Pathways to 2°C: The Controversy over the Place of Biomass in a Low-Carbon Energy Future

A Sociotechnical Research Paper
presented to the faculty of the
School of Engineering and Applied Science
University of Virginia

by

Eric Jess

April 8, 2021

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

Eric Jess

Sociotechnical advisor: Peter Norton, Department of Engineering and Society

Pathways to 2°C: The Controversy over the Place of Biomass in a Low-Carbon Energy Future

In 2015, nearly 200 countries adopted the Paris Agreement, the latest international treaty on climate change. The agreement outlines an international framework to limit global average temperature increase to "well below" 2°C above pre-industrial levels and urges signatories to "pursue efforts" to limit this increase to 1.5°C. Achieving this goal, the agreement asserts, requires countries to curtail emissions as soon as possible and "undertake rapid reductions thereafter" (Paris Agreement, 2015). Since then, parties to the agreement have considered new ways to meet reduced emissions targets.

Bioenergy is one alternative, which is classified as carbon neutral under the Kyoto Protocol of 1997. Bioenergy is energy derived from organic matter, most commonly via direct combustion of biomass. Burning biomass releases energy stored in the chemical bonds of organic compounds as heat, which can be used for building and water heating, as industrial process heat, or in steam turbines to generate electricity (U.S. EIA, 2020). This contributes to carbon emissions just like fossil fuels, but the carbon released from biomass is already a part of the carbon cycle, whereas fossil fuels are effectively removed from the carbon cycle. In other words, burning biomass releases carbon dioxide previously absorbed from the atmosphere during photosynthesis, which can imply net zero emissions if the entire lifecycle is considered.

In the context of carbon accounting and satisfying reduced emissions targets, there are clear advantages to treating bioenergy as carbon neutral. Under the European Union's revised Renewable Energy Directive (RED II) of 2018, member states must adapt their energy infrastructure to accommodate greater shares of renewable energy by 2030 (European Union, 2019). Bioenergy offers a convenient alternative, since biomass is used to generate electricity by the same mechanism as fossil fuels (i.e. combustion). Across Europe, coal-fired power plants are being converted to burn biomass. States thereby reap the benefits of bioenergy's carbon neutral status while minimizing operational disruption (Buchsbaum, 2018). As carbon pricing makes fossil fuels less practical for industry, renewable substitutes such as bioenergy occupy an increasing share of European energy mix (Best & Burke, 2020).

One form of biomass in particular has emerged as a favorite: wood pellets. Compared to other forms of biomass, pellets are more energy dense, consistent in quality, and versatile. U.S. wood pellets, mainly from the southeast, support the transition; exports grew by a factor of 6.5 from 2008 to 2016, largely due to rising demand in the European Union. The United Kingdom, which imports 56% of its supply from the States, is leading the way. During the same period, UK consumption of wood pellets grew by a factor of 9.1. By 2015, the UK accounted for a quarter of global pellet consumption. These trends are expected to continue as southeast Europe, Japan, and South Korea import more wood pellets to supplement power generation and the UK continues to expand its bioenergy production capacity (Thrän et al., 2019).

As industrial pellet producers and consumers continue to scale their operations, the future of bioenergy has come into question. Burning biomass releases carbon that was once absorbed from the atmosphere during photosynthesis, but the consequences of these emissions are complex and unsettled. In the U.S., the world's largest producer of wood pellets, forestry and agriculture are also at stake. The rising global demand affects prices of forest and agricultural products, which may incentivize changes to land use (Wang et al., 2015). Therefore, it is critical now more than ever to consider the place of biomass in a low-carbon energy future. Given the urgency of the climate emergency, the role of bioenergy must be limited. Changes to land use and carbon emissions from biomass may come at the expense of biodiversity, agriculture, and overall carbon savings. Policymakers should curtail subsidies and revise carbon neutral policies encouraging the exploitation of biomass to prevent further harm to the environment.

