Denmark's energy strategy and the viability of bioenergy

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Denmark has ambitious climate goals of reducing carbon emissions by 70% from 1990 levels by 2030 and approaching carbon neutrality by 2050. The nation's energy and electricity demands will rely heavily on the production of renewable energy sources, including wind energy and bioenergy. The sustainability of large-scale biomass combustion has been questioned. This article explains the overall Danish energy strategy and explores the viability of bioenergy as a transitory form of electricity generation for Denmark.

Introduction

Denmark is a small country as measured by both land area and population, yet the Nordic nation appears at the forefront of the global shift toward sustainability and climate awareness. The country borders both the North and Baltic seas; it includes nearly 400 islands and boasts 7314 km of coastline. The nation is mostly flat, with an average elevation above sea level of only 34 m. Denmark's vast coastline and low elevation make the country vulnerable to sea level rise due to global warming. This geographic characterization in conjunction with public support for climate activism has contributed to Denmark's desire to be a global leader in sustainability.

The Danish general election of 2019 is known colloquially as the climate election, as much of the younger electorate expressed their concern about the state of the environment and overall sustainability of the nation. Climate change was ranked by 46% of voters as their top issue, propelling the Social Democrats and their commitment to sustainability to victory (Sorensen, 2019). In response to public opinion, Denmark's government has instituted a series of goals and policies related to sustainability and climate change. Parliament's June 2020 Climate Act outlined these goals for the foreseeable future. By 2030, the nation aims to reduce emissions by 70% from 1990 levels, which will require a reduction of nearly 24 million tons of carbon dioxide equivalent (CO_2e) from 2020 to 2030. Ultimately, its goal is to become a net-zero carbon emitting nation by 2050 (Danish Parliament, 2020). The agreement specifies that Denmark must ensure the actual reduction of domestic emissions and not merely a reallocation of fossil fuel emissions outside the country's borders, known as leakage. Additionally, the act states that Denmark's green transition will be overseen by the Danish Council on Climate Change.

As a subsequent step, in October 2020, the Danish Ministry of Foreign Affairs and the Ministry of Climate, Energy and Utilities released a long-term strategy for global climate action. This report acknowledges Denmark's role among global polluters as a small country with fewer than six million people. The Danish strategy is one of international influence; by investing in emerging technology, such as wind power, bioenergy, central heating, heat pumps, and carbon capture, the Danes wish to position themselves as a green superpower. Their strategy of influence is two-pronged. First, they aim to use their diplomatic influence within the EU and the United Nations to push both organizations to increase regulation regarding emissions and energy usage. Second, Denmark wants to build strategic partnerships across the globe with climate allies whose environmental economies play a major role in reaching the aims of the Paris Agreement. Denmark wants to bring its knowledge and technology to countries that are developing and improving their sustainability strategies (Ministry of Foreign Affairs of Denmark, 2020).

As Denmark embarks on an ambitious climate strategy, the nation's energy mix will play a crucial role in the successfulness of its plan. This includes the use of wind turbines, solar panels, and bioenergy. The utilization of bioenergy on a transition basis as a sustainable energy source will shape the future of the Denmark's energy mix and the climate strategies it wishes to see implemented abroad.

The Danish climate strategy

To achieve its sustainability goals, the Danish climate strategy is multifaceted; it relies on eliminating fossil fuel combustion while investing in and expanding sources of renewable energy along with developing new emission reduction strategies to include carbon

capture. Understanding the current energy mix in conjunction with plans for an expansion of renewable energy production, the electrification of the society, and the short-term utilization of bioenergy as a transition fuel is important to an evaluation of the achievability of Denmark's sustainability goals.

