, Agro Business Park (September 2019).

[35] Lise Skovsgaard, Danish Energy Agency [personal communication], February 11, 2022.

[36] "Increased amounts of biogas towards 2030," Danish Energy Agency, April 12, 2020, https://kefm.dk/aktuelt/nyheder/2020/dec/oegede-maengder-biogas-frem-mod-2030.

and other green gases totaling $446 million from 2024 through 2030 (2020 prices).[37] This new scheme is in the form of tenders, where a biogas project can bid on the level of subsidy they need to trigger the investment. An annual subsidy pool is set aside, to be allocated to the bids selected each year.

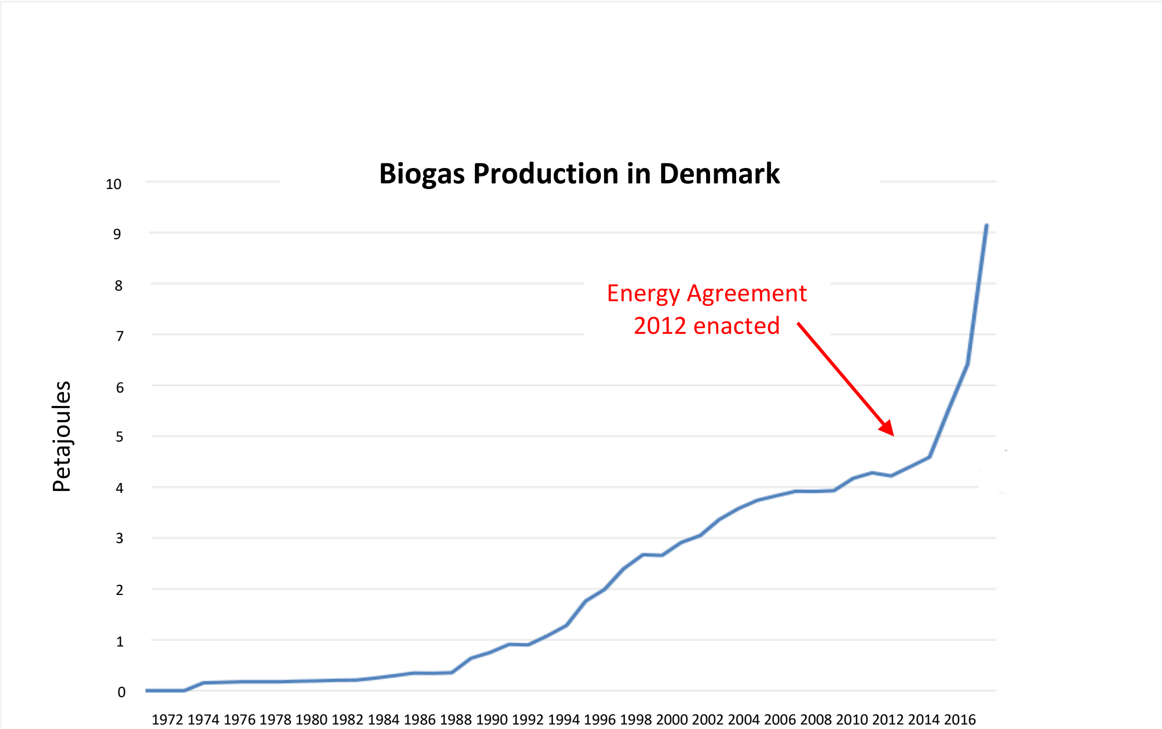


*Figure 11 - Impact of Energy Agreement 2012 Subsidies*

The subsidies that were in place under the 2012 Climate Act remain available through 2032 for any project that was operating and connected to the natural gas network, the town gas system, or the electricity grid before January 1, 2020. Plants that supply upgraded biogas to the natural gas network were also eligible for the subsidies with support extending for 20 years from the first year "in action" if they had a binding agreement for construction in place prior to February 2019, they applied for the subsidy before July 1, 2020, and they were operating and connected to the gas system no later than December 31, 2021.[38, 39] As a result, a rush of new construction proposals was submitted in 2019, with many projects still under construction. This will likely manifest itself as a steep climb in biogas production beginning in 2022, with a flattening of the curve between 2022 and 2023, until the funds will first be released under the new support scheme.[40]

## 6.2 Environmental Taxes

As of 2014 Denmark had environmentally related tax revenues of 3.97% of GDP – the highest level of environmental taxes as a percentage of GDP among the 39 countries and partner economies that were

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[37] *Climate agreement for energy and industry 2020 (Translated from Klimaaftale for energi og industri mv. 2020),* (June 22, 2020), https://fm.dk/media/18085/klimaaftale-for-energi-og-industri-mv-2020.pdf.
[38] "Framework agreed for the changes to the biogas subsidy scheme," (Kromann Reumert, March 18, 2019), https://kromannreumert.com/en/news/framework-agreed-the-changes-to-the-biogas-subsidy-scheme.
[39] Marianne Tjørning, Danish Energy Agency [personal e-mail communication with the author], January 18, 2022.
[40] Marianne Tjørning, Danish Energy Agency [phone conversation with the author], November 23, 2021.

members of the Organization for Economic Co-operation and Development (OECD).[41] The price signals for $CO_2$ emissions are based on a combination of national energy taxes and the EU Emissions Trading System (ETS), the European "cap and trade" scheme.

The energy tax is levied on both fossil fuels and electricity, with the tax rate varying according to the energy content of each product. As of 2021 electricity used for heating households was taxed at $0.0012 per kWh (0.8 øre / kWh) while fossil fuels used for heating were taxed at $0.98 per therm (62.3 DKK / GJ). Biomass is not taxed in order to promote the use of renewable energy.[42]

Denmark was one of the first countries to introduce a carbon tax, in 1992. The tax covers road transportation (through fuel taxes) and non-process heating. The current tax rate is equivalent to $26 per ton, which is at the top end of carbon pricing schemes.

Emissions from the power sector, district heat production, industry, and domestic aviation are covered by the EU ETS. Energinet[43] registers and issues certificates to Danish biogas producers who upgrade biogas to RNG and inject the RNG into the gas distribution system. These certificates document that the upgraded biogas injected into the natural gas distribution system is produced from biomass. Energinet's green certificates are accepted by the EU ETS as an offset for carbon reporting purposes and may be traded commercially.

EU allowance prices have recently been rising rapidly, increasing from an average of $38 per ton in January 2021 to almost $95 per ton in January 2022,[44] which could result in additional costs of almost $0.04/kWh for electricity generated from burning natural gas. The EU commission has proposed to decrease the ETS allotment by 61% in 2030, as compared to 2005 levels. Analysts and researchers have estimated that this will increase carbon prices to between $100 and $147 [45, 46] per ton of $CO_2$ by 2030.

Rather than relying exclusively on the EU ETS scheme, under which the tax per ton of carbon differs greatly across sectors, the Danish Council on Climate Change (DCCC)[47] has recommended a relatively high, uniform carbon tax that would apply across industry, agriculture, transport, and heating of buildings, with carbon prices rising to $200 to $250 per ton by 2030. In December 2020, the Danish Parliament agreed that a uniform carbon tax will be a key measure in reaching the new GHG reduction targets and established an expert group to prepare a recommended model. The group presented three

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[41] David Bradbury and Kurt Van Dender, "Environmentally Related Taxes: Taxes on Energy Use," (OECD Centre for Tax Policy and Administration) https://www.oecd.org/tax/tax-policy/environmental-tax-profile-denmark.pdf.

