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Life-cycle assessment of U.S. biomass supply and the role of biomass electricity for meeting UK emission objectives

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ABSTRACT

Recent research publications and popular press articles have questioned the greenhouse gas (GHG) benefits of wood-powered bio-electricity relative to coal. Whereas critical research cautions against greenhouse gas increases from unsustainable biomass production scenarios, this research clarifies that low-carbon intensity biomass supply chains are demonstrable. GHG emissions were estimated throughout the wood pellet life-cycle including harvest, transport, storage, pellet manufacturing, and shipment from the United States to power plants in the United Kingdom. We considered electricity-only and combined heat and power (CHP) applications. Results for the electricity-only case study found that emissions from wood pellet electricity production were 0.13 kgCO_2e/kWh, 87% lower than for coal electricity and 71% lower than for natural gas electricity. For the CHP system, the GHG intensity for wood pellet electricity was 0.055 kgCO2e/kWh, 94% lower than coal and 82% lower than natural gas combined cycle with CHP. The potential for wood pellet electricity to displace GHG emissions from coal and natural gas was considered for the UK power sector. A scenario expanding only wind and solar generation resources reduced GHG emissions by 42% between 2020 to 2040. Over the same period, scenarios that additionally expanded wood pellet electricity generation reduced GHG emissions by 53% and by 73% when coal was eliminated by 2024 as anticipated. The supplemental 20-year emission reductions were 205 and 474 million tonnes CO_2e, respectively. These results demonstrate that when biomass pellets are sourced sustainably, biomass electricity generation can support decarbonization of the electricity sector.

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[1] We do not imply that independent reviewers endorse Boundless' findings.

Background

Controversy around biomass electricity emissions has intensified in press articles that cite research questioning the GHG emission reduction benefits of biomass-electricity relative to coal (The Wall Street Journal 2019, The New York Times 2016). News articles have amplified the recent research that questions the merits of biofuel, as well as the carbon accounting practices used to measure carbon impact, from a range of research representing more diverse view points (Dwivedi, et al. 2011, Kadiyala, Kommalapati and Huque 2016, Röder, Whittaker and Thornley 2015, Sterman, Siegel and Rooney-Varga 2018, Whitaker, C et al. 2009, J. C. Tumuluru 2015, Sahoo 2018, Jonker, Junginger and Faaij 2014, Cornwall 2017). Given the compressed timeline for effective climate action, these concerns are critical. In addition to public confusion, regulators may feel increasingly uncertain about the emission impact of bioenergy, at a time when electric utilities seek to rapidly decarbonize their generation portfolios.

While the concerns raised above are valid to consider, industries are moving to more sustainable generation through implementation of industry and government standards and regulations, and thus this research focuses on biomass supply with good sustainability aspects. We acknowledge that the benefits of biomass are case specific and that poorly conceived systems could negatively impact carbon emissions and ecosystems. Our objectives, however, were to consider how well-designed biomass supply chains might deliver beneficial emissions reductions and to better understand the contributions of individual supply chain emission sources. Further, we consider the net emission impacts at market scale, in scenarios where wood pellet electricity is deployed as part of a multi-technology strategy for deep decarbonization within the UK electricity sector.

This research reports methods and results for a life-cycle assessment (LCA) of wood pellet biomass fuel and reports greenhouse gas (GHG) intensity for biomass-electricity (kgCO_2e/kWh). This LCA documents a scenario for wood pellet production using south-eastern U.S. forest resources, shipment to the UK, and combustion as a power plant fuel. This case study is highly relevant given the UK's increasing reliance on imports of US wood pellets for electricity generation. Analysis further considered greenhouse gas performance relative to initial capital investment cost to compare a carbon return on investment (CROI) metric. Further, we considered the timing of carbon offsets when applying LCA accounting to the long-term forest carbon cycle. Electricity carbon-intensity results were compared against published values for both fossil and renewable generation technologies. While side-by-side comparisons are helpful, real-world power markets operate using a combination of these technologies to meet consumer electricity demand cost-effectively, while simultaneously managing environmental restrictions and reliability concerns. We used an integrated resource model to consider the net systemic impact of biofuels across the UK power sector. We provide estimates for avoided emissions from the deployment of biomass electricity at scale and discuss the role of dispatchable low-carbon fuel within a rapidly decarbonizing electricity sector.

Methodology

We examined the life-cycle carbon intensity of wood pellet bioenergy for a prescribed scenario of pellet production, using south-eastern U.S. forest resources, and subsequent delivery to UK power plants for use as wood pellet fuel. The functional unit of our LCA was 1 ton (907 kg) of wood pellet. The scenario examined was principally based on public reporting by Enviva (NYSE: EVA) available via regulatory filings. We researched the material, energy, and performance characteristics for the wood pellets' life cycle, based on detailed public information for Enviva, describing the energy inputs, stages of wood sourcing, pellet production and transportation. We performed a spreadsheet analysis supported by SimaPro v9.0.0.41 software. GHG emission factors assumed a 100-year global warming potential and are sourced from the Eco Invent database (Wernet, et al. 2016) except as noted. We applied sensitivity analysis to our LCA calculations to report a range of results given uncertainty around key variables, including for fugitive methane release during raw material storage. The analysis considered emission impacts both with and without waste heat utilization, i.e., combined heat and power (CHP). Operations within the system boundary included wood harvest, raw material transport, storage, pellet manufacturing, ground transportation to port, marine shipment directly to customer facilities, and power plant combustion. We excluded material and fuel used for retrofitting power plants (to utilize biomass) for lack of readily available data; this contribution is expected to be relatively small, given that it represents the conversion of an existing facility with fewer material requirements than new construction. Assumptions for process operations and shipping were based on public reporting by Enviva for seven US-based facilities: Amory, Ahoskie, Sampson, Cottondale, Northampton, Southampton and Hamlet (Enviva Partners 2019). Transportation steps included trucking from the forest to the pellet manufacturing facility and to U.S. ports, and marine transport directly to UK power plant with shipping distances based on supplier auditor reports (Sustainable Biomass Partnership 2019).