Review of Research

Bioenergy and Carbon Neutrality

Bioenergy is considered carbon neutral under current international carbon frameworks, but the classification's validity is disputed. McKechnie et al. (2011) showed that biomass harvest temporarily increases overall emissions and only over a long term (16-38 years) can power from biomass such as wood pellets emit less greenhouse gas than power from coal. This depends on the source of biomass, as agricultural residues and standing trees vary in carbon payback. Booth (2018) argues that demand for biomass may also deplete vital carbon sinks, namely forests, which standard carbon accounting ignores. Sterman et al. (2017) warn that climate policies that ignore the payback period of carbon debt from burning biomass may fail. The success of future policies will hinge on proper assessments of long-term effects.

Carbon Capture and Storage

While the carbon neutrality of bioenergy is disputed, carbon emissions from the fossil fuel industry are well acknowledged. In 1990, Finland became the first country to levy a carbon tax; it was applied to gasoline, diesel, light fuel and heavy fuel oil, jet fuel, aviation gasoline, coal and natural gas. From 1990 to 1992, other northern European countries also adopted carbon taxes. Lin and Li (2011) found that these taxes imposed a negative impact on per capita carbon dioxide emissions in Denmark, Finland, the Netherlands and Sweden. Despite also adopting a carbon tax, per capita emissions continued to increase in Norway due to the country's robust oil and natural gas exploration. Nevertheless, the cost of carbon emissions was palpable for petroleum companies. In 1992, to avoid taxation, Norway's largest oil company Statoil opted to inject carbon dioxide separated from natural gas deep underground into a geological formation beneath the North Sea. This and subsequent projects throughout the 1990s demonstrated the commercial value of carbon capture and storage (CCS) and established an innovation system around the technology (van Alphen et al., 2009).

Carbon taxes may have been effective in furthering CCS innovation in Norway, but their overall impact on emissions reductions was relatively insignificant. Bruvoll and Larsen (2004) found that carbon taxes constituted only a 2 percent reduction in Norwegian emissions from 1990 to 1999, partly due to exemptions and inelastic demand. In comparison, lower energy intensity and changes in energy mix accounted for 14 percent reduction during this period. (Note: overall emissions experienced a 19 percent net increase from 1990 to 1999, largely due to scale, thus the reductions are expressed as component estimates).

The Norwegians were not the first ones to inject carbon dioxide underground, however. The concept of capturing carbon dioxide and injecting it deep underground first arose in the 1970s in the United States, but this practice was motivated by enhanced oil recovery (EOR). Today, ExxonMobil among other major oil and gas players are beginning to launch CCS projects in response to climate change while still reaping the benefits of EOR (ExxonMobil, 2021).

Bioenergy with Carbon Capture and Storage (BECCS)

The idea to combine bioenergy with carbon capture and storage (BECCS) -- and achieve negative emissions -- did not arise until the late 1990s. Dr. Robert H. Williams of Princeton University is credited with the concept, which first appears in a chapter of *Eco-restructuring:*

Implications for Sustainable Development published by the United Nations University Press in 1998 (Hickman, 2016). Williams (1996) contends that "In the case of biomass grown on a sustainable basis, net lifecycle emissions with sequestering would be strongly negative." Williams goes on to argue that, if used to produce hydrogen fuel, BECCS may offer even greater potential for negative net lifecycle emissions if internal combustion engine vehicles are displaced by fuel cell vehicles. Not long thereafter, other researchers began to recognize the potential of BECCS. Obersteiner et al. (2001) assert the need for technologies that remove CO2 from the atmosphere, and suggest BECCS could serve the purpose while also providing energy to generate carbon neutral energy carriers such as electricity and hydrogen. They claim that "The long-run potential of [BECCS] is large enough to neutralize historical fossil fuel emissions and satisfy a significant part of global energy and raw material demand."

Industrial processes with significant biomass inputs were identified as an early opportunity to study the feasibility of BECCS. Möllersten, Yan, and Westermark (2003) calculate carbon capture and storage can offer substantial emissions reductions in Swedish pulp and paper mills. (In this study, biomass combusted in pulp and paper processes was regarded as carbon neutral due to the fact that, since the 1920s, the growth of Swedish forests has outpaced gross felling.) The pulp and paper sector was not the only prospect. Möllersten, Yan, and Moreira (2003) show how sugar cane-based ethanol mills can also incorporate carbon capture and storage in combustion and fermentation processes. The cumulative emissions reduction potential in these mills was estimated at 2-7% of overall reductions needed in the twenty-first century, based on IPCC estimates at the time. By showing how industrial energy systems can achieve negative emissions, Möllersten and his colleagues demonstrate the value of BECCS as a powerful carbon accounting tool that can be used to comply with Kyoto Protocol and Paris Agreement targets.