[42] *Climate agreement for energy and industry 2020 (Translated from Klimaaftale for energi og industri mv. 2020),* (June 22, 2020), https://fm.dk/media/18085/klimaaftale-for-energi-og-industri-mv-2020.pdf.

[43] Energinet is an independent public company under the Ministry of Climate, Energy and Supply, that owns and develops electricity and gas transmission networks in Denmark.

[44] "Daily Carbon Prices," EMBER, accessed January 15, 2022, https://ember-climate.org/data/carbon-price-viewer/.

[45] Frédéric Simon, "Analyst: EU carbon price on track to reach €90 by 2030," EURACTIV, July 18, 2021 (updated July 22, 2021), https://www.euractiv.com/section/emissions-trading-scheme/interview/analyst-eu-carbon-price-on-track-to-reach-e90-by-2030/.

[46] Robert C. Pietzcker, Sebastian Osorio, and Renato Rodrigues, "Tightening EU ETS targets in line with the European Green Deal: Impacts on the decarbonization of the EU power sector," Applied Energy, 293: 116914, July 1, 2021.

[47] The Danish Council on Climate Change was established under the Danish Climate Change Act and is responsible for making annual recommendations for and providing a status update on the government's climate action efforts.

potential models in an interim report in February 2022, with final recommendations expected to be released in fall 2022.[48]

## 6.3 Agricultural Regulations

Animal farming and growing industrial feed crops for forage is an above-average contributor to Denmark's total GHG emissions, relative to peers. According to Eurostat data, Denmark's share of GHGs from crop and animal agriculture in 2019 was over double the average in other EU countries.[49] Much of Denmark's biogas is generated from agricultural waste and, as a result, the regulations that control the use and processing of these materials can have a large impact on the pricing for biofuel production.

The Danish Ministry of Environment and Food enforces laws that regulate manure management from livestock production, the use of organic waste as fertilizer on farmland, and the use of residues from slaughterhouses. Per these regulations, nutrients in manure and slurry must be used as fertilizers on cropland. However, there are defined limits for the amount of nitrogen and phosphorus that can legally be applied to each acre of agricultural land. If a farm has more manure than can be applied on its own land the excess manure must be transferred to another farm or to a biogas plant.

These regulations have incentivized many farmers to send their manure and other agricultural waste products to be processed in biogas production plants. Biogas and organic farming are very good partners. When slurry, green waste, organic clover grass and other organic waste products are treated in the biogas plant, the biomass is degassed. The remaining natural fertilizer can be returned to farmers, where it generates higher yields in the fields, is easier for the plants to absorb, and reduces leaching of nitrogen to the aquatic environment. Trucks can deliver the liquid digestate from the biogas plant at the same time they pick up the slurry from a given farm, thereby epitomizing circular economy principles in action. The result of these agricultural regulations is that biogas plants are now viewed as a means to a) protect valuable soil and water resources, b) provide advanced waste management options for organic waste streams, c) produce organic fertilizers for crop production, and d) diversify revenue sources for the agricultural sector.

## 6.4 Biogas Taskforce

The Danish Energy Agency established a Biogas Task Force with the purpose of "investigating and supporting specific biogas projects with a view to ensuring the assumed biogas expansion up to 2020." The Biogas Taskforce, which convened from 2012 to 2016, prepared status updates of biogas development and estimates of the expected biogas expansion through 2020. These were presented to the parties behind the Energy Agreement of 2012 so that they could determine whether expansion of biofuel production was meeting expectations. The Task Force also collaborated with the industry and completed several projects in collaboration with universities and consultants. These projects are described in a series of reports that can be downloaded from the Danish Energy Agency's website.[50]

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[48] Mads Mose Vikkelsø, "Here are the experts' three bids for a new CO2 tax," Altinget, February 8, 2022, https://www.altinget.dk/artikel/her-er-eksperternes-tre-bud-paa-en-ny-co2-skat.

[49] Nicoletta Batini, Ian Parry, and Philippe Wingender, "Climate Mitigation Policy in Denmark: A Prototype for Other Countries," International Monetary Fund, November 2020, https://www.imf.org/-/media/Files/Publications/WP/2020/English/wpiea2020235-print-pdf.ashx.

[50] "Biogas Taskforce," Danish Energy Agency, accessed November 26, 2021, https://ens.dk/ansvarsomraader/bioenergi/biogas-taskforce.

## 6.5 Collaborative Approach

The Danish government has worked closely with the biogas industry to help create business opportunities both domestically and abroad. This relationship has strengthened industry support for government policies related to climate change, even though government taxes and regulations may impose a financial burden on these companies. As an example, in Biogas Go Global government agencies, industry and NGOs are working together to achieve the common goal of increasing uptake of biogas technology in the United States. The purpose of Biogas Go Global is to create new business models and reduce the financial risks of biogas production, thereby accelerating the green transition in both countries. The initiators behind the project include:

- **Food & Bio Cluster Denmark** was created to strengthen knowledge-based innovation and knowledge collaboration across the entire value chain for food and bioresources – both at home and internationally. The Cluster has over 300 members, including businesses, knowledge institutions, and municipalities, and has published papers and organized summits highlighting the positive benefits that biogas and RNG have on the economy and environment in Denmark.
- **Danish Innovation Network for Bioresources (INBIOM)** is a national innovation network that serves as a catalyst for the development of new, sustainable biomass-based technologies and companies, to ensure that Denmark stays in the lead within the field of bioeconomy. It includes the Danish Bioenergy Group, which serves to identify business opportunities and strengthen the Danish bioenergy industry's competitiveness internationally.
- **Danish North American Trade Council's Waste, Recycling & Biogas Advisory (WBA)** is organized under the Danish Ministry of Foreign Affairs Trade Council and consists of industry experts with a deep commitment to advancing biogas and innovative waste management solutions in North America. The WBA aims to unlock commercial opportunities and accelerate sustainable waste management projects, including biogas.
- **Danish Energy Agency** is responsible for administering the policies, regulations, financial instruments, and programs that affect every aspect of the Danish biogas market, and the energy supply of the country in general.

Academia also plays an important role in supporting research and market adoption of innovative processes and technologies that will further the production of biofuels in Denmark and abroad. Several Denmark universities and research institutes – including Aarhus University, Aalborg University, University of Southern Denmark, Roskilde University, and the Technical University of Denmark (DTU) – are performing research in biogas production. Their main goal is to find methods to increase the profitability of biogas production in a sustainable way, and to explore the biogas potential of new substrates and other wastes to supplement livestock manure.

Academic involvement has been enhanced by the widespread adoption of the "triple helix" approach, which encourages cooperation between government, industry, and academia. The three participating groups in the triple helix model typically have different interests, with universities interested in the "production of knowledge," industry in "wealth generation," and government bodies in "public wellbeing."[51] However, despite their different motivations, they all benefit from effective collaboration. As an example, INBIOM is housed at the Agro Food Park, a consortium of more than 80 business

[51] Tove Brink and Svend Ole Madsen, University of Southern Denmark, "The Triple Helix Frame for Small and Medium-sized Enterprises for Innovation and Development of Offshore Wind Energy," Triple Helix, 3, [4], (2016), https://doi.org/10.1186/s40604-016-0035-8.

start-ups and academic institutions all sharing knowledge, with Aarhus University operating the world's largest full scale biogas plant for research purposes there.

## 6.6 Social/Political Engagement

Danish society has traditionally valued social cohesion and inclusiveness, with this orientation toward the common good reflected in every aspect of life, including public policy. It is inherent in the Danish way of doing things that to move in a certain direction, everyone needs to be on board. Getting everyone on board takes time and effort, but once that alignment has occurred, bold ideas can move forward quickly and consistently.