Enviva's feedstock categories include mill residues (chips, sawdust and other wood industry by-products), low grade wood fiber (trees or wood that are unsuitable or rejected for sawmilling or lumber), tops and limbs (parts of trees that cannot be processed into lumber), and thinnings (harvests that promote the growth of higher value timber and/or trees removed to improve wildlife habitat). Distribution of materials to the wood pellet manufacturing varies. This case study assumed raw materials were comprised of 17% sawmill residues (e.g., sawdust and shavings) and 83% other by-products. Of the 83% by-products, the assumed distribution was 50% wood chips, 30% roundwood, and 20% combined thinning and secondary green material. Wood harvest and transport assumptions are summarized in Table 1. Emission factors for operations and transport reflect *diesel combusted in industrial equipment* and *single unit long-haul diesel truck*, respectively. Inputs to wood pellet manufacturing operations include diesel for raw material handling, electricity, and process heat provided by biomass combustion. Electricity emission factors were based on regionally specific CO_2e intensity reported by U.S.EPA (US Environmental Protection Agency 2019). Quantities of wood pellet-based biomass required for drying were based on supplier auditor reports and reported carbon content for wood (Röder, Whittaker and Thornley 2015).

Table 1. Summary of life-cycle GHG emissions per 1-ton wood pellet production.

Component	**Amount per ton**	**Unit**	**kgCO2e / unit**	**kgCO2e / ton**
Forest Operation (diesel)	2.6	liter	2.720	7.1
Fertilization				8.7
Wood Production Subtotal				**15.8**
Electricity (grid)	207.6	kWh	0.569	81.7
Raw material handling and storage	7.8	kgCO2e	1	**7.8**
Biomass drying	net zero		-	0.0
Processing Subtotal				**89.5**
Raw material transport	89.7	ton·km	0.202	11.3
Transport to port	133.9	ton·km	0.202	16.8
Marine Transport	3597.0	ton·mile	0.016	57.6
Transport Subtotal				**85.7**
Energy Conversion CO_2	net zero		-	0.0
Energy Conversion CH_4	0.17	kg	25	4.3
Energy Conversion N_2O	0.11	kg	298	31.5
Energy Conversion Subtotal				**35.8**
Total				**227**

Power plant emission of methane (CH_4) and nitrous oxide (N_2O) during energy conversion are based on U.S. EPA emission factors (US Environmental Protection Agency n.d.) for wood combustion. The EPA source notes that formation of nitrous oxide and methane during the combustion process is complex and dependent upon many factors. As such, we do not assert that these factors are representative for wood pellet power generation facilities. Rather, we use them conservatively in the absence of facility-specific emission factors. For carbon dioxide, we assumed that the emissions from energy conversion and biogenic uptake represent a steady state net-zero carbon flux. Put simply, an equal amount of carbon dioxide is absorbed from the atmosphere during forest growth as is released during the wood-fuel combustion, and land use management or conversion does not result in other systemic emissions or loss of carbon stock from soil. Net carbon flux is a critical assumption in the accounting for any bioenergy LCA. Justification for the net-zero carbon flux assumption is that net increases in forest carbon stocks are occurring for the geographic area of study and that biomass production is not derived from the conversion of forest land to other non-forest uses with harmful ecological and emission consequences

As reported by Brack, contributions of fugitive methane emissions from storage are not usually included in calculations, but can have a major impact (Brack 2017). Some reporting [(Wihersaari 2005a, Wihersaari 2005b),(Röder, Whittaker and Thornley 2015)] suggests that fugitive methane emissions during biomass storage may significantly impact overall supply chain emissions. For example, Röder's estimate using one-month of storage time increased the reported GHG intensity by 140%. In contrast, Tumuluru et al. translated methane off-gas emission measurements from wood-pellets into an emission factor of 0.76 mg CH_4/kg (Tumuluru 2015), a negligible rate equivalent to only 0.02 kg CO_2e/ton. This study relied on estimates developed by Sahoo et al. for the raw material handling phase of wood chips that including fugitive emissions assuming a six-month storage time (Sahoo 2018). Reported practices for Enviva were seven days storage under typical conditions and fourteen days storage under unusually long conditions. Given the much shorter storage times in the case study compared with the published study (seven days versus six months), this LCA used the low value reported by Sahoo as the reference value for fugitive methane and the high value from Sahoo as the upper sensitivity boundary. Sensitivity analysis created a variation of all other operational parameters described above by +/- 10% to 30%.

For the purpose of creating side-by-side comparisons to alternative generation technologies, we converted life-cycle GHG per ton into GHG per kWh based on the assumptions that each ton of wood pellet yields 1.84 MWh electricity based on 17 Gigajoules per ton of heat content and assuming a 39% thermal efficiency for the power plant (Forest Research n.d.). Metric comparisons provided in the results are for two use cases: the retrofitting of coal-fired power plants for biomass combustion including waste heat utilization; and new dedicated biomass power plants without waste heat utilization. We intended our consideration of combined heat and power CHP-systems to approximate a best-case scenario with total system efficiency of 90%[2]. We compared the net emission savings when each alternative displaces coal electricity using the life-cycle GHG intensity for wood pellet electricity estimated herein, as well as reported values for wind, solar, and natural gas alternatives (House of Parliament 2011, Wernet, et al. 2016, Spath, Mann and Kerr 1999, Tagliaferri, et al. 2017, University of Colorado Denver n.d., Sargent & Lundy n.d., Nugent and Sovacool 2014, and Wang and Mu, 2014).

To calculate the Carbon Return on Investment (CROI) metric, we compared the net emissions savings from displacing one kWh of coal-derived electricity relative to equity investment (50% of initial capital cost) for new construction of the renewable, natural gas, or wood pellet electricity generation technology. Assumptions for the CROI metric calculation are provided in Table 2. Capital cost for biomass pellet with CHP was based on modelling assumptions for the conversion of existing coal power plants, as reported by an energy industry consultancy (Aurora Energy Research 2018). The capital costs for biomass pellets without CHP are based on an industry estimate for new construction of a small-scale electricity only facility based on informal cost benchmarks

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[2] DONG Energy's Avedore CHP is claimed to achieve 89% fuel efficiency (Brack 2017).

provided to Enviva by a power plant developer. Capital costs for solar PV was based on industry trade publication and for all other new generating technologies based on characteristics for new generating technologies reported by USEIA (US Energy Information Administration 2019). Natural gas and biomass facilities assume annual utilization of 72% representing significant baseload utilization. Renewable utilization assumes commonly reported values for these technologies.