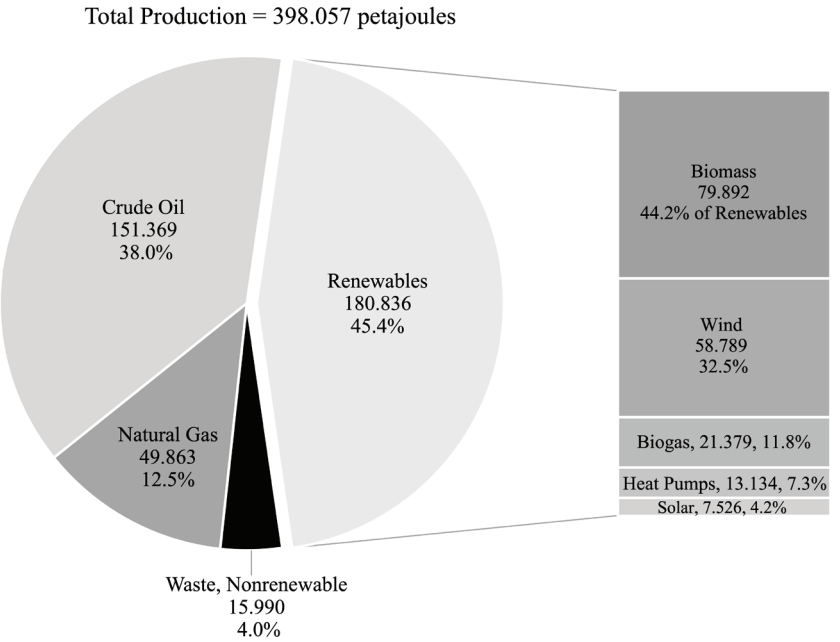
Danish energy mix

Denmark must produce enough sustainable energy in order to meet existing and future demands for energy, while continuing to lower domestic emissions to meet national carbon emission goals. In terms of total energy production, Denmark produces 398 petajoules (PJ) of energy. (For reference, 1 PJ is enough energy to power 19,000 households for one year.) This figure has decreased dramatically as the country produced 1165 PJ and 979 PJ of energy in 2000 and 2010, respectively. In 2000, more than 1000 PJ of energy were produced using the combustion of fossil fuels, decreasing to approximately 830 PJ in 2010. By 2020, energy from fossil fuel combustion accounted for 201 PJ of total energy production. The largest changes in total energy production by source come from crude oil and natural gas. In 2000, Denmark produced 765 PJ from crude oil and 310 PJ from natural gas. In 2020, Denmark produced 151 PJs from crude oil and 50 PJ from natural gas (Danish Energy Agency, 2020a). This massive drop-off in energy produced domestically by fossil fuel combustion reflects the effectiveness of the Danish climate strategy.

Energy production comes from four main sources, as shown in Figure 1 in decreasing order based on percentage of total production: renewables (including bioenergy), crude oil, natural gas, and nonrenewable combustion of waste. Renewable energy comprises 181 PJ (45.4%) of total energy produced. The country derives 151 PJ (38.0%) of energy from crude oil as well as 49 PJ (12.5%) from natural gas. Finally, the remaining 16 PJ (4.0%) of total production is sourced via the combustion of nonrenewable waste (Danish Energy Agency, 2020a).

Energy usage is not directly tied to domestic energy production. In 2020, Denmark consumed a total adjusted gross energy of 700 PJ, down from 1990 and 2000, when the country consumed 819 PJ and 839 PJ of energy, respectively. This decrease in energy consumption created an opportunity for the nation to shift away from fossil fuels. Currently, the country produces renewable energy accounting for 45.4% of domestic energy production. However, the percentage of renewable energy consumption sits at 40.3%. This discrepancy is attributable to energy imports. Denmark is less dependent on energy imports than other nearby nations but still imports significant amounts of biomass, crude oil, natural gas, and coal. In 2020, Denmark imported 761 PJ of total energy, whereas the nation exported 451 PJ. This makes

Figure 1
Energy production by source, in petajoules



Source: Danish Energy Agency, 2020a.

Denmark a net importer of nearly 310 PJ of energy. Of the total imported energy, the Danish Energy Agency estimates that only 81 PJ of these imports are sustainable. Most renewable energy imports come in the form of biomass (mostly wood pellets and chips), primarily from Estonia and Latvia, the US, and neighboring Scandinavian countries. The low ratio of imported sustainable energy drives the percentage of renewables consumed below the percentage of domestic renewable energy production (Danish Energy Agency, 2020a and 2020b).

