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Scope of Work:

Carbon life cycle assessment for torrefied biomass from forest restoration treatments in the Malheur National Forest, Oregon, for electricity production in Japan

Project report to:

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Picture title page: 2019 restoration thinning to support cottonwood groves in the Malheur National Forest in collaboration with the Blue Mountains Forest Partners.

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EXECUTIVE SUMMARY

Across the western US, forest health is declining. More than a century of wildfire exclusion has left these forests vulnerable to the effects of climate change. Forest Service management practices, concurred in by many private forest landowners, hold that reversing these trends will require increasing restoration treatments across the landscape. Markets for forest biomass removed as a result of these treatments may also act as a tool to help support the economics of their implementation.

Any such restoration treatments, and the disposition of the materials removed from the landscape, will need to account for the carbon effects on that landscape and across the broader world of carbon emissions released into the atmosphere, or recaptured from it. Forests perform in both these dimensions, and at a scale – with respect to both emissions and carbon capture and sequestration -- comparable to fossil fuel emissions and societal efforts to reduce these. *Thus interventions (harvest; fuel treatments) in forests must account for the near-term net carbon releases of such interventions, the period of recovery of prior forest carbon levels, and the potential for forest carbon capture of atmospheric carbon beyond present embedded levels.*

In the Malheur National Forest, treatments that may yield such a fuel supply include landscape-scale and long-term restoration projects. Markets for the type of biomass produced in stewardship contracts are thin, constraining the viability of such projects. Restoration Fuels, LLC, funded by the U.S. Endowment for Forestry and Communities, is currently constructing a torrefaction plant in John Day, Oregon. The business model of Restoration Fuels is to test a new market outlet for low-grade biomass, i.e. no-value to low value material such as small diameter logs (boles) or otherwise damaged, charred or diseased trees or the utilization of pulpwood-grade material in the absence of viable pulpwood markets. The goal is to improve market conditions to support restoration and fuel reduction projects in a manner that does not add to net greenhouse gas (GHG) emissions from forests.

This study was undertaken to evaluate the range of potential carbon implications from utilizing non-sawlog biomass from forest restoration treatments in Restoration Fuel's business model. This study provides direction when developing specific procurement plans and identifies areas for additional study.

Pinchot Institute for Conservation (PIC) and Spatial Informatics Group LLC (SIG) developed a biomass supply assessment (PIC) as well as an in-depth carbon life cycle assessment (C LCA; SIG) to help Restoration Fuels and its partners understand key sustainability issues related to the business model.

We ran C LCAs for a scenario where non-sawlog or pulpwood-quality logs and/or slash currently harvested under guidance of the Unites States Forest Service (USFS) as part of ongoing forest restoration treatments (USFS Rx) in the Malheur National Forest are being redirected from traditional use or disposal to a bioenergy route.

We also analyzed the C LCA outcomes for a hypothetical pre-commercial thinning prescription (PCT Rx) in which only small-diameter trees would be removed.

The analyzed bioenergy route consists of shipping biomass torrefied in John Day, Oregon, to Japan where it would be combusted for electricity production – substituting emissions from the current country-specific grid mix. These scenarios were chosen to represent the bookends of potential alternatives, not specifically to model proposed or actual on the ground activities. Selecting Japan as the destination only reflects the presence of a viable market for such biomass there, and its present absence in the United States.

This analysis compares different uses of harvested pulpwood and slash from timber/pulp harvests for their carbon outcomes. It uses current USFS "restoration treatment" practices in Malheur National Forest as a baseline (although depending on market circumstances, the USFS may use pulpwood for durable wood products, or may burn the pulpwood along with slash in situ). We look at different possible torrefaction options measured against different assumed forest management practices. The analysis also posits a "pre-commercial thinning" optional baseline (Scenario 3), where only small (<7" DBH) trees and related slash are torrefied and used as biomass fuel (see Table 3, page 6, for description of scenarios).

Results (see Table 5 on page 11 and Figure 4 on page 13) suggest that using pulpwood-quality feedstock for torrefied wood production to be burnt for electricity production in Japan delivers the highest carbon emissions per MWh, the lowest carbon savings, and climate benefits that are delayed by several decades (Case 1a). This result is mostly driven by the fact that pulpwood in this region is currently mostly used for long-lived wood products in construction.

If, however, all slash or small diameter material from the current restoration treatments are added to the pulpwood as feedstock for the torrefied fuel production instead of being pile-burnt (Case 1b), the climate benefits are immediate and significant. Because more biomass is quantitatively available, more generating capacity is supported and the emissions savings are substantially higher.