To date, BECCS has not been implemented as a single energy system, but that has not prevented its inclusion in integrated assessment models (IAMs). Van Vuuren et al. (2007) show how the negative emissions potential of BECCS could enable lower stabilization levels of carbon dioxide by the end of the century that were formerly considered not attainable. Some of these models show that warning below 2°C may be impossible without the negative emissions potential of BECCS, yet this is based on assumptions that bioenergy alone is carbon neutral. As BECCS gains traction in scientific literature, uncertainties around its feasibility and true potential to achieve negative emissions prevent its inclusion in climate policy.

The Status Quo of Bioenergy

The Role of Bioenergy in Emerging Markets

In countries where annual growth of electricity demand outpaces that of GDP, there are opportunities for bioenergy to supplement an increasing share of energy production. This is especially true for agricultural economies such as Vietnam, where biomass byproducts from post-harvest activities are abundant and tend to go unused. Rice straw, one of the most common agricultural wastes in Asia, is often burned out of convenience in the field shortly after harvest, which releases large amounts of harmful pollutants and greenhouse gases into the atmosphere (Le et al., 2020). Therefore, utilizing wastes such as rice straw could in some cases allow for energy production at no additional cost of emissions.

Despite the abundance of biomass residues, these resources are underutilized in Vietnam. The World Bioenergy Association highlights several barriers: lack of access to information to assess project potential and feasibility, inadequate planning and licensing procedures, inability of financial institutions to evaluate and finance projects, and poor understanding of bioenergy technologies. To facilitate market development, the “Climate Protection through Sustainable Bioenergy Markets in Vietnam” project was commissioned by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in partnership with Vietnam’s Ministry of Industry and Trade (MOIT). The project, which aims to address legal and regulatory frameworks, capacity development, and technology cooperation, began in 2019 and is set to continue until 2023 (GIZ Vietnam, 2020b).

Bioenergy in Vietnam has big shoes to fill. Cuong et al. (2021) estimate rice straw could be used to produce as much as 2,565 MW of electricity in Vietnam, which corresponds to 4.7 percent of the country’s power generation capacity. While it may seem insignificant, this is 19 times current power generation from other renewable sources (135 MW). According to Le Thi Thoa, a senior officer of the German-Vietnamese market development project, policy tools have an important role to play. Revised feed-in tariffs are expected to encourage co-generation projects utilizing bagasse residues from sugarcane processing. These types of synergies between agricultural byproducts and bioenergy are intended to support Vietnam’s goal of increasing the share of bioenergy in total electricity generation to 2.1 percent by 2030 and 8.1 percent by 2050 (GIZ Vietnam, 2020a). Land is required to support this growth, and in an agricultural economy like Vietnam, arable land is a finite resource. Considering the estimated upper bound of power generation capacity from biomass, continued expansion of bioenergy as Vietnam’s primary source of renewable energy may be unsustainable in the long run.

Winners and Losers of Bioenergy in Europe

The German government’s involvement in Vietnam is another signal of the European Union’s commitment to bioenergy. Germany, often regarded as the most influential country in the EU, has made bioenergy a pillar of their energy transformation. Energiewende, which translates to "energy turnaround," has enabled a slew of bioenergy projects across the country. Most of these projects are biogas plants, which convert a mix of maize and animal manure coupled with an assortment of bacteria into methane and carbon dioxide via anaerobic digestion. Market conditions are poised courtesy of government subsidies, and rural communities have been the beneficiary. Low-cost energy along with income from commercial taxes and land leases have helped many communities thrive. Altogether, nearly 120,000 Germans are employed by the bioenergy sector (Appun, 2016).