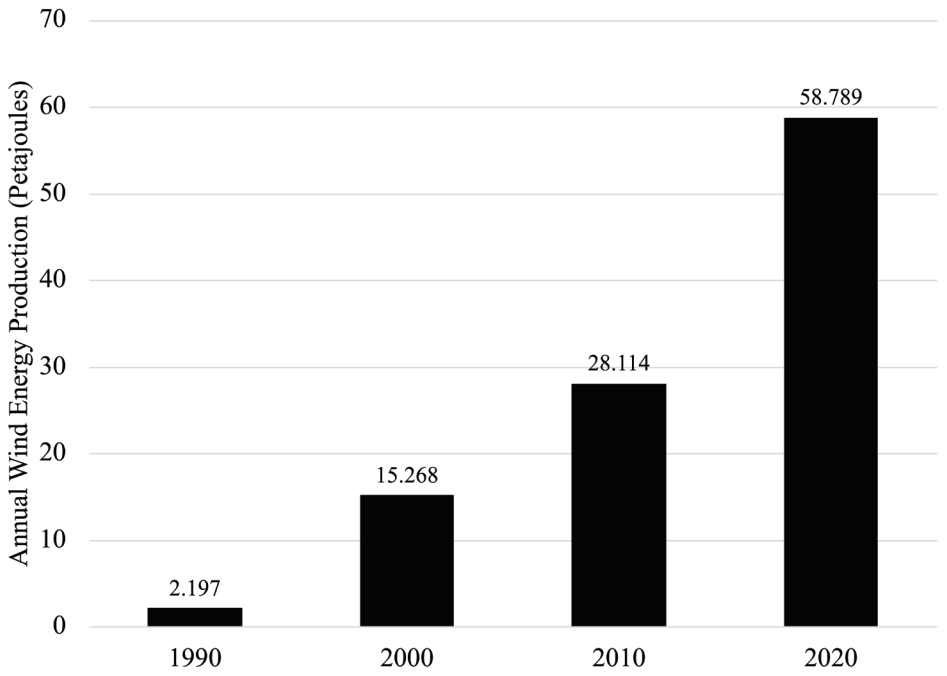
Renewable energy production

Denmark has made significant strides in increasing renewable energy production, from 45 PJ in 2000 to 181 PJ in 2020, representing 45.4% of its total domestic energy production. The primary source of renewable energy in Denmark is biomass, almost 80 PJ of its energy. As shown in Figure 1, wind power is the second largest source, contributing 58 PJ of energy. Biogas and heat pumps generate 21 PJ and 13 PJ of energy, respectively. Solar energy makes up 8 PJ of Denmark's renewable energy mix, whereas hydro and geothermal account for the remaining share (Danish Energy Agency, 2020a).

Denmark's extensive windswept North Sea coastline has enabled the nation to produce 32.5% of its renewable energy via wind power. In 2020, offshore and onshore wind capacity grew to 58 PJ, a substantial increase from the 1990 capacity of 2 PJ, the 2000 capacity of 15 PJ, and 2010 capacity of 28 PJ, as noted in Figure 2 (Danish Energy Agency, 2020a).

Denmark plans to continue expanding its wind power capacity, but the main driver of renewable energy in Denmark, at least in the short to medium term, will be bioenergy, which includes biomass and biogas production, and at present provides 56% of the nation's renewable energy. As of 2020, Denmark utilized 80 PJ of biomass and 21 PJ of biogas for domestic energy production, the vast majority coming from wood products, including 19 PJ from straw, 19 PJ from wood chips, and 14 PJ from firewood. Denmark also imported 18 PJ of wood chips, 46 PJ of wood pellets, and a net of 7 PJ of biodiesel. Combining these figures reveals that Denmark consumes nearly 181 PJ of bioenergy across domestic production and energy imports. The country consumes 260 PJ of renewable energy in total, so bioenergy constitutes nearly 70% of renewable energy consumption in the nation (Danish Energy Agency, 2020a). Wind energy and bioenergy make up most of the Danish renewable energy mix. To achieve the goal of becoming carbon neutral, Denmark must focus on increasing domestic production of sustainable

Figure 2
Annual wind energy production 1990–2020, in petajoules



Source: Danish Energy Agency, 2020a.

energy to meet changing energy demands driven by emerging technologies and greater electrification.