If there is a durable wood products market for the pulpwood while the slash is diverted to torrefaction (Case 1c), there is less biomass available for fuel but the combined emissions savings is larger (adding sequestration in wood products to slash-to-biomass generation displacing fossil fuel).

If there is no durable product market for the pulpwood, and current USFS practice would pile-burn it, diverting this wood into torrefaction (Case 2a) while still burning the slash in situ would result in immediate but modest carbon benefits.

However, diverting both the pulpwood and slash in Scenario 2a into torrefaction (Case 2b), rather than pile-burning them, results in the largest net carbon savings (from the largest quantity of material available for torrefying).

Finally (Case 3), if inputs are limited to only slash and small-diameter material from a Pre-Commercial Thinning (PCT) that would otherwise be pile-burnt, and no pulpwood is involved, still significant but much smaller net emissions gains are realized. However, more carbon is left as standing live trees in the forest,

In all cases, the carbon in "slash" that includes mostly branches and tops, is captured in the analysis, while the carbon from stumps and roots is left in place and not included in the analysis.

A sensitivity analysis suggested that results are robust and not sensitive to transport and processing (forest and torrefaction operations) emissions. To further improve climate benefits of non sawlog-derived torrefied wood, applying the fuel to combined heat and power applications could further significantly improve carbon emission profiles. Next steps could also explore the impact on results if grid electricity emission profiles are adapted over future decades as the global trend for increasing the share of renewables suggest. A different outcome might be realized if the same materials were displacing conventional thermal generation from the US electricity grid, but quantifying such an outcome would require specifics of the marginal thermal plant output being displaced, a reference point that is shifting rapidly in today's power grid.

The restoration treatments as currently practiced reduce forest carbon stocks significantly while leaving forests at what the Forest Service deems a more stable and resilient level compared to a no harvest scenario. However, current Forest Service and private timber harvest practices continue to deliver merchantable timber from many or most thinning activities. This analysis also compares carbon outcomes from such existing practices with more alternative approaches that would be more conserving of in-forest carbon (e.g., taking only small diameter standing trees while reducing quantities of existing downed materials).

Most forest wildfire includes larger areas of low and medium severity, with smaller areas of high severity. Such fires are within the ambit of historical fire activity, and do not release exorbitant levels of carbon dioxide. Areas suffering ahistorical levels of severe wildfire in untreated forests where fuel has accumulated can release substantial amounts of carbon and can trigger substantial shifts from the live to the dead carbon pool in forests. Current Forest Service practice relies upon strategically placed and implemented fuel treatments to alter fire behavior from higher to lower severity and reduce wildfire size, resulting in lower wildfire-induced carbon emissions. This change in carbon fluxes can be analyzed and quantified in future studies.

1 RATIONALE

Across the western US, forest health is declining. More than a century of wildfire exclusion has left these forests more vulnerable to the effects of climate change (e.g., drought, longer fire seasons, more virulent insect infestations; Westerling et al., 2006). Fire exclusion has also contributed to an accumulation of small trees beyond historic records, to the tune of at least 1.5 billion cubic feet of wood accumulation annually (USDA Forest Service, 2005). Reversing these trends will require increasing well-designed restoration treatments across the landscape that can revert forest conditions towards a more resilient ecosystem (Franklin et al., 2013; Franklin & Johnson, 2012). Implementing these treatments might require markets for forest biomass.

Mobilizing this supply has faced a series of challenges but treatments are being accomplished through a variety of mechanisms, including landscape-scale and long-term restoration projects, such as the Blue Mountains 10-year stewardship contract on Malheur National Forest (Figure 1). Markets for the type of biomass produced in stewardship contracts are thin, decreasing the viability of such projects (Pinchot Institute, 2017). Restoration Fuels, LLC, funded by the U.S. Endowment for Forestry and Communities is currently constructing a torrefaction plant in John Day, Oregon. The business model of Restoration Fuels is to test a new market outlet for low-grade biomass with the goal to improve market conditions to support restoration and fuel reduction projects. The company envisions several such plants around the interior forests of the West, and is using the John Day facility as a test case, with one objective being to analyze the sustainability of the model, and make improvements where feasible, on the way to replication and deployment.

Pinchot Institute for Conservation (PIC) and Spatial Informatics Group LLC (SIG) developed a biomass supply assessment (PIC) as well as an in-depth carbon life cycle assessment (C LCA; SIG) to help Oregon Torrefaction and its partners understand key sustainability issues related to the business model.