There are still side effects of widespread bioenergy. In northern Germany, the Nawaro Bioenergie Park, one the largest biogas plants in the world, consumes more than 1,000 tons of corn each day. The agricultural footprint required to support operations of this scale is at the detriment of small-scale farmers. In the past decade, bioenergy giants such as Nawaro have purchased 15 to 30 percent of the land in some areas, which has resulted in a 55 percent increase in land prices. Farmers are not the only ones affected. According to Florian Schone, an ecologist with the German Nature Conservation Union (DNR), "Valuable grasslands have been plowed up and converted to monocultures of maize production, and this leads to broad loss of grassland birds which used to breed on these sites." Schone continues on by acknowledging the need for renewable energy, but believes bioenergy should play a minor role given the implications for biodiversity and sustainable agriculture (BirdLife Europe and Central Asia, 2017).

The United Kingdom is also enthusiastic about biomass, but instead of agricultural feedstock, wood pellets are used. The majority of their supply comes from the U.S. and Canada, which also adds emissions costs associated with transport across the pond (Ambrose, 2019). Nearly all go to the Drax Power Station in northern England, which is being converted to burn wood pellets. Former Drax CEO Andy Koss denies that biomass enterprises are responsible for clearcutting; instead, they scavenge land that others clear-cut for lumber. He claims “most foresters will tell you” that such biomass collection “is the best way to get regrowth to come back, and that it’s good for biodiversity across a managed landscape” (Elbein, 2019). Both the World Bioenergy Association and Drax refer to biomass collection as “harvest,” which invokes notions of a recurring and replenishable cycle.

This Land Is Your Land

Plants and People Alike

Forests and the biodiversity they support are not the only ones adversely affected by bioenergy projects. In the Southeastern U.S., wood pellet production facilities are being built in low-income, African American communities. Koester and Davis (2018) found that pellet production plants in the southeast were 50 percent more likely to be located in environmental justice (EJ) communities, which are defined as communities where the poverty level exceeds the state median and more than 25 percent of the population is nonwhite. This is especially concerning given the history of most industrial process plants being placed in EJ communities. Similar to coal and natural gas power plants, wood pellet plants release particulate matter and other harmful pollutants into the air, which pose health risks to neighboring communities. In February 2021, the Mississippi Department of Environmental Quality (MDEQ) fined the Drax-owned Amite pellet production facility $2.5 million for underreporting pollution and exposing nearby residents to volatile organic compounds (Sneath, 2021). Pellet producers tell a different story. Enviva, a major pellet producer, highlights that the projects create jobs and revitalize struggling local communities (Purifoy, 2020).

The Land-Use Dilemma of BECCS

The amount of land required to execute BECCS at scale has some scientists concerned. Smith et al. (2016) estimate BECCS would require 25-46% of arable and permanent crop area by 2100 to satisfy 2°C pathways. Harper et al. (2018) show that BECCS could produce a net loss in removal of atmospheric carbon dioxide if lands supporting carbon-rich ecosystems are repurposed to grow feedstocks. Searchinger and Heimlich (2015) point out that bioenergy feedstocks may compete with crops and are relatively inefficient; present-day photovoltaic systems can generate 100 times the usable energy per hectare, less the carbon emissions.

The problem, according to Stanford climate scientist Chris Field, is that photosynthesis only converts 0.5% to 1% of sunlight into energy stored in biomass -- a fraction of the conversion efficiency today's photovoltaics achieve. The caveat, as Field phrases it, is that "there aren't many photovoltaics that self-assemble from planting a seed, so when we're talking about low-technology approaches, there are some wonderful features of [bioenergy]." Nevertheless, the relative inefficiency of photosynthesis means tremendous amounts of land would be required to cultivate feedstocks (Stanford ENERGY, 2018). The energy densities of wind and solar, while less than that of fossil fuels, are still greater than bioenergy (HarvardX, 2017). When changes to land use are also considered, the indirect costs of bioenergy become more apparent.