Table 2. Assumptions for estimating carbon return on investment

	Biomass Pellet with CHP	Biomass Pellet No CHP	Solar PV Large	Onshore Wind	Offshore Wind	Natural Gas CC	Natural Gas CC with CHP
Initial Capital Cost (USD$/kW)	251	2,717	580	1,518	4,758	736	810
Investment Equity	50%	50%	50%	50%	50%	50%	50%
Annual Utilization	72%	72%	15%	30%	45%	72%	72%
Lifetime (years)	10	20	20	20	20	20	20

Using the calculated life-cycle bio-electricity emission factors calculated herein, we sought to consider the market-wide net emission impacts from biomass generating facilities across the entire UK national electricity sector. The UK power sector was evaluated using the myPower[3] integrated resource (aka capacity expansion) model (JuiceBox 2018). We used the model to simulate the utilization of UK power plants, as described below, over the duration of two 20-year power sector scenarios (2020 – 2040):

- *Renewable Expansion with Constant Biomass (RECB)* – Wind and solar electricity generation are both expanded 1.8-times their respective 2018 production by 2030 and 2.1-times by 2040. The entire renewable contribution (including existing biomass and hydro) reaches 43% by 2030 and 50% by 2040. Biomass and coal generation are maintained at their 2018 levels, 10% and 5% respectively. No changes to natural gas, nuclear, hydro, or other generating units were considered relative to UK power plant assumptions below. UK electricity demand was based on IEA reported values for 2018 and was held constant (International Energy Agency 2020).
- *Renewable Expansion with Increased Biomass (REIB)* – Same as above, except that new wood pellet electricity generation facilities are also deployed. Wind, solar, and biomass power generation are each expanded 1.8-times their respective 2018 production by 2030 and 2.1-times by 2040. By 2040, biomass electricity comprises 20% of the generation mix and non-biomass renewables provide 50% of the generation mix, bringing the entire renewable contribution to 70%.
- *Renewable Expansion with Increased Biomass and Coal Retirement (REIBc)* – Same as REIB, except that the remaining coal generation (5% of UK electricity in 2018) is phased out by 2024 as anticipated.

Parameters for UK power plants were based on the open-source Global Power Plants Database (GPPD), which reports generating capacity and fuel-type aggregated at the facility level (Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute 2018). Generator-level data was reviewed from the European Environment Agency's Large Combustion Plant (LCP) reporting (European Environment Agency 2019) and used to characterize facility specific fuel-use where power plants could be readily cross-referenced between the two data sets. We assume that all biomass facilities have the same life-cycle GHG intensity as reported for the supply chain examined herein. Life-cycle emissions for the mining and transport of coal were assumed at 0.1518 $kgCO_2e/kWh$ based on Wang and Mu (Wang and Mu 2014) and for the production and transport of natural gas at 0.104 $kgCO_2e/kWh$ based on Tagliaferri (Tagliaferri, et al. 2017). Thermal efficiency

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[3] Dr. Meier has an ownership interest in Meier Engineering Research LLC, which owns the myPower model used in this study.

for coal and natural gas power plants were based on characteristics published by USEIA (US Energy Information Administration 2019).

Results

Electricity GHG Intensity

Greenhouse gas (GHG) emissions were estimated in terms of $kgCO_2e$/ton wood pellet and per kWh of electricity produced. Wood pellet emissions consider wood harvest and transport from the forest, raw material storage, pellet production, ground transportation to port, international shipment, and conversion to electricity by the UK power plant customer. Per ton fuel consumed, the GHG emissions of wood pellet derived electricity was estimated as 227 $kgCO_2e$ without waste heat recovery (CHP), equivalent to 0.13 $kgCO_2e$/kWh. A summary of contributions from each process step is illustrated in Figure 1. The largest contributor is due to the manufacturing of wood pellets, at 38%. After this, transport had a contribution of 37%. Additional contributions are from energy conversion, wood production, and raw material handling and storage at 15%, 7%, and 3% respectively.

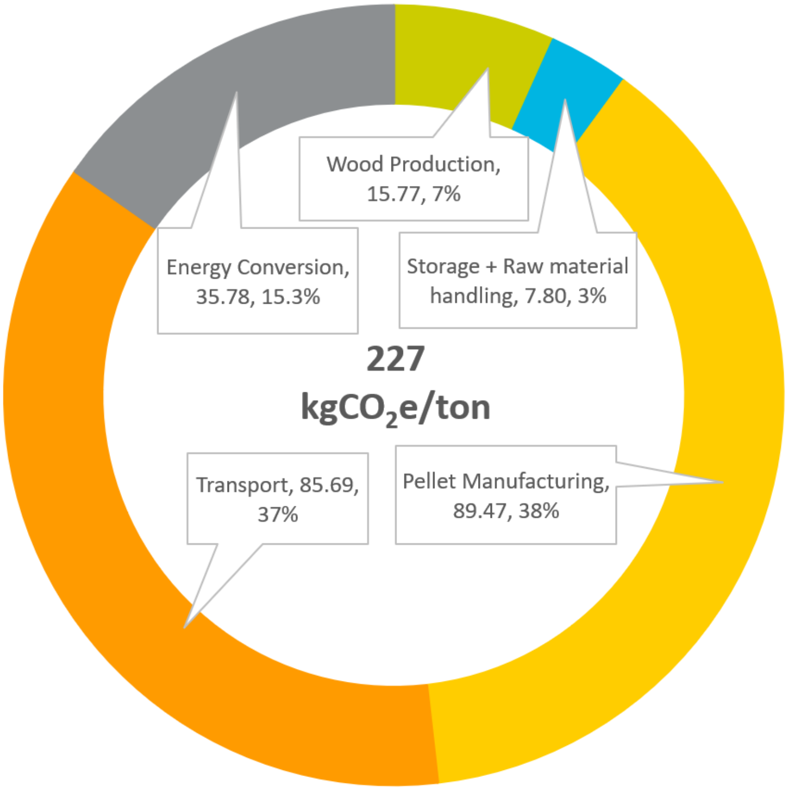


Figure 1. Summary of life-cycle greenhouse gas intensity ($kgCO_2e$/ton) for wood pellet biomass electricity case study, without combined heat and power. Relative contributions are shown for wood production, manufacturing storage, transport and energy conversion.