This report presents C LCA outcomes when pulpwood quality logs and/or slash currently harvested under guidance of the United States Forest Service (USFS) as part of ongoing forest restoration treatments (USFS Rx) in the Malheur National Forest are being redirected from traditional pulpwood use to a bioenergy route. We also analyzed the C LCA outcomes for a hypothetical pre-commercial thinning prescription (PCT Rx) in which only small-diameter trees would be removed. The analyzed bioenergy route consists of shipping biomass torrefied in John Day, Oregon, to Japan where it would be combusted for electricity production – substituting emissions from the current country-specific grid mix. These scenarios were chosen to represent the bookends of potential alternatives, not specifically to model the actual on the ground activities. The C LCA metric applied is the “carbon parity” in years (Mitchell et al., 2012), i.e. the time it requires to offset additional landscape (forest harvests) and fossil fuel (processing, transport) carbon emissions under a bioenergy scenario compared to a business as usual scenario with fossil fuel emissions associated with electricity generation.

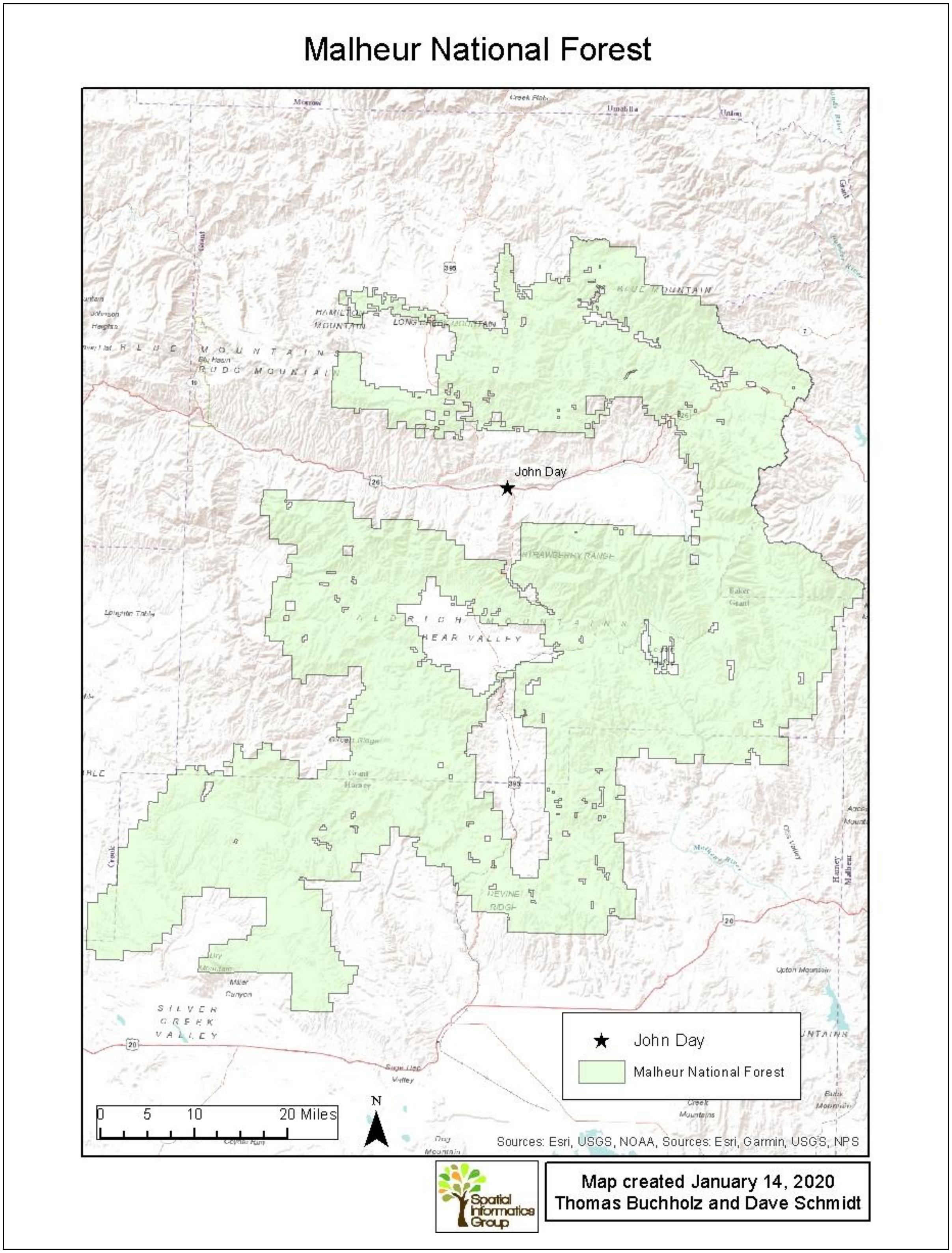

Figure 1: Malheur National Forest (1,890,009 acres) and location of torrefaction site (John Day, OR).