The electrification of Denmark

Energy production and use are essential for any nation to have a functioning, let alone dynamic, economy. Electricity plays a crucial role in this balance with an interdependency to almost every facet of the national economy. Electricity is needed to pump water; to electrify transportation; to support communications, information technology, and industry; and even to facilitate the operation of oil, natural gas, and biomass electric power generation plants. One of the most effective strategies to reduce greenhouse gas emissions is electrification. Electrification refers to the process of replacing fossil fuel–powered technologies with electricity-powered alternatives, which can be generated from low-emission renewable sources. As Denmark pursues its strategy of greater electrification, electricity consumption is projected to increase significantly in the period up until 2030 (Danish Energy Agency, 2021), and, with that demand, Denmark will need to continue investing in clean sources of electricity production.

As of 2020, Denmark produces 103 PJ of electricity, of which 85 PJ, approximately 82%, is from renewable sources. However, Denmark requires more electricity than it produces, which results in a net import of electricity of nearly 25 PJ. The net import brings the percentage of renewable electricity consumed down to 68%. Although this percentage represents a massive improvement over the 1990 and 2000 rates of 5.3% and 15.9%, respectively, there is still room for significant improvement (Danish Energy Agency, 2020a).

Denmark plans to meet its future clean electricity needs primarily through wind energy and on an interim basis with bioenergy. Currently, renewable electricity production is driven mainly by bioenergy and wind energy, representing 48.5% and 48.0% of the total production, respectively, with solar contributing the remaining 3.5% (Danish Energy Agency, 2020a). Electricity generated from wind power is intermittent as it relies on variable weather patterns that can lead to times with low electricity output, a result of the wind not blowing. On the other hand, bioenergy, which the country has been using for more than two decades, is readily dispatchable and can serve the crucial role of providing electricity when wind turbines are suffering from intermittency. Together the two forms of generation can readily complement each other. Denmark must continue to invest heavily in clean electric generation with its predominant focus on wind and bioenergy. By doing so, the country can reduce its greenhouse gas emissions while maintaining the requisite electricity supply needed to power a fruitful economy and a healthier society.

Demand for biomass and biogas energy

A 2017 Danish Council on Climate Change report identified a list of elements that would reduce CO_2e, at the same time meeting the future demands for energy and electricity. Although the nation's long-term strategy is to expand total wind turbine capacity in order to satisfy electricity demand, the report also included the increased development of wood pellet boilers and the integration of biogas in the natural gas grid (Danish Council on Climate Change, 2017). An updated 2020 report detailed plans to use bioenergy as a transitory electricity source while domestic wind capacity is increased to meet total electricity demand. The report notes that biomass electricity production must meet criteria for sustainability. For biomass, this means the carbon emitted from combustion must be less than the carbon absorbed while growing. In addition to electricity production, the report specifically describes the need to increase biogas production to 35 PJ by 2025 in order to replace natural gas use (Danish Council on Climate Change, 2020).

Biomass that is used strategically to combat intermittency caused when the wind is not blowing or the sun is not shining will remain a crucial part of the Danish energy strategy for the foreseeable future even as wind turbine capacity is increased (Danish Council on Climate Change, 2020). Nonetheless, there are concerns about the long-term sustainability of such a high reliance on biomass for electricity production. First, biomass electricity production still requires the combustion of natural material, and the concern is that emissions from combustion may outweigh the carbon absorbed during the growing process. Second, Denmark imports biomatter, which could cause high carbon emissions from transportation. Finally, Denmark's use of biomass per capita is nearly three times the sustainable supply of biomass-based energy available globally (Danish Council on Climate Change, 2018). Because global influence plays such a large role in the Danish Climate strategy, the scalability of biomass electricity production becomes doubtful. The next decade of developments in domestic electricity demand will bring into question the viability of bioenergy to meet these changing demands. Bioenergy is certain to play a major role in the Danish energy economy, but it is not a strategy that can be implemented globally.

Denmark's next decade

To better understand the future of the Danish energy mix, it is important to break down the energy economy by sector. Five major areas (households, transportation, service, manufacturing and construction, and agriculture) present opportunities for electrification and increased clean energy use.