The Carbon Neutral Controversy

Two Sides of the Same Coin

On March 4, 2019, environmentalists from five European countries and the U.S. sued the European Union to stop RED II, citing bioenergy's contributions to emissions. The directive, which sets a target of 32 percent energy consumption from renewable sources by 2030, encourages member states to "exploit the full potential of biomass" (European Union, 2018). The plaintiffs argued that "RED II will accelerate widespread forest devastation and significantly increase greenhouse gas emissions by not counting CO2 emissions from burning wood fuels" (Hajjar & Olden, 2019). The suit was dismissed on account of insufficient standing.

Concerns are also being raised in the U.S. In 2015, the Partnership for Policy Integrity (PPI) and Environmental Advocates of New York petitioned the EPA and states to "include in any biomass policy a detailed system for verifying that feedstock being burned is actually coming from a sustainable source." The petition failed (LaRoss, 2015). According to Debbie Hammel, a senior resource specialist with the Natural Resources Defense Council (NRDC), pellet manufacturers such as Enviva are cutting down standing trees, which is detrimental to natural habitats and releases carbon that had been locked up for many years (Drouin, 2015).

Ensuring Sustainably Sourced Biomass

One of the biggest assumptions underlying the carbon neutral argument for bioenergy is that biomass inputs are sourced sustainably. This implies that harvested biomass is replenishable and does not come at the expense of terrestrial carbon sinks responsible for large net removals of carbon from the atmosphere. Maryland-based Enviva, the world's largest supplier of wood pellets, recognizes the need to provide sourcing transparency. The company runs a program known as "Track & Trace," which is designed. Dogwood Alliance, a nonprofit organization dedicated to protecting forests in the Southeast United States from unsustainable forestry, is critical of Enviva, especially Track & Trace. They claim Enviva misrepresents the extent to which standing trees are cleared -- and even their data from Track & Trace will indicate so

(Frost, 2019). Enviva, who claims to acquire most wood from forest residues and fallen trees, frames pelleting as a fossil fuels exit strategy and complement to wind and solar (Enviva, 2020).

Scientists argue there are no effective mechanisms for ensuring biomass is sourced sustainability. The concept of transnational sustainability certification has been attempted, but this failed due to conflicting interests of producers and consumers (Vogelpohl, 2021). William Moomaw, Professor Emeritus of International Environmental Policy at the Fletcher School, Tufts University and lead author on five reports of the IPCC, calls for "proforestation" -- the practice of allowing existing forests to grow to their full ecological potential, which favors maximum carbon sequestration and biodiversity preservation. Moomaw maintains that, in order to meet near-term climate goals, we must protect carbon sinks that are presently removing carbon from the atmosphere (proforestation), because the contributions of afforestation and reforestation to carbon sequestration are much farther in the future (Montaigne, 2019).

Conclusion

The uncertainty surrounding bioenergy's carbon neutral status is a question of the time horizon considered. However, there are other potentially damaging impacts of large-scale bioenergy. Impacts on communities, biodiversity, and agriculture are at stake. Not all bioenergy is created equal; agricultural byproducts offer the most responsible form of bioenergy inputs, but still may create competition for land. Given alternatives such as wind and solar that do not release additional carbon into the atmosphere, bioenergy should be limited to a minor role in long-term energy mix.

References

Appunn, K. (2016, September 30). Bioenergy – the troubled pillar of the Energiewende. Clean Energy Wire. https://www.cleanenergywire.org/dossiers/bioenergy-germany

Best, R., & Burke, P. J. (2020). Energy mix persistence and the effect of carbon pricing. *Australian Journal of Agricultural and Resource Economics, 64*(3), 555–574. https://doi.org/10.1111/1467-8489.12370

BirdLife Europe and Central Asia. (2017, December 14). Bioenergy: The Ugly Truth. https://www.youtube.com/watch?v=A_7N2940w2Y

Booth, M. S. (2018). Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. *Environmental Research Letters*, *13*(3), 035001. https://doi.org/10.1088/1748-9326/aaac88

Bruvoll, A., & Larsen, B. M. (2004). Greenhouse gas emissions in Norway: Do carbon taxes work? *Energy Policy, 32*(4), 493–505. https://doi.org/10.1016/S0301-4215(03)00151-4