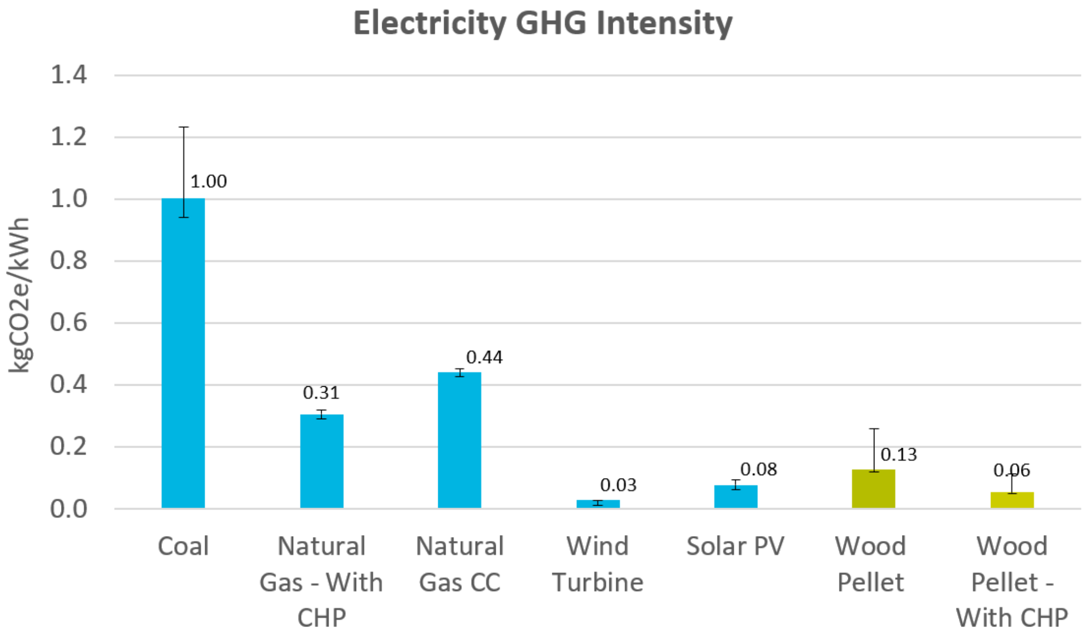


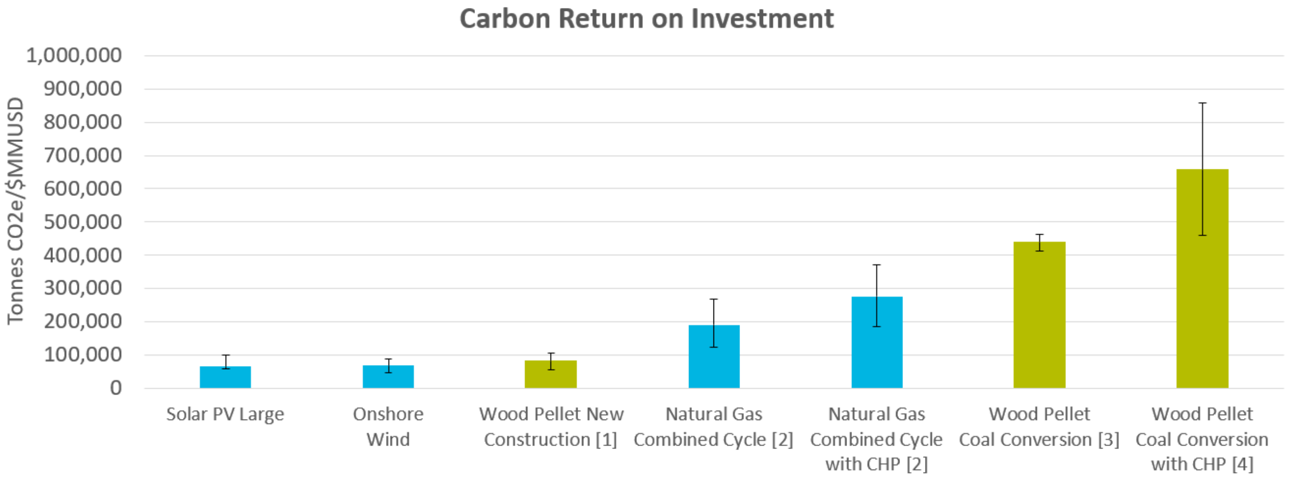
Figure 2. Electricity GHG intensity (kgCO$_2$e/kWh) comparison for coal, natural gas with CHP and without CHP, wind, solar, wood pellet with CHP and without CHP. Sensitivity bars reflect a range of results from reported literature as well as sensitivity to input assumptions for wood pellet electricity.

Figure 2 compares GHG intensity for electricity generation from wood pellets (with and without CHP) against coal, natural gas (with and without CHP), wind, and solar PV generation technologies. Wood pellet electricity emissions per kWh were estimated between 74% - 87% lower than coal electricity emissions and 42 – 71% below natural gas electricity emissions. Life-cycle emissions for wind and solar electricity, respectively, were 97% and 92% lower than coal, 94% and 82% lower than natural gas without CHP, and 91% and 74% lower than natural gas with CHP. Values for industry alternatives relied on published literature reported above. For alternative technologies, sensitivity bars reflect the range of literature-reported values. For wood pellet results, sensitivity bars reflect the range of values resulting from the sensitivity analysis. Based on assumptions discussed in the methodology section, methane emissions from storage were the largest influence for sensitivity analysis, comprising between – 3 - 15% of the pellet's life-cycle GHG.