Denmark's evolution toward achieving energy independence and carbon neutrality is a prime example. It began during the 1970s oil embargo as a simple acknowledgement that Denmark had to develop its own energy resources rather than relying on imports, as it had historically done. Citizens understood that if it did not develop its own energy supply, Denmark would remain economically vulnerable. As a result, development of wind energy resources was embraced across the society. Farmers became not only wind energy supporters but wind turbine owners. Groups of farmers formed collectives and purchased wind turbines to put on their lands, providing a way for them to directly benefit from the national efforts to achieve energy independence. Everyday citizens came together to help fund the Middlegrunden Wind Turbine Cooperative, a wind facility just offshore from Copenhagen. When it was built in 2000, it was the world's largest offshore farm, with 20 turbines and a capacity of 40 MW. This project was an early example of community wind energy, with 50% owned by the 10,000 individual customer-investors and 50% by the municipal utility company

Denmark has since taken this successful model and applied it to biofuels. Many of the early biogas plants were financed and owned by groups of 10 to 20 farmers, continuing the strong tradition of cooperative ownership. As the government instituted more policies to promote the biogas industry, utilities and other companies stepped in to scale up the operations, but always in ways that continued to benefit the agricultural communities.

This tradition had led to a strong sense of inclusion and shared purpose, with everyone feeling they have a role to play and something to gain from the clean energy revolution in Denmark. Since biofuel production is heavily dependent on agricultural waste streams, this perspective is very noticeable in the rural portions of the country, where farmers are motivated both by a sense of environmental/social values and a desire for financial rewards. This sharing of common values across different regions and socio-economic groups in the country, including those that are often at odds in places like the United States, helps to explain the wide-spread and long-lasting support for the government policies that have catalyzed the growth of the biofuels industry.

# 7 Biofuel Sources

Denmark appears to have sufficient resources to produce enough biofuel to displace most, if not all, of its current fossil gas consumption. Green Gas Denmark issued a memorandum as early as November 2017 concluding that by 2035 enough biogas would be available to cover Denmark's total expected gas consumption of 68 million MMBtu (72 PJ). This assessment was based on a continued rise in use of manure and waste, improvements in the efficiency of biogas production, and a 50% utilization of straw resources. Taking advantage of the gas system's potential for electricity storage through methanization could further boost the total annual biogas potential to 95 million MMBtu (100 PJ).[52]

To maximize performance, Danish biofuel plants often co-digest a diversified stream of materials rather than relying on a single waste stream, as is typical in the U.S. The stream may include a combination of livestock manure, liquid slurry (a mixture of manure and water), and organic wastes from households and industry. By adjusting the proportions of the various components, the biogas plants achieve the following benefits:

- Enhanced gas production: higher yields can be achieved by mixing energy-rich organic waste with slurry
- Supply diversity: centralized plants receive waste from many industries, which is more manageable than dedicated digesters for each industry and allows greater economies of scale
- Stable digestion process: co-digestion with slurry makes digestion of solid waste more stable, thereby producing more consistent and controllable results

The different sources for the feedstocks used for biofuel production are described in more detail below.

## 7.1 Agricultural Residues

Agricultural residues, particularly different forms of manure, are by far the largest source of materials for biogas production in Denmark, and have long been considered an important resource. Agriculture plays a significant role in Denmark's economy and is characterized by large volumes of livestock production. Denmark produces about 35 million tons of livestock manure per year, equal to 6 tons for each of Denmark's 5.8 million inhabitants.[53] Many Danish pig and dairy farmers are involved in livestock manure-based biogas production, most of them via cooperatively owned, industrial sized biogas plants. As a result, these biogas plants are typically located in rural

### Global Warming Potential

**Global Warming Potential (GWP)** is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide ($CO_2$). The larger the GWP, the more that a given gas warms the Earth over that time period. The time period usually used for GWPs is 100 years.

- $CO_2$, by definition, has a GWP of 1 regardless of the time period used. $CO_2$ remains in the climate system for a very long time. $CO_2$ emissions cause increases in atmospheric concentrations of $CO_2$ that will last thousands of years.
- Methane ($CH_4$) is estimated to have a GWP of 28 to 36 over 100 years. $CH_4$ breaks down much more rapidly than $CO_2$, only lasting about a decade on average, but it absorbs much more energy than $CO_2$ while it is in the atmosphere. The 20-year GWP of $CH_4$ is 84 to 87.
- Nitrous Oxide ($N_2O$) has a GWP 265 to 298 times that of $CO_2$ for a 100-year timescale. $N_2O$ emissions remain in the atmosphere for more than 100 years, on average.

[52] *Greening the Gas Grid in Denmark* (IEA Bioenergy Task 37, February 2019), https://www.ieabioenergy.com/wp-content/uploads/2019/03/IEA_Greening-the-Gas-Grid_end.pdf.

[53] Michael Støckler, Bodil Harder, Daniel Berman and Thomas Young Hwan Westring Jensen, "Biogas production: Insights and experiences from the Danish Biogas Sector," Biogas Go Global, June 2020, https://www.biogasgoglobal.com/Admin/Public/DWSDownload.aspx?File=%2fFiles%2fFiles%2fBiogas-Go-Global%2fResults%2fBIOGAS_FoodBioClusterDenmark_English_light.pdf.

areas, where waste from nearby farms can be cost effectively trucked to the processing plant.

The EU's Climate and energy package (Directive 2009/28/EU on renewable energy) determined that energy produced from biomass such as livestock manure is categorized as CO2 neutral. When livestock manure is used for energy production the methane and nitrous oxide that would otherwise be released into the atmosphere as the manure decomposes is instead captured and repurposed. Since these gases have many times the global warming potential of an equivalent weight of CO2, using agricultural waste to produce biogas has very positive environmental benefits.[54] Furthermore, anaerobic digestion of these waste streams improves the bioavailability of the nitrogen it contains, reducing dependence on petrochemical-based fertilizers. Livestock manure energy projects generate much larger emission reductions than other biomass-based energy projects, making these projects among the most cost-efficient.[55]

## 7.2 Energy Crops

As in many European countries, Denmark has limited the use of dedicated energy crops, moving biogas production away from crops that can be used for food. Using dedicated energy crops to produce biofuels not only has the potential to increase food prices, but the sustainability benefits and GHG reduction benefits are diminished to the point that it can be equivalent to consuming fossil natural gas.[56] To be eligible for government subsidies no more than 12% of the material used by a biogas plant, by weight, can consist of energy crops, including corn, grain, sugar beets, artichokes, and grass. This limit will be reduced to no more than 4% by 2024. As shown in the table below, manure and slurry represent more than three quarters of the feedstock for Denmark's biogas plants, with energy crops providing a very small contribution.

| Feedstock | Percentage |
|---|---|
| **Cattle and pig slurry** | 70% |
| **Manure from other animals** | 8% |
| **Organic industrial waste** | 15% |
| **Energy crops** | 2% |
| **Other** | 5% |

*Table 3 - Feedstocks for Biogas Production* [57]

## 7.3 Municipal Solid Waste and Wastewater Treatment

Denmark's circular economy philosophy has shaped its strategies for generating energy and handling waste, with the goal being to extract the maximum potential of both energy and materials from any processed waste. For many years this perspective led to the construction of waste-to-energy (WtE)

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[54] "Understanding Global Warming Potentials," United States Environmental Protection Agency, accessed January 17, 2022, https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#Learn%20why.