Buchsbaum, L. (2018, June 1). The Shift from Coal to Biomass Is on in Europe. *POWER Magazine*. https://www.powermag.com/the-shift-from-coal-to-biomass-is-on-in-europe/

Cuong, T. T., Le, H. A., Khai, N. M., Hung, P. A., Linh, L. T., Thanh, N. V., Tri, N. D., & Huan, N. X. (2021). Renewable energy from biomass surplus resource: Potential of power generation from rice straw in Vietnam. *Scientific Reports, 11*(1), 792. https://doi.org/10.1038/s41598-020-80678-3

Drouin, R. (2015, January 22). Wood Pellets: Green Energy or New Source of CO2 Emissions? Yale E360. https://e360.yale.edu/features/wood_pellets_green_energy_or_new_source_of_co2_emissions

Elbein, S. (2019, March 4). Europe's renewable energy policy is built on burning American trees. Vox. https://www.vox.com/science-and-health/2019/3/4/18216045/renewable-energy-wood-pellets-biomass

European Union. (2018, December 11). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union, 5*, 82-209.

European Union. (2019, July 23). Renewable Energy – Recast to 2030 (RED II). EU Science Hub - European Commission. https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

ExxonMobil. (2021, February 1). ExxonMobil Low Carbon Solutions to commercialize emission-reduction technology. ExxonMobil. https://corporate.exxonmobil.com:443/News/Newsroom/News-releases/2021/0201_ExxonMobil-Low-Carbon-Solutions-to-commercialize-emission-reduction-technology

Frost, R. (2019, October 25). Track & Trace? More like "Trick or Trace." Dogwood Alliance. https://www.dogwoodalliance.org/2019/10/track-trace-more-like-trick-or-trace/

GIZ Vietnam. (2020a, June). Encouraging biomass energy to buttress turn to renewables. GIZ Energy Support Programme. http://gizenergy.org.vn/en/article/encouraging-biomass-energy-buttress-turn-renewables

GIZ Vietnam. (2020b, August 26). Bioenergy Project in Vietnam. World Bioenergy Association. https://www.worldbioenergy.org/news/554/56/Bioenergy-project-in-Vietnam/

Hajjar, D., & Olden, M. (2019, March 4). EU Renewable Energy Policy Devastates Forests and Accelerates Climate Change, New Lawsuit Claims – EU Biomass Legal Case. EU Biomass Legal Case. http://eubiomasscase.org/eu-renewable-energy-policydevastates-forests-and-accelerates-climate-change-new-lawsuit-claims/

Harper, A. B., Powell, T., Cox, P. M., House, J., Huntingford, C., Lenton, T. M., ... & Shu, S. (2018). Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications, 9*(1), 1–13. https://doi.org/10.1038/s41467-018-05340-z

HarvardX. (2017, May 5). Energy and land use. https://www.youtube.com/watch?v=-HpInEyrAkU

Hickman, L. (2016, April 13). *Timeline: How BECCS became climate change's "saviour" technology*. Carbon Brief. https://www.carbonbrief.org/beccs-the-story-of-climate-changes-saviour-technology

Keith, D. W. (2001). Sinks, Energy Crops and Land Use: Coherent Climate Policy Demands an Integrated Analysis of Biomass. *Climatic Change, 49*(1-2), 1–10.

Koester, S., & Davis, S. (2018). Siting of Wood Pellet Production Facilities in Environmental Justice Communities in the Southeastern United States. *Environmental Justice, 11*(2), 64–70. https://doi.org/10.1089/env.2017.0025

LaRoss, D. (2015). Advocates Press EPA For Strict Biomass Policy In ESPS Compliance Plans. *Inside EPA's Clean Air Report, 26*(24), 7-8.