Carbon Return on Investment

In Figure 3, we compare the potential for emissions abatement, when lower emission technologies provide a 1:1 substitution for coal, relative to the capital cost for the generation facility's initial construction. The conversion of an existing CHP coal facility to burn biomass has the highest emissions abatement potential. This is due to its relatively low capital cost and higher emission reductions achieved through a higher level of annual utilization (see Table 2) than can be achieved from intermittent renewable resources.

As electric utilities decarbonize their generation portfolio, a fundamental question is which investments will yield the highest GHG mitigation per investment cost. As illustrated in Figure 3, converting existing CHP coal facilities to use biomass fuel is very attractive in this regard, with between two and twenty-one times the GHG mitigation per dollar of equity investment relative to competing technologies compared in Figure 3. This result is due to lower investment costs required to retrofit an existing facility as compared to new construction. Relative to intermittent renewables, the biomass CHP facility can operate nearly continuously, displacing much more coal electricity emissions per kW of nameplate capacity. The biomass facility with no CHP has lower CROI than natural gas due to relatively higher capital cost of the assumed small-scale facility, although its annual capacity factor is high. Solar and wind technologies have lower capital cost, but also lower annual capacity factors (generation potential) to displace coal. Natural gas CROI results were high due to low capital cost and high annual capacity factor, i.e., replacing more coal for fewer investment dollars. Given the relatively high GHG intensity of natural gas electricity (refer to Figure 2), Figure 3 should not be used to justify investment in natural gas where deep decarbonization is the ultimate goal.



[1] New construction of electricity only wood-pellet biomass power plant with inital capital cost of 2,717 $/kW.

[2] See discussion in report text regarding the limitations of natural gas for achieving deep decarbonization objectives.

[3] Conversion of existing coal power plant to use wood pellets with initial capital cost of 270 $/kW.

[4] Conversion of existing CHP coal power plant to use wood pellets with initial capital cost of 270 $/kW.

Figure 3. Carbon return on investment (Tonnes CO_2e/MMUSD). CROI is highest when substituting wood pellets directly 1:1 at a retro-fitted coal facility with combined heat and power. Comparisons provided for a new construction of dedicated biomass natural gas combined cycle with CHP and NGCC without CHP, wind, and solar PV.

Power Sector Market-wide Emissions Impact Analysis

The system-wide emission impact of biofuel utilization was evaluated for the UK power sector using an integrated resource (aka capacity expansion) model and open-source data for UK power plants. We compared power sector emissions under scenarios with expanded versus constant contributions from wood pellet electricity. The long-term generation supply and carbon emissions were compared between three 20-year power sector scenarios:

- RECB - With constant biomass and only wind and solar expanded 2.1 times 2018 levels, total renewable contributions reach 50% of supply by 2040 and CO_2e emissions decline by 42% between 2020 and 2040.
- REIB - With wind, solar *and* biomass expanded 2.1 times, renewable supply reaches 70% and CO_2e emissions decline 53% between 2020 and 2040.
- REIBc - With wind, solar and biomass expanded 2.1 times, *and* the anticipated phase-out of the remaining 5% coal contribution by 2024, renewable supply reaches 70% and CO_2e emissions decline 73% between 2020 and 2040.

As illustrated in Figure 4, expanding wood pellet electricity, along with other renewable generation resources, results in considerable emissions mitigation relative to a scenario that holds biomass contributions constant at current levels. Figure 4 demonstrates that, given any scenario with a specified rate of solar or wind (or other renewable) expansion, the corresponding rate of fossil fuel displacement is faster if the decarbonization strategy is supplemented with low-carbon biofuels. As expected, the rate of emissions reduction is more rapid when the anticipated phase out of coal is also modelled (REIBc) The cumulative 2020-2040 supplemental (relative to RECB) carbon mitigation resulting from increasing wood pellet biomass was 205 million tonnes CO_2e in the REIB case where coal generation is maintained, and 474 Million tonnes CO_2e in the REIBc case where coal generation is retired.[4]