[55] Henning Lyngsø Foged, Agro Business Park, *Livestock Manure to Energy: Status, Technologies and Innovation in Denmark*, Innovation Network for Biomass, December 2012, https://foodbiocluster.dk/admin/public/download.aspx?file=/Files/Files/ecom/products/Biogas-Go-Global/Livestock-Manure-to-Energy.pdf.

[56] *Agreement on new requirements for the use of energy crops for biogas production of 30 June 2021* (*translated from "Aftale om nye krav for anvendelsen af energiafgrøder til produktion af biogas af 30. juni 2021),* https://ens.dk/sites/ens.dk/files/Bioenergi/aftaletekst_-_nye_krav_til_anvendelsen_af_energiafgroeder_i_biogasproduktion.pdf.

[57] Bo Riisgaard Pedersen, "Green Energy in Denmark" [PowerPoint presentation from in-person meeting with the author], September 15, 2019.

plants that were designed to burn municipal solid waste in ultra-clean facilities, thereby minimizing the volume of materials that needed to be landfilled, while producing no harmful pollutants, and generating electricity and thermal energy for the district heating grid. This approach was combined with an emphasis on upstream recycling to minimize the waste streams that needed to be processed in these WtE plants. As a result, only 3% of the household and industrial waste generated in 2019 (by weight) was sent to landfills, while 72% was recycled.[58] 25% of the waste, including energy-intensive materials such as plastics that could not be economically recycled, was processed by WtE plants to maximize the benefits that could be extracted from these materials.[59]

Recently, Danish policy makers have also started to rethink the role of wastewater treatment plants. As in the United States, these have historically been viewed as facilities that remove pollutants from domestic and industrial waste, so that the treated effluent can be returned to streams, rivers, or oceans without harmful environmental impacts. However, wastewater treatment is energy intensive. Meanwhile, the wastewater itself contains large amounts of energy and nutrients which now can be cost effectively utilized, due to new processes developed in recent years.

### 7.3.1 Case Study: Billund Biorefinery

The Billund Biorefinery (BBR), which began operations in 2017, presents a model where the role of a wastewater treatment plant is not to simply reduce the harmful effects of sewage and household waste, but rather to extract the highest possible value out of all nutrients and other materials in the waste stream and return them to the economy for reuse.

[58] Recycling includes any recovery operation where waste materials are processed into products or materials. This includes processing of organic materials, but not energy recovery or processing into materials for incineration or landfilling.

[59] Sara Elisabet Svantesson, "StatBank Denamark: Environment and energy", Statistics Denmark, https://www.statbank.dk/statbank5a/SelectVarVal/Define.asp?MainTable=AFFALD&PLanguage=1&PXSId=0&wsid=cftree.

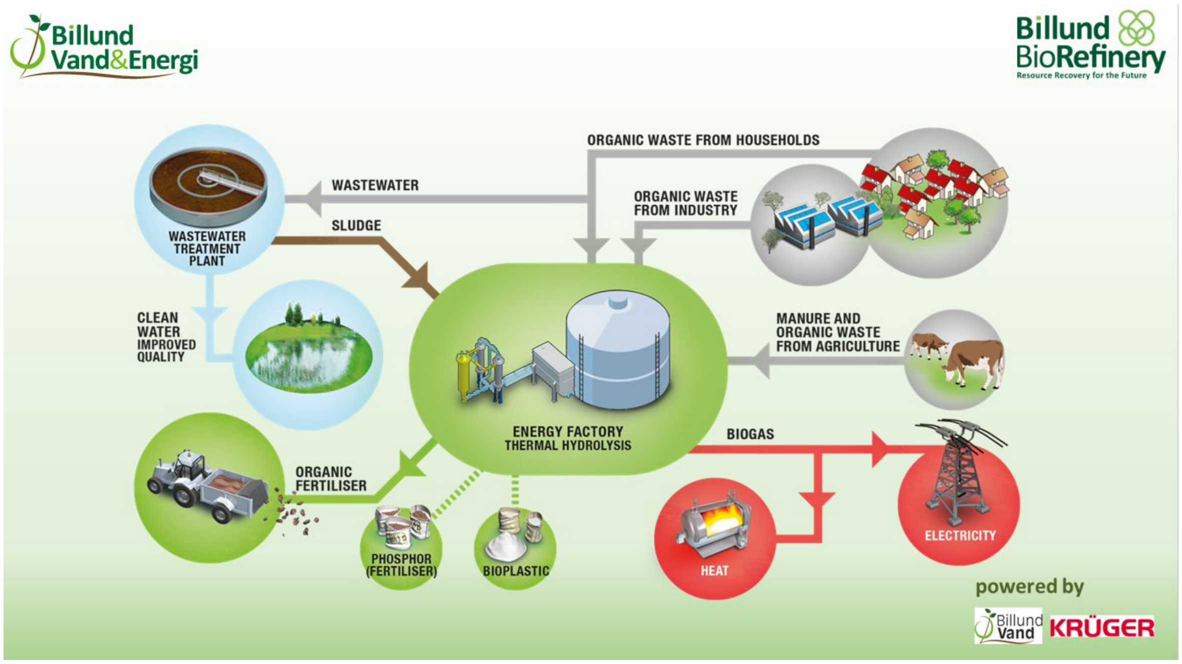


*Figure 12 - Billund Biorefinery Resource Flow [60]*

As the name biorefinery suggests, the BBR is a modern-day refinery that uses waste streams instead of traditional crude oil to generate electrical and heat energy, and to produce RNG, cleaned water and high-quality natural manure. By employing thermic hydrolysis, the plant combines wastewater treatment with biogasification of organic waste. The result is more efficient purification of wastewater than traditional wastewater treatment plants. At the same time, the BBR generates three times the energy it uses for its operations, including the energy for water supply, sewage collection and the treatment processes themselves.

Depending on market conditions, the plant can monetize the excess electrical and heat energy, RNG (which is injected into the gas distribution system), phosphate rich fertilizers, and other materials. At present, the plant relies heavily on the variable green energy subsidy that it receives for electricity. Since the subsidy value is tied to natural gas prices the current price the BBR receives is very low, and it is exploring alternative ways of selling the electricity. Also, for now it has to pay farmers to take the manure it produces, so the plant is exploring ways of selling the manure in the form of more highly processed recovered nutrients or using further energy recovery processing such as pyrolysis. As with any organization, the operators have found that they must be able to plan for contingencies and react quickly to changes in the business environment.[61]

The plant operators found that they could improve the efficiency of their biodigestion process by modifying the input stream and accepting greater quantities of industrial waste from a nearby DuPont plant. By increasing the industrial waste load by 110% the plant was able to improve production of fertilizers by 14% and RNG by 130%, thereby allowing them to reduce their net operating costs while saving the DuPont plant $2 million per year in treatment costs. This more holistic look at the value of the

[60] Ole P. Johnsen and Chitra S. Raju, "Billund Biorefinery: WWTP contributes to Circular Economy" [PowerPoint presentation from in-person meeting with the author], September 12, 2019.
[61] Chitra S. Raju and Thomas Kruse Madsen, Billund Vand & Energi [personal communication], March 21, 2022.

entire resource stream changed the financial equation and made it possible to produce greater quantities of RNG than would be apparent through a more siloed analysis.