2 MATERIAL AND METHODS

2.1 C LCA boundary and scenario descriptions for the C LCA

Figure 2 visualizes C LCA steps, pools, and boundaries that underpinned this analysis. Table 1 provides an overview on the business as usual (BAU) and alternative future scenario components while Table 3 and Figure 3 provide information on BAU and alternative future Cases along with a rationale for each Case. The scenarios were framed to provide bookends for greater or lesser carbon loss effects, from a "Let Grow" where zero fuel materials were removed from the forest, to current USFS fuels reduction practices that generally include removal of merchantable timber as well as downed fuel materials and small diameter standing trees. Thus, we are able to compare the carbon reduction value added of torrefying the quantities of fuels removed, and their subsequent combustion for electricity production, under different forest removal and harvest strategies.

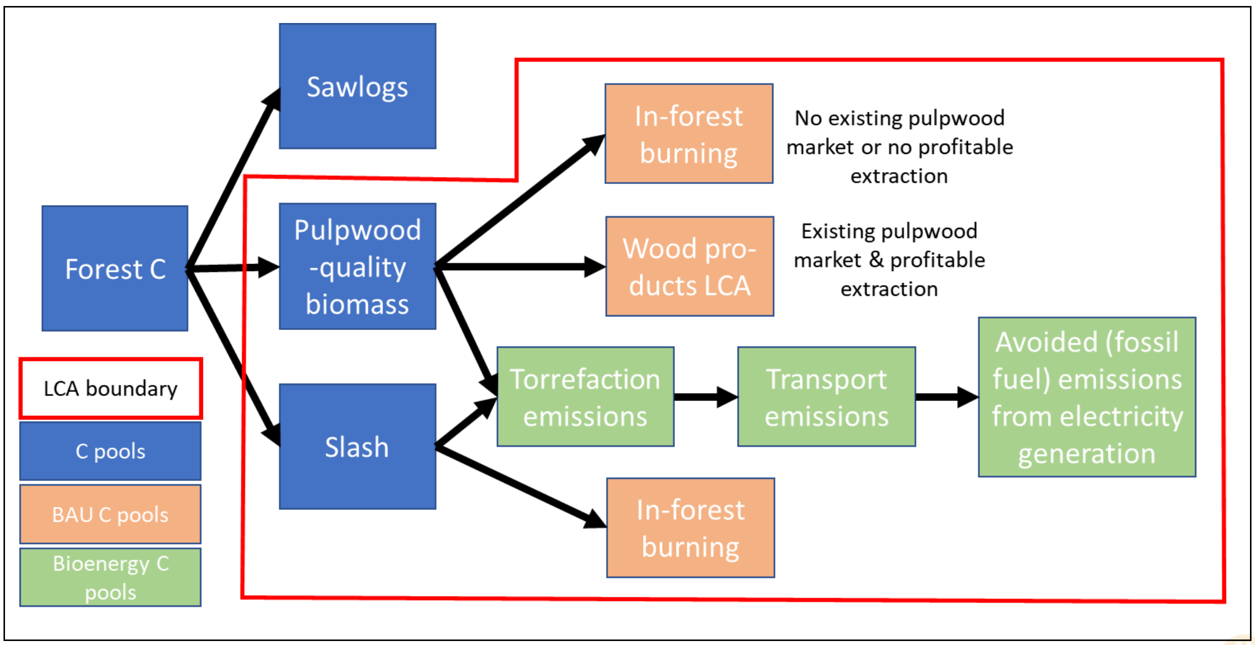

Figure 2: C LCA boundary, C pools, and assessment steps. The Forest C and Sawlog C pool were excluded since treatments would occur unchanged under both BAU and bioenergy scenarios. Forest-to-torrefier transport and processing fossil fuel emissions for slash scenarios involving slash were inconsequential (see section 3.1) and hence excluded.