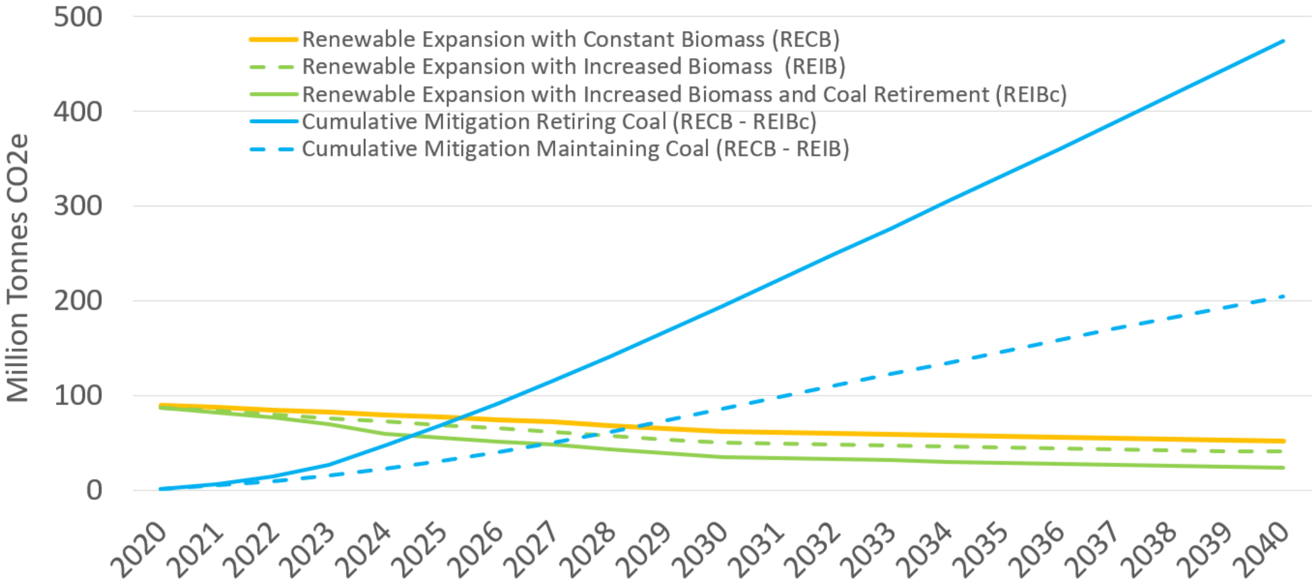


Figure 4. GHG emissions are compared for the UK power sector for two scenarios from 2020 to 2040. For the Renewable Expansion with Constant Biomass (RECB) case, wind and solar electricity generation are both expanded 1.8-times their respective 2018 production by 2030 and 2.1-times by 2040. For the Renewable Expansion with Increased Biomass (REIB) case, wind, solar, *and* biomass power generation are each expanded 1.8 times by 2030 and 2.1 times by 2040. For the Renewable Expansion with Increased Biomass and Coal Retirement (REIBc) case, wind, solar, *and* biomass power generation are each expanded and the remaining UK coal generation (5%, 2018) is retired between 2021 and 2024.

Discussion

This LCA case study demonstrates the potential for low carbon intensity electricity from wood pellet biomass fuel. As illustrated in Figure 1, the reported carbon intensity result was 227 kg/ton including consideration of harvest, transport, storage, pellet manufacture, shipping, and methane and nitrous oxide combustion emissions. This result is 22% lower than a study of similar scope that estimated carbon intensity of 292 kg/ton for wood pellets from the Southeast US, including pelletizing and shipment to power plants in the Netherlands (Jonker, Junginger and Faaij 2014). Reasons for this discrepancy likely include a shorter international shipping distance and a declining emission rate for US electricity. Comparing electricity only-facilities (without CHP), the wood pellet electricity GHG intensity for this case study was 0.13 kg CO_2e / kWh, 87% lower than for coal electricity and 71% lower than for natural gas electricity. For the CHP system, the estimated 0.055 kgCO2e/kWh intensity for wood pellet electricity was 94% lower than coal and 82% lower than natural gas combined cycle with CHP. Fugitive methane was included along with storage emissions, comprising 3% of the total GHG intensity. Methane and nitrous oxide emissions from energy conversion were based on emission factors for wood combustion in boilers, generically, and may over-estimate emissions from new state-of-the-art facilities. Still, even with these conservative assumptions, the per kWh carbon intensity for biomass electricity was far below the estimates for coal and natural gas derived electricity.

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[4] Supplemental information describing power sector scenario modelling is posted at this link.

Whether the biogenic carbon flux of raw material supply is justifiably carbon-neutral is a critical determination when evaluating carbon intensity for any bioenergy supply chain. Three pre-conditions helped assure us that our carbon-neutral assumption was valid for this case study:

- Net increases in forest carbon stocks are occurring for the geographic area of study. The South-eastern U.S. is one such region where the total carbon stock of forest biomass has demonstrably increased in recent decades. When looking at regional and state-level forests including all ownership types; area, volumes, and forest carbon stock have grown annually by a steady percentage (USDA Forest Service 2019, Johnston and Crossley Jr. 2002).
- Raw materials are sourced from mill residues and forest-harvest by-products. Enviva's sustainable sourcing policy requires that sourced raw materials fit specified categories; leftover wood or waste materials disregarded by the timber industry (Enviva Partners n.d.). These materials typically include sawmill residues, treetops, branches, and whole trees that are too small or of too low quality to be used in other sectors of the forest products industry.
- Biomass production is not derived from the conversion of forest land to other non-forest uses with harmful ecological and emission consequences. The European Commission's Renewable Energy Directive (RED II) (European Commission 2019a) sets criteria for feedstock for biofuels, bioliquids, and biomass, with special attention to land-use change. It states that areas designated for nature are to be protected, harvested forests are to be regenerated, and long-term production capacity and forest health are to be maintained and improved (Official Journal of the European Union 2018, European Commission 2019b). For example, the wood pellet raw material cannot be sourced from forest lands that are intended to be used for anything else than reforestation. US-based wood pellet suppliers are subject to these rules for their European Importers to label the wood pellets as sustainable biomass.

Recent popular press has perpetuated confusion by generically paraphrasing that biomass may emit more carbon dioxide than coal. Stakeholders should attempt to parse whether such comments are based on a holistic life-cycle comparisons, whereas they may ambiguously refer to the combustion process only. Owing to fuel and combustion chemistry, combustion efficiency for coal may frequently be higher than for biomass, more so when using green wood chips as opposed to dry wood pellets examined herein, and more so without waste heat recovery (i.e., CHP). The rate of CO_2 released during fuel combustion, however, should not be conflated with the total system GHG intensity given proper life-cycle accounting. The complexity of bioenergy supply chains necessitates case-specific life-cycle assessment.

Decarbonization of complex power grids creates operational challenges for grid operators. In cases where sustainably-designed supply chains ensure low carbon intensity, wood pellets offer unique attributes that warrant consideration as part of deep decarbonization strategy. Biomass power plants can dynamically respond to balance the variable power supply from other intermittent renewable resources. While natural gas power plants have excellent load balancing capabilities, its associated GHG intensity is significant. By helping remediate their intermittency challenges, biomass electricity potentially increases the rate at which accompanying solar and wind energy infrastructure can be deployed within power markets. In addition, unlike other renewable resources, biomass electricity produces surplus heat which can potentially provide for low-emission building space heating or industrial process heat applications.