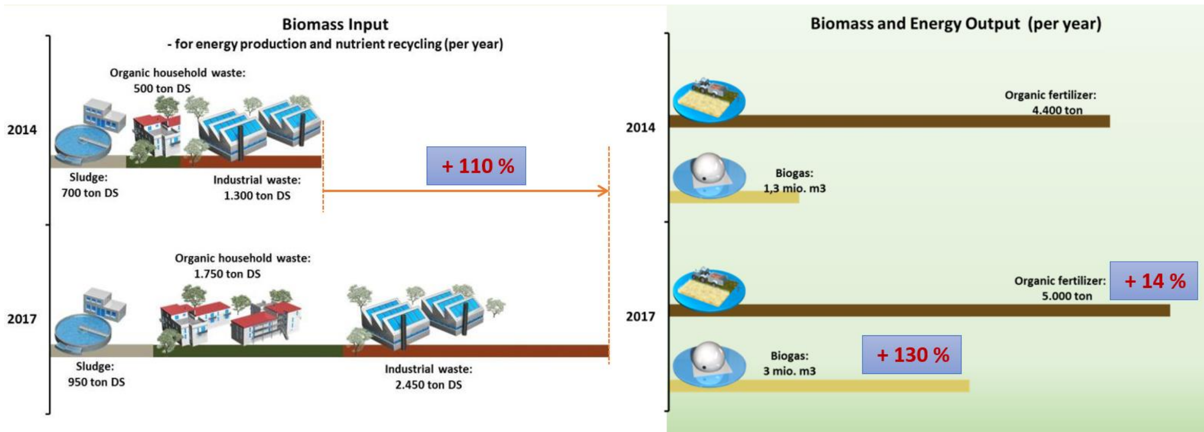


*Figure 13 - Billund Biorefinery Co-digestion Benefits* [62]

### 7.4 Industrial Residues

Landfilling of organic waste is banned in Denmark. Since residues from food production and biomass processing can be excellent resources for biogas production, virtually all organic residues in Denmark are collected and used, if not for other purposes, for biogas production. As described above, co-digesting industrial waste with sludge and slurry provides economic and operational benefits.

## 8 Beyond Biofuels

Today, almost all commercially viable renewable fuels in Denmark are biogenic (derived from plant and animal-based materials). However, considerable research and funding is being directed toward developing the next generation of non-biogenic renewable fuels, which would use a combination of electrolysis, carbon capture and electrochemical processes to generate carbon-neutral synthetic fuels from basic CO2 and hydrogen building blocks.

### 8.1 Power-to-X

Power-to-X (PtX) is a concept whereby renewable electricity is stored or converted into green fuels in order to eventually free transport, heating, and industrial process from fossil fuels. PtX represents a major paradigm shift, where carbon-neutral fuels can, in the future, be produced without necessarily relying on biogenic feedstocks. In addition, PtX processes also generate large amounts of surplus heat, which can potentially be utilized in the district heating sector.

Today, wind turbines in Denmark sometimes produce so much electricity that they must be disconnected from the grid, and there are plans to construct new offshore wind farms with 6 GW of additional capacity, much more than Danish consumers are projected to need for ordinary purposes. A large share of the electricity is expected to be exported to neighboring countries. However, although its electric transmission system has strong interconnections with both the predominantly hydro- Nordic electricity system and the thermal Central European electricity system, there are limits to how much

[62] Ole P. Johnsen and Chitra S. Raju, "Billund Biorefinery: WWTP contributes to Circular Economy" [PowerPoint presentation from in-person meeting with the author], September 12, 2019.

excess electricity Denmark can sell into these markets.[63] With PtX, the excess or low-cost green electricity generated during periods of high wind energy production would be used to split water into oxygen and hydrogen through electrolysis. The renewable hydrogen could be stored and saved for less blustery days, used to power high-temperature industrial processes, go into fuel cells for trucks and ships, or be exported through pipelines to neighboring countries.

Additional PtX products can be produced by adding nitrogen or CO2, which can be obtained via carbon capture or other sources. By adding carbon to hydrogen in a synthesis process, renewable fuels such as e-diesel, e-methanol, e-kerosene, e-methane can be produced. These fuels can directly replace current fossil fuels, and therefore be readily used in road transport, shipping, and aviation. Green ammonia (e-ammonia), produced by adding nitrogen to hydrogen, can be used for fertilizer or, eventually, as a shipping fuel. Since the production of ammonia for fertilizer is currently the largest consumer of fossil hydrogen worldwide, PtX can play a major role in decarbonizing the agriculture industry.[64]

Although biogas and RNG are not anticipated to play a major role in transportation, renewable hydrogen and synthetic PtX generated fuels could be a dominant source of fuel supplies for aviation, shipping, and heavy road transport, as well as the chemical industry, if prices of wind and solar power, and electrolysis continue to drop significantly. To produce these fuels at scale, technologies and conversion processes will need to be further developed and commercialized, and economic, infrastructure and regulatory barriers solved.[65]

Funding for development and commercialization of PtX was first introduced as part of the *Climate Agreement for Energy and Industry 2020*. The bill also allocated $439 million (DKK 2.9 billion) in funding between 2020 and 2030 to develop biogas and other green gases, which are especially needed in parts of industry where green electricity cannot be utilized directly. An additional $7.6 million (DKK 50 million) has been allocated to support the green transition in transport, targeting charging stations, heavy transport, and ferries.[66] In 2022 the Danish government established a target of building four to six GW of electrolysis capacity by 2030, with the all of the hydrogen documented as renewable by being produced with electricity from renewable energy sources and complying with EU regulations for certification.[67] The PtX projects operating in Denmark and producing green hydrogen today only have a combined capacity of 2.4 MW. However, as of April 2022, 16 projects with the capacity to produce an additional

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[63] *Security of Electricity Supply in Denmark: Working group report on methodology, concepts and calculations concerning security of electricity supply* (Danish Energy Agency, 2015), https://ens.dk/sites/ens.dk/files/Globalcooperation/security_of_electricity_supply_in_denmark.pdf.

[64] Lars Aagaard et al, *Recommendations for a Danish Power-to-X strategy* (Dansk Energi, November 2020), https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2021-03/Recommendations-for-a-Danish-Power-to-X-strategy.pdf.

[65] Morten Stryg, Danish Energy Association "Hydrogen" from Final FutureGas Report (September 2020), https://futuregas.dk/wp-content/uploads/2020/10/FG-Final-report-5-10.pdf.

[66] *Danish Climate Agreement for Energy and Industry 2020 – Overview*, June 22, 2020, https://en.kefm.dk/Media/C/B/faktaark-klimaaftale%20(English%20august%2014).pdf.

[67] *Development and Promotion of Hydrogen and Green Fuels (Power-to-X strategy): Agreement between the Government (Social Democrats), Left, Socialist People's Party, Radical Left, The Unity List, Conservative People's Party, the Danish People's Party, the Liberal Alliance and the Alternative*, translated from *Udvikling og fremme af brint og grønne brændstoffer (Power-to-X strategi)* (March 15,2022), https://www.regeringen.dk/media/11146/aftale-om-udvikling-og-fremme-af-brint-og-groenne-braendstoffer.pdf.