In scenarios where pulpwood-quality logs are used for torrefied fuels, it is important to understand pulpwood market conditions. If pulpwood material can be extracted profitably and traditional pulpwood markets exist, a key to understanding C LCA outcomes under this scenario is understanding the current fate of this material. Contrary to intuition, only a fraction of the pulpwood-quality sections of a log harvested in the northern Rocky Mountains are used for short-lived products such as pulp or paper (15%; see Table 2) with a large section being used for construction and composite wood products. There is a ~30% immediate loss within the first year of the harvested pulpwood (see Table 6 in Smith et al., 2006), representing the fraction that will not make it into products, i.e. is 'waste'. Of that 30%, two thirds or around 20% of the delivered pulpwood-quality log is assumed to be used for energy, most likely at the local sawmill. The remaining 10% are other immediate emissions by using the material for e.g. mulching, animal bedding, etc.

Table 1: Assumptions on forest treatment prescriptions, biomass fate, and energy scenarios. For a detailed list of Cases see Table 3 and Figure 3.

Scenario element	Description
Forest treatments prescriptions (Rx)	**USFS Rx:** Forest restoration prescriptions as currently practiced by Forest Service **PCT:** Pre-commercial thinning (hypothetical) – Thin from below of trees with no commercial value (</= 7” diameter at breast height; DBH), pile- or broadcast-burning of cut biomass **Let grow:** No harvest, prescribed burning, mastication or thinning activities
Biomass fate (BF)	**Conventional pulpwood use:** Pulp-quality roundwood in-use and post-use fate modeled based on regional C LCA pathway (Smith et al., 2006) **Pulpwood pile-burnt:** Pulp-quality roundwood pile-burnt at landing site or within stand **Wood slash pile-burnt:** Non pulp-quality roundwood pile-burnt at landing site or within stand **Torrefied biomass:** Biomass chipped and torrefied
Energy scenarios (ES)	**Grid mix Japan:** Current grid mix emissions per MWh electricity generated **Bioenergy:** Torrefied biomass burnt in conventional electricity-only boilers

Table 2: Fraction of each classification of industrial roundwood according to category as allocated to primary wood products for the Rocky Mountain region (see Table D6 in Smith et al., 2006).

Softwood lumber	Softwood plywood	Oriented strand board	Non-structural panels	Other industrial products	Wood pulp	Fuel and other emissions
0.402	0.054	0	0.033	0.062	0.153	0.296

Table 3: C LCA scenario descriptions for torrefied biomass production and use at the Malheur National Forest. For a definition of treatments (Rx), biomass fate (BF) and energy scenarios (ES) see Table 1. For a visualization of these Cases see Figure 3.

Scenario #	Business as usual (BAU) scenario: No production and use of torrefied biomass	Alternative future (AF): Production and use of torrefied biomass	Scenario rationale/Comments
1a	Rx: USFS Rx BF: Conventional pulpwood use (slash pile-burnt) ES: Grid mix Japan	Rx: USFS Rx BF: Torrefied biomass from pulpwood (slash burnt) ES: Bioenergy	AF: Pulp-quality biomass used for torrefied product AF: Price competition with pulp market AF: Slash not used (extraction too expensive; insufficient quality)
1b	Rx: USFS Rx BF: Conventional pulpwood use (slash pile-burnt) ES: Grid mix Japan	Rx: USFS Rx Torrefied biomass from pulpwood & slash ES: Bioenergy	AF: Pulp-quality biomass used for torrefied product AF: Price competition with pulp market AF: Slash used for bioenergy
1c	Rx: USFS Rx BF: Conventional pulpwood use (slash pile-burnt) ES: Grid mix Japan	Rx: USFS Rx BF: Torrefied biomass from slash (pulp: conv. use) ES: Bioenergy	AF: Pulp-quality biomass not used for torrefied product AF: Price competition with pulp market AF: Slash used for bioenergy
2a	Rx: USFS Rx BF: Pulpwood and slash pile-burnt ES: Grid mix Japan	Rx: USFS Rx BF: Torrefied biomass from pulpwood (slash burnt) ES: Bioenergy	BAU: Absent pulp market/Stand conditions uncompetitive for pulp sale. AF: Pulpwood retrieval is cost-effective AF: Slash not used (extraction too expensive; insufficient quality)
2b	Rx: USFS Rx BF: Pulpwood and slash pile-burnt Grid mix Japan	Rx: USFS Rx BF: Torrefied biomass from pulpwood & slash ES: Bioenergy	BAU: Absent pulp market/Stand conditions uncompetitive for pulp sale. AF: Pulpwood and slash retrieval is cost-effective
3	Rx: PCT BF: Logs/slash pile-burnt ES: Grid mix Japan	Rx: PCT BF: Torrefied biomass from logs and slash ES: Bioenergy	BAU: Absent pulp market/Stand conditions uncompetitive for pulp or timber sale. AF: Pulpwood and slash retrieval is cost-effective