Conclusions

This case study examined the life-cycle GHG intensity for wood pellet electricity with consideration of emissions occurring during wood harvest, transport, raw material storage, pellet production, shipment, and conversion to electricity. In systems without CHP, the GHG emissions of wood pellet fuel was 227 $kgCO_2e$/ton and 0.13

$kgCO_2e/kWh$, of which 10% of the GHG intensity derived from wood production along with raw material handling and storage, 38% derived from pellet production electricity, and 37% derived from transportation. Emissions for wood pellet electricity without CHP were 87% lower than for coal and 71% lower than for natural gas. For CHP applications, the per kWh GHG intensity for wood pellet electricity in this case study was in a similar range as values reported for solar electricity and much lower than for coal and natural gas electricity. The estimated 0.055 $kgCO_2e/kWh$ intensity for wood pellet electricity was, by comparison, 94% lower than coal and 82% lower than natural gas combined cycle including CHP. Given the relatively low investment cost to convert a coal facility for biomass combustion, the carbon return on investment (CROI) for converting coal to wood pellet CHP systems was more than twice that of the next closest competitor when compared to natural gas and renewable electricity alternatives. In examining future scenarios for the U.K power sector, expanding only wind and solar generation resources reduced GHG emissions by 42% between 2020 and 2040. The scenarios that additionally expanded wood pellet electricity reduced GHG emissions by 57% when coal units were maintained and by 77% when coal units were phased out by 2024 as anticipated. The supplemental emission reductions over 20 years were 249 and 453 million tonnes CO_2e, respectively. Suggested for future research is the assessment of net-zero emission power sector scenarios that include life-cycle GHG impacts for wood pellet electricity, grid energy storage (e.g., batteries), and carbon capture and storage.

References

Abel, D. W., T. Holloway, M. Harkey, P. Meier, D. Ahl, V. S. Limaye, and J. A. Patz. 2018. "Air-quality-related health impacts from climate change and from adaptation of cooling demand for buildings in the eastern United States: An interdisciplinary modeling study." *PLOS Medicine* 15 (7): 1-27. doi:https://doi.org/10.1371/journal.pmed.1002599.

Aurora Energy Research. 2018. "National Infrastructure Commission." Accessed June 12, 2020. https://www.nic.org.uk/wp-content/uploads/Power-sector-modelling-final-report-1-Aurora-Energy-Research.pdf.

Brack, Duncan. 2017. "Woody Biomass for Power and HEat - Impacts on the Global Climate." *Chatham House, The Royal Institute of International Affaris.*

Cornwall, W. 2017. *Is wood a green source of energy? Scientists are divided.* 01 05. https://www.sciencemag.org/news/2017/01/wood-green-source-energy-scientists-are-divided.

Department for Business, Energy & Industrial Strategy. 2018. "2018 Government GHG Conversion Factors for Company Reporting." Report. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/726911/2018_methodology_paper_FINAL_v01-00.pdf.

—. 2013. "Energy Trends: UK Electricity." *National Statistics.* 06 27. Accessed 09 10, 2019. https://www.gov.uk/government/statistics/electricity-section-5-energy-trends.

—. 2019. "Energy Trends: UK gas." *National Statistics.* 12 27. Accessed 01 20, 2020. https://www.gov.uk/government/statistics/gas-section-4-energy-trends.

Dwivedi, P, M Khanna, and Madisen Fuller. 2019. "Is wood pellet-based electricity less carbon-intensive than coal based electricity? It depends on perspectives, baselines,feedstocks, and forest management practices." *Environ. Res. Lett. 14 (2019) 024006.*

Dwivedi, P, R Bailis, T Bush, and M Marinescu. 2011. "Quantifying GWI of wood pellet production in the southern United States and its subsequent utilization for electricity production in the Netherlands/Florida." *Bioenergy Research* 180-192.

Enviva Partners. 2018. "Enviva's Global Responsible Sourcing Policy and Pledges in Conservation Leadership ." *Enviva Partners.* 12 18. Accessed 12 20, 2019. http://www.envivabiomass.com/wp-content/uploads/Enviva-Revised-Responsible-Sourcing-Policy_5_30_19.pdf.

—. n.d. *Enviva's Responsible Wood Supply Program.* Accessed 01 06, 2020. http://www.envivabiomass.com/sustainability/track-and-trace-3/enviva-responsible-wood-supply-program/.

—. 2019. "Investor Relations." *Business Overview.* 01 10. Accessed 09 12, 2019. https://ir.envivapartners.com/sites/envivabiomass.investorhq.businesswire.com/files/doc_library/file/EVA_Investor_Presentation_January_2020_vFinal.pdf.

European Commission. 2019a. *Renewable Energy - Racast to 2030 (RED II).* 07 23. Accessed 12 22, 2019. https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii.

—. 2019b. *Sustainability criteria for biofuels specified.* 03 13. Accessed 01 07, 2020. https://ec.europa.eu/commission/presscorner/detail/en/MEMO_19_1656.

European Environment Agency. 2019. "Reported data on large combustion plants covered by the Industrial Emissions Directive (2010/75/EU) ." *European Environment Agency.* 12 17. Accessed 01 16, 2020. https://www.eea.europa.eu/data-and-maps/data/lcp-9.

Forest Research. n.d. *Typical calorific values of fuels.* Accessed 01 30, 2020. https://www.forestresearch.gov.uk/tools-and-resources/biomass-energy-resources/reference-biomass/facts-figures/typical-calorific-values-of-fuels/.

Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute. 2018. "Global Power Plant Database." *Published on Resource Watch and Google Earth Engine.* http://resourcewatch.org/ https://earthengine.google.com/.

House of Parliament. 2011. "Carbon Footprint of Electricity Generation." *House of Parliament.* 06. Accessed 10 11, 2019. https://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf.

International Energy Agency. 2020. "Electricity statistics." *International Energy Agency.* 01 20. Accessed 01 15, 2020. https://www.iea.org/subscribe-to-data-services/electricity-statistics.

IPCC (Intergovernmental Panel on Climate Change). 2013. *Climate Change 2013: The Physical Science Basis.* Cambrigde: Cambridge University Press: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Johnston, J. M., and D. A. Crossley Jr. 2002. "Forest ecosystem recovery in the southeast US: soil ecology as an essential component of ecosystem management." *Forest Ecology and Management* 155 (1-3): 187-203. doi:https://doi.org/10.1016/S0378-1127(01)00558-8.