5.9 GW of green hydrogen, methanol, and kerosene have been announced, an almost 2,500-fold increase over current production levels.[68]

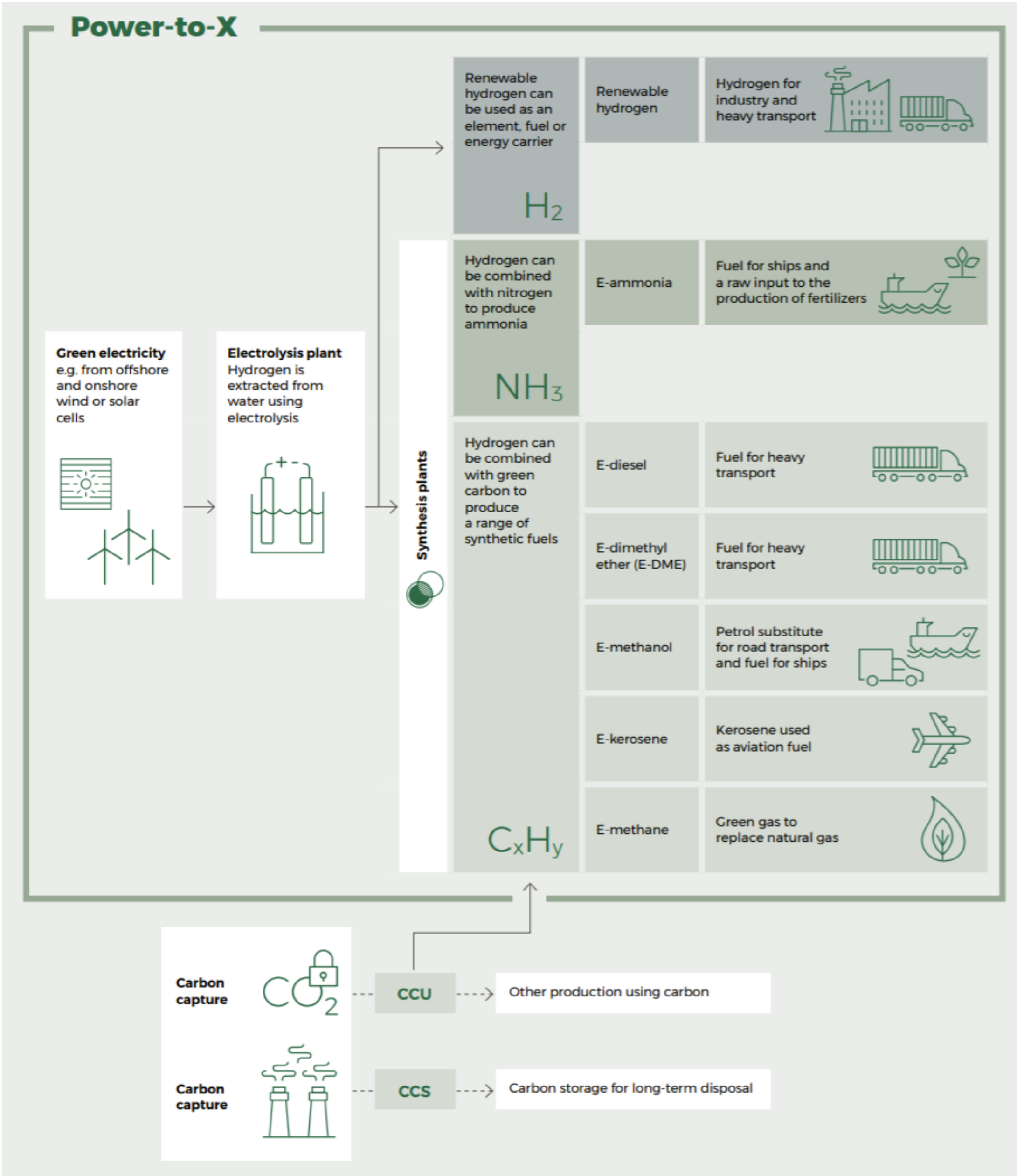


*Figure 14 - Power-to-X from Production to Application [69]*

[68] "New strategy accelerates Denmark's Power-to-X ambitions," State of Green, March 15, 2022, https://stateofgreen.com/en/partners/state-of-green/news/new-strategy-kick-starts-denmark-production-of-green-hydrogen-and-e-fuels/.

[69] *Recommendations for a Danish Power-to-X strategy* (Dansk Energi, Bain & Company analysis, November 2020), https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2021-03/Recommendations-for-a-Danish-Power-to-X-strategy.pdf.

### 8.1.1 Case Study: Green Fuels for Denmark

One of the first projects designed to demonstrate PtX technologies, Green Fuels for Denmark, is currently being developed as a partnership between Copenhagen Airports, A.P. Moller - Maersk, DSV Panalpina, DFDS, SAS and Ørsted. The goal is to construct an industrial-scale facility to produce sustainable fuels for road, maritime and air transport in the Copenhagen area. As currently envisioned, this project would be implemented in three phases:

- Phase 1 (operational by 2023): develop a pilot 10MW electrolyzer to produce renewable hydrogen used to fuel buses and trucks.
- Phase 2 (operational by 2027): develop a 250MW electrolyzer facility which will combine the renewable hydrogen produced from excess wind turbine output with sustainable CO2 captured from point-sources in the Greater Copenhagen area to produce renewable methanol for maritime transport and renewable jet-fuel (e-kerosene) for the aviation sector.
- Stage 3 (operational by 2030): upgrade the project's electrolyzer capacity to 1.3GW and capture sufficient CO2 to produce more than 250,000 tons of sustainable fuels each year for use in buses, trucks, ships, and airplanes.

The project has the potential to displace 5% of fossil fuels at Copenhagen Airport by 2027 and 30% by 2030. If the feasibility study confirms the viability of the project vision, a final investment decision for the first stage of the project could likely be taken as soon as 2021.[70]

## 8.2 Carbon Capture

Carbon capture is the process of capturing and reusing the carbon in GHG emissions from industrial, waste management, or fossil fuel extraction processes that would otherwise escape into the atmosphere. Capturing and storing the carbon produced from North Sea oil and gas production, and from industrial processes such as waste incineration and cement production, has recently been elevated as an important strategy for Denmark to achieve its climate goals, with the country allocating $2.43 billion for carbon capture and storage subsidies over the coming decade.[71] The Novo Nordisk Foundation is also providing a $97 million grant to the University of Aarhus to establish the Novo Nordisk Foundation CO2 Research Center, with a mission to efficiently capture, store, and recycle CO2. The research will focus on employing microbes and electrochemistry to turn the gas into components for fuel and plastic.[72] Thus, even though the CO2 from carbon capture is not yet being used for producing biofuels, as the technology matures it could soon prove to be an important supply source.

Carbon capture is seen as providing the foundation for developing the PtX concept in Denmark. The government is planning to capture half a million tons of CO2 from biogas plants between 2024 and 2032. This biogenic CO2 can be sent by ship to the North Sea oil and gas fields, where it will then be

[70] "Leading Danish companies join forces on an ambitious sustainable fuel project," Copenhagen Airports, May 26, 2020, https://www.cph.dk/en/about-cph/press/news/2020/5/leading%20danish%20companies%20join%20forces%20on%20an%20ambitious%20sustainable%20fuel%20project.

[71] "Denmark Bets on North Sea Carbon Capture to Hit Climate Goals," Reuters, December 14, 2021, https://www.reuters.com/markets/commodities/denmark-bets-north-sea-carbon-capture-hit-climate-goals-2021-12-14/.

[72] Anita Chakraverty, "Novo Nordisk Foundation Pumps €85M into Carbon Capture Research", Labiotech.EU, January 10, 2021, https://www.labiotech.eu/trends-news/carbon-capture-novo-foundation/.

pumped underground together with the non-biogenic CO2 collected from oil and gas production. This stored CO2 will be made available for PtX production as that technology becomes commercially viable.[73]

# 9 Denmark's Energy Sector Future

Denmark's commitment to eliminating fossil fuels and GHG emissions from its economy is beginning to have a profound impact on the role of traditional energy companies. These providers are facing great challenges, but also discovering that by repositioning themselves or expanding into new offerings they can navigate the future and take advantage of emerging business opportunities.