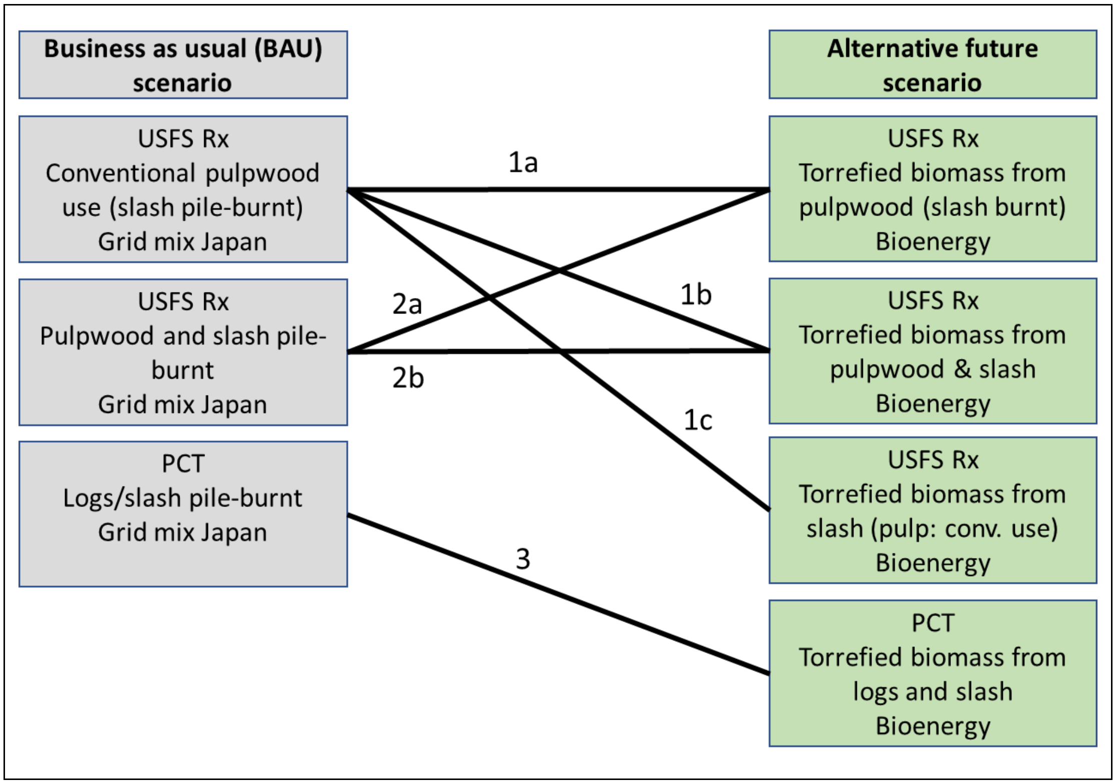

Figure 3: Visualization of Cases explored in this C LCA study. For an in-depth description of BAU and Alternative future scenarios see Table 3.

2.2 Modeling inputs

2.2.1 Spatial datasets

We used an existing vegetation spatial dataset for the Malheur National Forest to define approximately 90,000 stands across the study area of 1,890,009 acres. Each forested stand was assigned tree inventory data, updated to 2018 conditions ('grown forward' and added harvest and thinning activities; 2015 and 2016 included significant wildfires in the project area), and projected into the future with two management scenarios as described below.

Tree inventory data for running the Forest Vegetation Simulator (FVS, USFS, 2020a) such as species, diameter, and density (trees per acre) came from the USFS Fire Lab tree list inventory dataset (TLID; Riley et al., 2018). This spatial dataset imputes Forest Inventory and Analysis (FIA) plots to specific landscape locations, we obtained an updated dataset that reflected 2014 conditions.