Household energy demand is heavily dominated by space heating. Heating accounts for 80% of energy consumption, with the remaining 20% as regular electricity consumption (Danish Energy Agency, 2021). In order to lower emissions, Denmark is shifting from oil and gas heating toward district heating and heat pumps—65,000 new heat pumps were installed in 2020, and this figure is projected to grow steadily through 2030. The shift to heat pumps and district heating will result in higher electricity demand, which will increase by nearly 30% from slightly more than 35 PJ to nearly 50 PJ by 2030 (Danish Energy Agency, 2021). This rise in electricity demand will be supplied by the continued development of wind power and bioenergy.

Transportation emissions are driven by road transport, rail transport, domestic aviation, and domestic shipping, all of which include both private and public passenger transport as well as transport of goods. CO_2 emissions are derived primarily from road transportation. Both the road transport and rail transport sectors have been targeted for emission reduction practices via electrification as well. Road transport is dominated by automobiles running on internal combustion engines. In order to reduce emissions from road transport, the Danish government has enacted a series of subsidies and tax breaks in order to incentivize citizens to purchase electric cars. With these measures, the Danish Energy Agency projects that 22% of cars on the road in 2030 will be zero- and low-emission vehicles, corresponding to approximately 730,000 vehicles. By 2030, it also projects that 48% of new vehicle registrations will be for electric and hybrid vehicles. As a result, electricity consumption from these vehicles is projected to increase from negligible levels in 2020 to 7.7 PJ by 2030 (Danish Energy Agency, 2021), a level that could be even higher if electric vehicle adoption is greater than projected levels.

The service sector comprises many activities, both private and public, including restaurants, banks, data centers, retail stores, daycares, schools, hospitals, and public administration facilities. Most energy consumption within the service sector comes from electricity and district heating. As heating via natural gas is phased out and replaced with heat pumps, the energy consumption mix will continue to shift in favor of electricity. The private sector is projected to see an energy demand increase of 13%, while retail and wholesale are expected to see 20% increases in their level of consumption by 2030. One peculiarity in the service sector is the electricity consumption of data centers. Data centers consume only 1 PJ of electricity, but expectations suggest that the industry will grow exponentially in the next decade. The Danish Energy Agency projects data centers will consume 17 PJ of electricity by 2030. Overall, a significant rise in total electricity demand from the sector can be expected. Usage was approximately 35 PJ in 2020 but is projected to climb to nearly 60 to 65 PJ by 2030 (Danish Energy Agency, 2021).

The manufacturing sector includes enterprises that produce goods such as textiles, furniture, and electronics as well as chemical and pharmaceutical products. It also includes building and construction. In many of these areas, the sector will undergo electrification with regard to utilizing different manufacturing equipment and the increased use of heat pumps. Thus, electricity demand will increase but only by approximately 5 PJ by 2030. However, the sector also includes the manufacture of products, such as glass, cement, and tiles, that require high temperatures currently only reachable using fossil fuels, especially natural gas. There is a planned shift to using biogas for machines that require fossil fuels to function in order to cut natural gas use by nearly half. This shift in fuels will require biogas production to increase substantially but in the long run should contribute significantly to reducing CO_2 emissions (Danish Energy Agency, 2021).

The agricultural industry contributes emissions through the production of livestock and crops and from land use as well as from energy consumption of fisheries and forestry. As a sector, agriculture contributes approximately 20% of Denmark's total greenhouse gas emissions (Danish Energy Agency, 2021). Utilizing animal waste to produce biogas will at once reduce the waste product itself and its greenhouse gas emissions and also increase production of a fuel source that can replace fossil fuel usage in many industries that currently burn fossil fuels. (For more detailed insights on the future of the agriculture industry, see the article in this volume by Ali.)

Given the expected growth in electricity demand across these five sectors of the economy, how will Denmark respond and how will that growth affect meeting the 2030 goal of a 70% reduction from 1990 carbon emission levels? As of 2020, Denmark had reduced total emissions by approximately 38%, equivalent to about 28 million tons CO_2e, leaving a further unmet reduction of 32%, or approximately 24

million tons of CO_2e, to be achieved by 2030. The Danish Energy Agency projected Denmark would meet only approximately half of that remaining reduction goal by 2030, corresponding to a predicted 11.8-million-ton gap of CO_2e (Danish Council on Climate Change, 2020). However, this does not mean the nation's measures have been unsuccessful, as the country's emissions are projected to decrease by a total of 11.7 million tons of CO_2e by 2030 (Danish Energy Agency, 2021). This decrease represents major progress, for Denmark will have made huge steps in replacing coal, oil, and natural gas with more sustainable forms of energy, such as wind and bioenergy. As Denmark continues to ramp up capacity for renewable energy production, the nation's carbon emissions will begin to approach its goal of carbon neutrality by 2050.