Historically, biogas in Denmark was used for electricity and heat production in combined heat and power plants. Under the Energy Agreement 2012 it became possible to upgrade biogas to RNG and inject it into the national gas network. Consequently, much of the biogas produced in Denmark is now being upgraded and distributed via the gas network, which is widespread and can be accessed almost anywhere in the country.

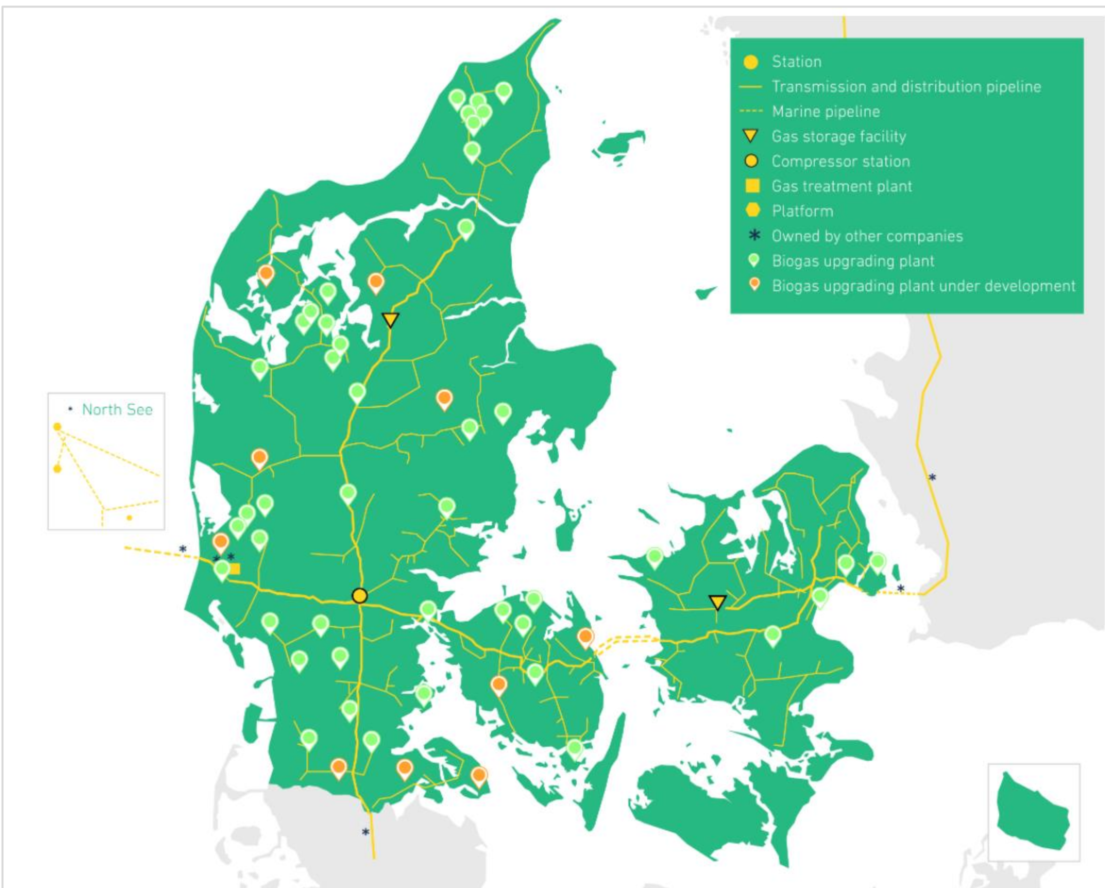


*Figure 15 - Denmark's Distributed Natural Gas Supply and Distribution System[74]*

[73] Frank Rosager, Biogas Denmark, "Record in biogas production provides a solid starting point for utilizing side production of biogenic CO2," Energy Supply, January 12, 2022, https://www.energy-supply.dk/article/view/828747/rekord_i_biogasproduktion_giver_solidt_afsaet_for_at_udnytte_sideproduktion_af_biogen_co2.

[74] "Biogas via the Gas Network," Energinet, updated November 2019, https://energinet.dk/Gas/Biogas.

The gas transmission system is managed by Energinet, the Danish national system operator for both electricity and natural gas. Energinet is an independent public enterprise owned and operated under the Danish Ministry of Climate and Energy. Before it can be injected into the gas distribution pipelines, biogas must be purified and upgraded to produce RNG, which has the same gas quality properties as conventional natural gas. The RNG must meet the standards defined in Energinet's Rules for Bio Natural Gas[75], which regulates the collaboration between the distribution system operator, Energinet, the upgrading facility owner, and the biogas producer.

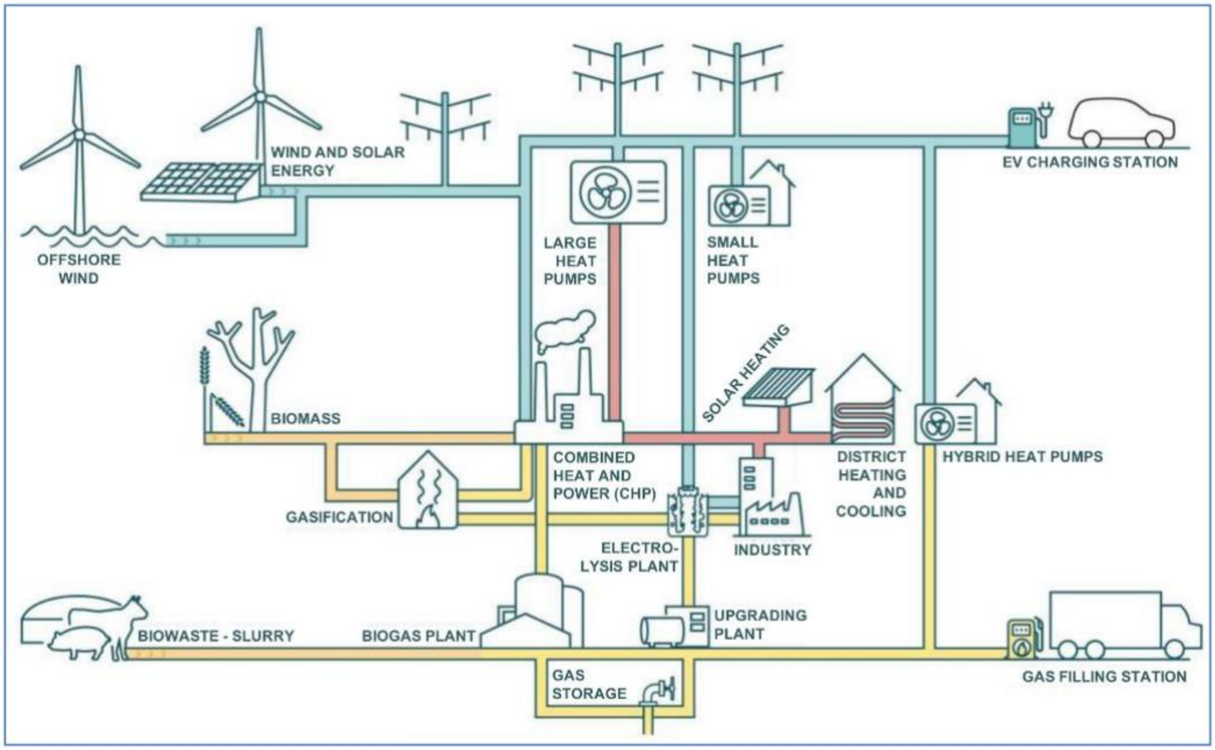


*Figure 16 - Future Danish Energy Ecosystem[76]*

The current gas network was built out during the 1980s to transport natural gas from the North Sea to Danish households and companies. The green transition of Denmark's energy supply means that gas consumption is expected to fall, and industry will account for a higher share of Danish gas consumption. Furthermore, with direct injection of RNG into the natural gas system becoming more prevalent, the Danish gas infrastructure is evolving into a decentralized green gas production and distribution system, with many small-scale biogas plants (more than 51 as of January 2022[77]) generating and injecting supplies into the gas network. Increasing diversity of supply is leading to increasing security of gas

[75] *Rules for the Supply of Upgraded Biogas (Bio Natural Gas) into the Danish Gas System, Version 1.0* (May 1, 2013), https://en.energinet.dk/-/media/8CBE0A487C7A46D59EA010A82BD3AD0E.pdf?la=en&hash=16DE594DBD028F234E4DA6D7506FF4E58EE64D1D.