The Nature Conservancy provided cleaned spatial data from USFS's Forest Activity Tracking (FACTS; USFS, 2020) that described timber harvest and fuels treatments on the Malheur National Forest between 2015 and 2018 (inclusive). These harvests and treatments were combined into the following codes: non-commercial thin, commercial thin, fuels treatment, pileburn, and planting. We created an FVS addfile (keyword component file) for each of these disturbances and used the Addfiles field of the FVS_StandInit table to set up FVS to simulate that particular disturbance in the correct year for the affected stands. Only FACTS entries whose phase was "Accomplished" were included as a disturbance. There were also a few stands that experienced high-severity wildfire in 2018 or 2019. These were identified and FVS was used to simulate wildfire in the same way as the other disturbances.

We used the USGS Protected Areas Database (PAD-US; USGS, 2020) for Oregon to identify stands that were legally protected in some manner (e.g., Federal Wilderness Areas).

We assigned the most common plot identifier from the TLID raster within each stand polygon to represent forest conditions within that stand. The TLID plot identifier linked stand polygons with the FIA inventory database. From this dataset we created the main FVS database inputs- the FVS_StandInit and FVS_TreeInit tables. The final FVS input database was current to 2014 but contained keywords so that at run-time FVS would grow forward each stand to 2019 after simulating the appropriate 2014-2018 disturbances.

2.2.2 Forest treatment projections

Two scenarios were simulated with FVS. FVS keyfiles for the exploratory, validation, and final FVS runs were created with the FVS Suppose interface and these keyfiles were then simulated with openfvs (USFS, 2020c) on a Linux virtual machine. Outputs were recorded in sqlite databases. Both scenarios used the Jenkins et al. (2003) carbon equations and both use the same FVS keywords to simulate tree mortality and regeneration based on Malheur National Forest staff specifications. Small (0-5 inch DBH) trees of all species were assigned 5% higher mortality than the FVS default rate and because the Blue Mountains variant does not include a full establishment model, natural tree regeneration had to be simulated. This was accomplished by simulating two pulses of new five-foot tall trees "planted" in 2015 and 2035. Each regeneration pulse consisted of 22 western larch trees per acre, 99 grand fir, five lodgepole pine, 14 ponderosa pine, and 21 Douglas-fir. Both simulations ran for 40 years with five-year timesteps.

The initial stand grouping was designed primarily to replicate current Malheur National Forest management. Seven groups (g1-g7)- one for each of seven five-year timesteps- were allocated stands such that the total area of each group would be about 90,000 acres (18,000 acres treated per year over the five-year timestep). Because of the 35-year stand re-entry prescription, the first and second groups (g1 and g2) were unique in that they were treated in both 2019 and 2054, and 2024 and 2059 respectively. A let-grow FVS simulation was completed to produce a Stand Density Index (SDI) value for each stand in 2019. Stands were sorted by descending SDI value for assignment into treated groups to simulate prioritizing high-density stands for early treatment. The original no-treatment group was comprised of stands flagged as protected or having experienced recent high-severity wildfire, or those that remained after meeting the total acreage target.

This effort closely replicated the targeted acreage goals but failed to match expected timber yields. A second stand grouping effort used FIA harvest and productivity records to assign stands to groups but this also failed to replicate current Malheur National Forest timber yields. The third and final grouping design was based more on manually matching yield than acreage. Group sizes ranged from about 40,000 acres to 116,000 acres but the average group size was about 74,000 acres. The target annual yield was 55 million board feet (mmbf) and this grouping produced an average of about 50 mmbf per year.

Two treatments were simulated in FVS: a restoration treatment that closely replicates current Malheur National Forest management, and a pre-commercial thin/mastication. For both simulations, stands were placed into either the no-treatment group or one of the seven treatment groups.

The restoration treatment prioritized retaining western white pine, followed by western larch, and lastly ponderosa pine. All other species had equal prioritization. The thinning was simulated as 95% efficient and all slash was left on-site. For each timestep, the stands in the treatment group assigned to that timestep received a thin from below of live trees between zero and 24 inches DBH. If a stand's forest type was ponderosa pine, incense cedar, Jeffrey pine, or Douglas-fir, then the residual target basal area was 60 square feet per acre. Any other forest type (generally mixed conifer) was thinned to 90 square feet per acre instead, from any tree diameter class. The thinning treatment was followed in the same year by a pile-burn to clean up logging slash and with a prescribed burn scheduled for five years after the thinning. The simulated pile-burn and prescribed fire were both designed according to Malheur National Forest specifications.