Lin, B., & Li, X. (2011). The effect of carbon tax on per capita CO2 emissions. *Energy Policy*, *39*(9), 5137–5146. https://doi.org/10.1016/j.enpol.2011.05.050

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. L. (2011). Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels. *Environmental Science & Technology*, *45*(2), 789–795. https://doi.org/10.1021/es1024004

Möllersten, K., Yan, J., & Westermark, M. (2003). Potential and cost-effectiveness of CO2 reductions through energy measures in Swedish pulp and paper mills. *Energy*, *28*(7), 691–710. https://doi.org/10.1016/S0360-5442(03)00002-1

Möllersten, K., Yan, J., & R. Moreira, J. (2003). Potential market niches for biomass energy with CO2 capture and storage—Opportunities for energy supply with negative CO2 emissions. *Biomass and Bioenergy*, *25*(3), 273–285. https://doi.org/10.1016/S0961-9534(03)00013-8

Montaigne, F. (2019, October 15). Why Keeping Mature Forests Intact Is Key to the Climate Fight. Yale Environment 360. https://e360.yale.edu/features/why-keeping-mature-forests-intact-is-key-to-the-climate-fight

Obersteiner, M., Azar, C., Kauppi, P., Möllersten, K., Moreira, J., Nilsson, S., Read, P., Riahi, K., Schlamadinger, B., Yamagata, Y., Yan, J., & Ypersele, J.-P. van. (2001). Managing Climate Risk. *Science*, *294*(5543), 786b–787b. https://doi.org/10.1126/science.294.5543.786b

Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015, T.I.A.S. No. 16-1104.

POWER. (2018, June 1). The Shift from Coal to Biomass Is on in Europe. *POWER Magazine*. https://www.powermag.com/the-shift-from-coal-to-biomass-is-on-in-europe/

Purifoy, D. (2020, October 5). How Europe's wood pellet appetite worsens environmental racism in the South. Southerly. https://southerlymag.org/2020/10/05/how-europes-wood-pellet-appetite-worsens-environmental-racism-in-the-south/

Searchinger, T., & Heimlich, R. (2015). Avoiding Bioenergy Competition for Food Crops and Land. World Resource Institute. https://www.wri.org/publication/avoiding-bioenergy-competition-food-crops-and-land

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., … Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, *6*(1), 42–50. https://doi.org/10.1038/nclimate2870

Sneath, S. (2021, February 25). Mississippi biomass facility fined for emitting three times more air pollution than permitted. Southerly. https://southerlymag.org/2021/02/25/mississippi-biomass-facility-fined-for-emitting-three-times-more-air-pollution-than-permitted/

Stanford ENERGY. (2018, October 10). *Bioenergy & Carbon Capture (BECCS) Panel | Energy @ Stanford & SLAC 2018*. https://www.youtube.com/watch?v=ZsXq7HcV4sU

Sterman, J. D., Siegel, L., & Rooney-Varga, J. N. (2018). Does replacing coal with wood lower CO 2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters*, *13*(1), 015007. https://doi.org/10.1088/1748-9326/aaa512

van Alphen, K., van Ruijven, J., Kasa, S., Hekkert, M., & Turkenburg, W. (2009). The performance of the Norwegian carbon dioxide, capture and storage innovation system. *Energy Policy*, *37*(1), 43–55. https://doi.org/10.1016/j.enpol.2008.07.029

van Vuuren, D. P., den Elzen, M. G. J., Lucas, P. L., Eickhout, B., Strengers, B. J., van Ruijven, B., Wonink, S., & van Houdt, R. (2007). Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change*, *81*(2), 119–159. https://doi.org/10.1007/s10584-006-9172-9

Vogelpohl, T. (2021). Transnational sustainability certification for the bioeconomy? Patterns and discourse coalitions of resistance and alternatives in biomass exporting regions. *Energy, Sustainability and Society, 11*(1), 3. https://doi.org/10.1186/s13705-021-00278-5

Wang, W., Dwivedi, P., Abt, R., & Khanna, M. (2015). Carbon savings with transatlantic trade in pellets: accounting for market-driven effects. *Environmental Research Letters, 10*(11), 114019. https://doi.org/10.1088/1748-9326/10/11/114019

World Bioenergy Association. (2012). The Carbon Neutrality of Biomass from Forests. https://worldbioenergy.org/factsheets

Williams, R. H. (1996). Fuel Decarbonization for Fuel Cell Applications and Sequestration of the Separated CO2. PU/CCES Report 295. *Center for Energy and Environmental Studies, Princeton University*.