For this projected emission decrease to occur, Denmark's energy landscape will have to undergo further significant changes. While total energy consumed is only estimated to increase by 5 to 10 PJ, electricity demand is projected to increase by 50 to 60 PJ. Considering total electricity consumption in 2020 was around 112 PJ, this represents a nearly 50% growth in electricity consumption (Danish Energy Agency, 2020a). Concerns regarding the sustainability of Denmark's high levels of bioenergy production may be exacerbated by an increased demand for electricity. Denmark will require higher levels of electricity production primarily from biomass combustion and wind turbines by 2030. Additionally, there will be a requirement to expand biogas production for use in transportation and manufacturing.

The viability of biomass

As the demand for renewable electricity production increases with the greater electrification of Danish society, biomass is expected to continue playing a crucial role in meeting that demand. Unlike solar or wind power, biomass energy cannot be considered inherently carbon neutral since the carbon emissions associated with the production, transportation, and combustion of biomass must be taken into account (Danish Council on Climate Change, 2018).

International climate and accounting regulations consider biomass carbon neutral if significant sustainability measures are met. The vast majority of biomass comes from forest-based wood products. During the growth phase, the tree absorbs carbon from the atmosphere. For the process to be considered carbon neutral, the total absorbed carbon must be greater than what is released through production, transportation, and combustion. Sustainable forestry includes both selective logging and replanting in order to maintain the carbon stock of the forest and protect its integrity over time. Biomass products can be either locally sourced or imported. During the process of transporting the physical products, CO_2e particles are emitted especially in cases of longer transit times and distances. The final phase includes the combustion of the biomass in large incineration facilities, where it is converted to electricity. This process also releases carbon into the atmosphere. Denmark's reliance on biomass combustion as the source of 70% of its renewable energy consumption in 2020 brings forth potential sustainability issues corresponding to utilization of biomass going forward (Danish Council on Climate Change, 2018).

How sustainable is biomass?

The carbon neutrality of biomass has been argued by scientists and academics for some time, but the consensus opinion is that the process is at least near carbon neutral. Some studies show negative carbon emissions; however, in most cases the biomass life cycle has been shown to produce slightly positive emissions. This means that on average the carbon released through combustion is slightly greater than the carbon absorbed through replanting (Evans et al., 2010).

The aggregate findings of seven individual studies from 1998 to 2007 demonstrate the average carbon emission from biomass energy is 62.5 g CO_2e/kWh, with the highest being 132 g CO_2e/kWh. This high-end figure of 132 g CO_2e/kWh is less than one-third the emission of natural gas and one-fifth the emission of coal combustion. These findings include the entire process, from cultivation to transportation to final combustion. Thus, there is evidence that the replacement of fossil fuels with biomass could see a minimum reduction in emissions of 74% and a maximum reduction of 98% (Evans et al., 2010).

Although the emissions-related data for biomass seem promising, some experts remain concerned over the potential land and water use associated with high demand for biomass. There are significant amounts of water required during the cultivation, harvesting, transportation, and processing of biomass. Additionally, biomass growing competes directly with other agricultural activities for land space. Experts have concluded that replacing valuable agricultural land with biomass production is inherently unsustainable, so further biomass production will require growing crops used for bioenergy on previously uncultivated land (Evans et al., 2010). This solution mitigates some potential issues with regard to the overall sustainability of biomass energy production.

Denmark relies heavily on imported biomass, and, as of 2018, nearly 43% of its biomass was imported from other countries. Denmark's high dependence on imported biomass brings potential challenges in mitigating emissions from transportation. However, Denmark imports biomatter primarily from Estonia, Latvia, and neighboring Scandinavian nations whose locations are relatively close to Denmark. These short distances keep carbon emissions from transportation relatively low. Additionally, Denmark can take advantage of its high imports of biomass products by importing from nations with more unused land. This would prevent biomass production from displacing more nutritionally and socially valuable agriculture (Danish Council on Climate Change, 2018).