Jonker, J., M. Junginger, and A. Faaij. 2014. "Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States." *GCB Bioenergy.*

JuiceBox. 2018. *Clean Energy Strategy & Decision Support Documentation. Paul J. Meier, PE, PhD.* Version 2.7. 08 01. https://juiceboxcleanenergy-my.sharepoint.com/:w:/g/personal/paul_meier_juiceboxcleanenergy_onmicrosoft_com/EQ-zRl1zs-1JoRvnMmhNpzABpCAW9FTIK3-rJ4xXyiJsSg?rtime=SJQQXjKj10g.

Kadiyala, A, R Kommalapati, and Z Huque. 2016. "Evaluation of the life cycle greenhouse gas emissions from different biomass feedstock electricity generation systems." *Sustainability* 1181.

Kaufman, A.S., P.J. Meier, J.C. Sinistore, and D.J. Reinemann. 2010. "Applying life-cycle assessment to low carbon fuel standards—How allocation choices influence carbon intensity for renewable transportation fuels." *Energy Policy* 38 (9): 5229-5241. doi:https://doi.org/10.1016/j.enpol.2010.05.008.

Nugent, D., and B.K. Sovacool. 2014. "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta-survey." *Energy Policy* 65: 229-244.

Official Journal of the European Union. 2018. *Document 32018L2001.* 12 21. Accessed 01 06, 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC.

Röder, M., C. Whittaker, and P. Thornley. 2015. "How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues." *Biomass and Bioenergy* 79: 50-63. doi:https://doi.org/10.1016/j.biombioe.2015.03.030.

Sahoo, K., E.M. Bilek, S. Mani. 2018. "Techno-economical and environmental assessments of storing woodchips and pellets for bioenergy applications." *Renewable and Sustainable Energy Reviews* 98: 27-39.

Sargent & Lundy. n.d. "Combined-Cycle Plant Life Assessments." *Sargent & Lundy.* Accessed 10 03, 2019. https://sargentlundy.com/wp-content/uploads/2017/05/Combined-Cycle-PowerPlant-LifeAssessment.pdf.

Spath, P.L., M.K. Mann, and D.R. Kerr. 1999. *Life Cycle Assessment of Coal-fired Power Production.* Colorado: National Renewable Energy Laboratory.

Sterman, J, L Siegel, and J Rooney-Varga. 2018. "Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy." *Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy* 2018.

Sustainable Biomass Partnership. 2019. *Certification Documents.* Accessed April 28, 2020. https://sbp-cert.org/documents/.

Tagliaferri, C., R. Clift, P. Lettieri, and C. Chapman. 2017. "Liquefied natural gas for the UK: a life cycle assessment." *The International Journal of Life Cycle Assessment* 22 (12): 1944-1956. doi:10.1007/s11367-017-1285-z.

The New York Times. 2010. *Net Benefits of Biomass Power Under Scrutiny.* 06 18. https://www.nytimes.com/2010/06/19/science/earth/19biomass.html.

—. 2016. *Next 'Renewable Energy': Burning Forests, if Senators Get Their Way.* 10 04. https://www.nytimes.com/2016/10/05/business/economy/next-renewable-energy-burning-forests-if-senators-get-their-way.html.

The Wall Street Journal. 2019. August 7. Accessed August 7, 2019. https://www.wsj.com/articles/wood-pellets-draw-fire-as-alternative-to-coal-11565175605.

Tumuluru, J.K., C.J. Lim, X.T. Bi, X. Kuang, S. Melin, F. Yazdanpanah, and S. Sokhansanj. 2015. "Analysis of Storage Off-Gas Emissions from Woody, Herbaceous, and Torrefied Biomass." *Energies* 8: 1745-1759.

Tumuluru, Jaya, and et al. 2015. "Analysis on Storage Off-Gas Emissions from Woody, Herbaceous, and Torreied Biomass." *Energies* 1749-1759.

University of Colorado Denver. n.d. *Capacity Factor.* Colorado. https://ucdenver.instructure.com/courses/342680/files/3776710/download.

US Energy Information Administration. 2019. "Annual Energy Outlook 2019 with projections to 2050."

US Environmental Protection Agency. 2019. *Emission Factors for Greenhouse Gas Inventories.* 03 09. Accessed 09 10, 2019. https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf.

—. n.d. "Wood Residue Combustion In Boilers." *US Environmental Protection Agency.* Accessed 10 01, 2019. https://www3.epa.gov/ttn/chief/ap42/ch01/final/c01s06.pdf.

USDA Forest Service. 2019. *Forests of North Carolina, 2018.* Resource Update (RU), Asheville; NC: Forest Service. Accessed 01 11, 2020. doi:https://doi.org/10.2737/FS-RU-225.

Wang, C., and D. Mu. 2014. "An LCA study of an electricity coal supply chin." *Journal of Industrial Engineering and Management* 7 (1): 311-335. doi:http://dx.doi.org/10.3926/jiem.1053.

Wernet, G., C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. Weidema. 2016. "The ecoinvent database version 3 (part I): overview and methodology." *The International Journal of Life Cycle Assessment* 21 (9): 1218-1230. Accessed 09 2019. http://link.springer.com/10.1007/s11367-016-1087-8.

Whitaker, C et al. 2009. "The life cycle analysis of using biomass for heat and electricity production in the UK." Final Project Report: Theme 3.

Wihersaari, M. 2005a. "Evaluation of greenhouse gas emission risks from storage of wood residue." *Biomass and Bioenergy* 28 (5): 444-453. doi:https://doi.org/10.1016/j.biombioe.2004.11.011.

Wihersaari, M. 2005b. "Greenhouse gas emissions from final harvest fuel chip production in Finland." *Biomass and Bioenergy* 28 (5): 435-443. doi:https://doi.org/10.1016/j.biombioe.2004.11.007.

Zhiyi, Y., and O. Xunmin. 2019. "Life Cycle Analysis on Liquefied Natural Gas and Compressed Natural Gas in Heavy-duty Trucks with Methane Leakage Emphasized." *Energy Procedia* 158: 3652-3657. doi:https://doi.org/10.1016/j.egypro.2019.01.896.