[76] Marc-Antoine Eyl-Mazzega and Carole Mathieu, *Biogas and Biomethane in Europe: Lessons from Denmark, Germany and Italy* (ifri Centre for Energy, April 2019), https://www.ifri.org/sites/default/files/atoms/files/mathieu_eyl-mazzega_biomethane_2019.pdf.

[77] Stuart Elliott, "Denmark hikes proportion of biogas in grid to 25%: grid operator," S&P Global Commodity Insights, January 10, 2022, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/011022-denmark-hikes-proportion-of-biogas-in-grid-to-25-grid-operator.

supplies, even as the North Sea production is dropping. This in turn provides the stability needed to plan for long-term decarbonization of those areas where electrification is not expected to be an option for many years to come. All of these changes are leading to the emergence of a new energy ecosystem in Denmark, with renewable fuels and the existing natural gas infrastructure playing a foundational role in connecting the pieces. Figure 16 shows how the different components could fit together in the new, unified energy production and delivery system of the future.

Looking ahead, if hydrogen demand continues to grow in Denmark and/or neighboring countries, dedicated hydrogen infrastructure will be needed to connect large-scale productions facilities with demand, as well as to ensure flexibility and security of supply. Plans are now being evaluated for Denmark to become part of a European Hydrogen Backbone, with the infrastructure likely being a mix of converted natural gas pipes and new hydrogen infrastructure that overlays and augments the existing gas system. Studies have shown that large hydrogen systems can have lower specific infrastructure costs than electric systems of similar capacity. As an added benefit, the visual impact of underground gas pipes is less that overhead power lines.[78]

In addition, facilities for long-term storage of hydrogen will soon come on-line. Green Hydrogen Hub Denmark, now being developed in northern Denmark, will use large caverns in natural salt deposits for hydrogen storage. This project will have sufficient capacity to store 200 GWh in hydrogen by 2025, and 400GWh by 2030.[79] The ability to store large amounts of hydrogen will allow electrolyzers to maximize production when wind energy output is highest and electricity prices are lowest, thereby reducing the cost of producing renewable hydrogen and other PtX products.

This new energy ecosystem will inevitably create both challenges and opportunities for utilities, energy providers, and other companies operating in this space. How these businesses transition toward this new landscape will help determine how successful the country is, as a whole, in achieving its dual goals of making deep cuts in GHG emissions by 2050 while continuing to increase economic competitiveness.

As an example, in 2009 DONG Energy (Danish Oil and Natural Gas) had one of the most carbon-intensive electricity-generation systems in Europe, and the world. At that time it launched a campaign to completely reinvent itself as Ørsted, a top-to-bottom renewable energy company, and in little more than a decade it transformed from a fossil-fuel based energy utility to a green energy provider. By 2018 Ørsted's green energy output was 75% of total output and the company had reduced its CO2 emissions intensity per kilowatt hour by 72%. Today, DONG employs 6,672 people and is a global leader in the transition to green energy.[80] By 2025, two years after the last of Ørsted's coal plants are to close, green energy is set to account for 99% of the company's output while CO2 emissions intensity is to fall by 98% below the 2009 level. Ørsted has captured key lessons learned through its transformation to a clean energy leader in a report, "Our green business transformation: What we did and lessons learned." [81]

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[78] Morten Stryg, Danish Energy Association, "Hydrogen" from Final FutureGas Report (FutureGas, September 2020), https://futuregas.dk/wp-content/uploads/2020/10/FG-Final-report-5-10.pdf.

[79] "About Us – Green Hydrogen Hub Denmark", accessed April 18, 2022, https://greenhydrogenhub.dk/about/#:~:text=Green%20Hydrogen%20Hub%20Denmark%20is,are%20created%20in%20salt%20deposits.

[80] "Ørsted: About Us", Ørsted, accessed November 21, 2021, https://orsted.com/en/about-us.

[81] *Our green business transformation: What we did and lessons learned* (Ørsted, April 2021), https://orstedcdn.azureedge.net/-/media/www/docs/corp/com/about-us/whitepaper/our-green-business-transformation---what-we-did-and-lessons-learned.ashx?la=en&rev=32e00a9058f14269946142348c0916fe&hash=2EE2AE8F69521DD2F7D1B4D6315B10F1

# 10 Conclusion

Over the past 50 years Denmark has shown itself to be a global leader in clean energy, developing and implementing bold plans that have led to the transformation of many fundamental aspects of its energy supply and distribution systems. During the most recent phase, Denmark has successfully pioneered the development of biofuels and carbon neutral synthetic fuels. These renewable fuels have already displaced more than 25% of the gas supplied through the country's natural gas infrastructure, and they are projected to play an ever-increasing role in serving industry and heavy transportation. Development of renewable fuels is seen as an important complement to Denmark's efforts to electrify loads, as approximately 40 to 60% of the country's energy needs projected for 2050 cannot easily be converted to direct electricity consumption. Increased reliance on these green fuels will also allow Denmark to continue to utilize much of its existing gas infrastructure, whose immense storage capacity can play a critical role in stabilizing the country's overall energy infrastructure.

Denmark's success can be attributed to a combination of technological innovation, supportive government policies, and broad-based social support. Government policies, including a combination of generous subsidies for biofuels, and financial disincentives imposed on high carbon fuels, have been instrumental in catalyzing the growth of renewable fuels. However, it is ultimately the Danish commitment to engaging all sectors of society when crafting a vision that that has led to consistent, long-term political support and success. Though Denmark is a country with relatively limited fossil fuel resources, by taking into consideration everything it has access to, not only things such as wind and waste, but also human intelligence and corporate prowess, Denmark has written a roadmap for how a country or region can reduce carbon emissions and dependence on imported energy supplies, while increasing economic competitiveness.

Every nation and business will face its own unique set of challenges as it attempts to reduce carbon emissions and navigate the changes that will be occurring in energy supply and distribution systems, and each will have to determine the solutions that work best for them. As the Danish Energy Administration has stated, "The policies and business models of yesterday will not work for the governments and energy companies of tomorrow. What may have seemed impossible 10 years ago is now happening." [82] Through the succesful development of its biofuel and synthetic fuel resources Denmark is charting a path and demonstrating to nations and individual businesses how they can rely on renewable fuels to transition to and prosper in a carbon neutral economy. However, though it is achieving remarkable successes at home, the country is all too aware that a zero-carbon Denmark alone is only a small step toward reducing global GHG emissions. Fortunately, Denmark has shown itself to be eager and willing to share these important lessons and technologies with others, to help ensure that partners around the world are also able to successfully tackle the carbon reduction challenge.

[82] *From black to green – a Danish sustainable energy growth story* (State of Green, May 2021), https://ens.dk/sites/ens.dk/files/Globalcooperation/sog_fromblacktogreenreport_210x297_v08_web_spreads.pdf