Even though replacing fossil fuels with biomass has proved to reduce emissions by 74% to 98%, the combustion process will still emit some carbon into the atmosphere. To bring emissions to zero by 2050, Denmark must continue to invest in carbon capture technology. The Danish Council on Climate Change 2018 report mentions reforestation and the creation of forest carbon sinks as forms of natural carbon capture. Denmark's ability to invest in and develop carbon capture technology domestically will allow the nation to offset the emissions created by biomass electricity production and biogas (Danish Council on Climate Change, 2020).

Bioenergy as a bridge to the future

Energy derived from biomass should be viewed as a strong component in the Danish energy strategy for the 2020s. Although the process of energy production from biomass is not completely carbon neutral, it is still a much cleaner alternative compared to burning fossil fuels, with a potential reduction of greenhouse gas emissions of at least 74%. Therefore, using biomass energy can be considered a positive step toward reducing carbon emissions from the energy sector.

Denmark, however, must view bioenergy for electricity production only as transitory. Biogas used for replacing fossil fuels in heavy vehicles and machinery will be more permanent, but biomass combustion for electricity must be utilized in a high quantity while the nation lacks more sustainable sources of electricity. Long term, the country must continue to invest in additional wind turbines, as currently they produce only 48.0% of the nation's renewable electricity. Wind turbines produced nearly 59 PJ of energy in 2020, a 2576% increase from 1990. In 2020, the nation was operating 6217 wind turbines, and this number must continue to increase (Danish Energy Agency, 2020a). Eventually, net-zero energy sources, primarily wind power, will provide almost all the domestic electricity. This will allow the nation to effectively phase out biomass used for electricity and further reduce the carbon output of the nation as Denmark approaches its net-zero goals by 2050.

Bioenergy in a global context

It is well known that the climate change emergency is a global issue. Within that global framework, Denmark is a relatively small nation with unique geographic and demographic features. Its population of fewer than six million people is almost negligible in relation to the eight billion people who live on planet Earth. Consequently, Danish carbon emission reduction is also almost negligible in comparison to global emissions. Denmark's diminutive size has shaped the nation's climate strategy by prioritizing both the development of wind and bioenergy for domestic consumption and the exportation of Danish green technologies on a global basis. Denmark believes its climate strategies and successes should be disseminated abroad either directly where applicable or as a model displaying the commitment necessary to combat the global crisis.

Large high-emission, high-population nations like India, China, and the US will have to play important roles to reduce greenhouse gas emissions. Those nations cannot expect to duplicate Danish climate efforts and successes, as their climate strategies and energy mix will be different, based on their own resources and energy demands. These countries will face a variety of challenges as they plan to decarbonize. Biomass energy represents one of these. Denmark's use of biomass in the transition to wind energy is prudent, but Danish consumption per capita is nearly three times the world potential for a sustainable supply of biomass-based energy globally (Danish Council on Climate Change, 2018). Almost every other country on a global scale is just too big to rely on bioenergy for such a large source of renewable electricity production. Denmark must continue to export solutions from its world-leading climate strategy, but bioenergy's role must not be included. This means that the climate strategies and energy mix for the rest of the globe will need to be different. These nations must create specialized energy plans for their own countries based on their unique resources and energy demands. Nonetheless, Denmark's demonstration of the feasibility of decarbonization is crucial for inspiring similar action around the world, thereby serving as a beacon of hope.

Conclusion

Denmark has committed itself to following an aggressive path to carbon emission reductions in the

face of climate change. It has done so by means of a long-term plan to expand renewable energy sources, one that includes an extensive electrification of society that will depend on expanded wind power. In the short to medium term, Denmark plans to depend heavily on the use and further development of renewable bioenergy sources. This is a sound near-term approach but should not be seen as the final end in itself, as there are significant limitations to what can be accomplished. While the development of bioenergy sources will work well for Denmark, it should not be seen as a solution applicable worldwide due to the many national differences in population, energy needs, and resource makeup. More appropriately, Denmark sees itself as a model of commitment for the larger family of nations in terms of what can be accomplished in the face of the climate threat and should be congratulated for its efforts.

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