The pre-commercial thin/mastication treatment utilized a thin-from-below of all live trees up to seven inches DBH while ensuring that at least 50 square feet per acre of basal area was retained. All cut material was hauled off-site. The existing shrub and herbaceous fuel load as well as the pre-thinning 3-6" coarse woody debris fuel load were calculated and saved in the FVS_Compute table. The pre-existing and new (slash) coarse woody debris was simulated as masticated and hauled off-site, followed by a pile-burn simulated in the same year as the thinning.

Slash production was calculated for both treatment scenarios. For the restoration treatment a separate FVS run with all branchwood removed was used. Slash was then calculated as FVS_Fuels.Biomass_Removed - FVS_Carbon.Total_Removed_Carbon. For the pre-commercial thin/mastication treatment slash was calculated simply as FVS_Fuels.Biomass_Removed.

2.3 Relevant C LCA inputs

Table 4 provides an overview on all relevant C LCA inputs besides forest biomass production inputs.

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Table 4: Relevant C LCA inputs for torrefied wood chips sourced in the Malheur National Forest, processed at John Day, OR, and consumed for electricity production in Japan.

General inputs	Unit	Input value	Source	Comment
Harvest mix specfic gravity	Mg/m3	0.4975	Miles & Smith, 2009	50% ponderosa pine, 50% Douglas-fir
Carbon fraction softwood	% of dry weight	0.48	Aalde et al., 2006	Chapter 4 Forest, Table 4.3
Torrefied wood production				
Prod. Eff. torrefied wood (TW) to wood	Mg TW/ Mg wood (0% moisture cont.)	0.91	Adams et al., 2015; Figure 3	
Tor. wood net cal. Lower heating value (LHV)	MWh/Mg	6.1	Adams et al., 2015	
Process heat demand	MWh/Mg TW	1.1	Adams et al., 2015	
Process heat emissions	Mg CO2e/MWh	0.016	EIA, 2020	Natural gas
Process heat efficiency	%	90.0%		
Electricity for densification	MWh/Mg TW	0.227	Adams et al., 2015	
Tor. wood trsp. and end use				
Destination		Japan		
Truck	Mg CO2e/Mg/mi	0.00023149	US EPA, 2018; Table 7	
Rail	Mg CO2e/Mg/mi	0.00002284	US EPA, 2018; Table 4	
Marine	Mg CO2e/Mg/mi	0.00000659	US EPA, 2018	Bulk carrier 60k-99k dwt, p 26
Truck	mi	166		John Day, OR to Tokyo, Japan
Rail	mi	150		Japan
Marine	mi	4,948		Japan
Electric efficiency TW	%	40%	McNamee et al., 2016	
TW power plant efficiency (LHV)	%	40.0%	McNamee et al., 2016	
C footprint electricity mix	Mg CO2e/MWh	0.475	IEA, 2019	Japan

3 RESULTS

3.1 C LCA results across scenarios

Net carbon results for our scenarios depend in each case on the baseline from which they are measured as well as what part of the materials withdrawn from the forest are used (and for what) or burned in place. All cases except for the PCT case assume a specified level of USFS harvest/treatment and different dispositions of the materials resulting from that harvest/treatment.

All cases except Case 1a provide immediate emission benefits. In terms of both scale and per-MWh electric emissions, the best carbon case (2b) results when both pulpwood and slash that would otherwise be burned instead become feedstock for the torrefaction process (Figure 4). The second-best carbon case (1c) results when pulpwood is used for product but slash that would otherwise be piled and burned in place instead becomes feedstock for the torrefaction process.

In the least attractive case (1a), when pulpwood-quality logs from restoration treatments are used as feedstock for the torrefied product instead of conventional pulpwood use (dominated by long-lived wood products; see section 2.1), 32 years of avoided fossil fuel emissions and regrowth is required to balance out forest carbon stock losses and foregone carbon sequestration (Case 1a; Table 5). Figure 4 provides a temporal overview on all cases in terms of accumulated net carbon emissions if total available feedstock volume would be used (Figure 4a) as well as on a per-$MWh_{electric}$ basis (Figure 4b).

All other cases provide instant climate benefits with negative average emissions per MWh electricity produced, i.e.:

- If both pulpwood and slash is used from restoration treatments as torrefaction feedstock (Case 1b) although pulpwood markets are available;
- If only slash is used from restoration treatments as torrefaction feedstock (Case 1c);
- If no pulpwood market is available and only pulpwood is used from restoration treatments as torrefaction feedstock (Case 2a);
- If no pulpwood market is available and both pulpwood and slash is used from restoration treatments as torrefaction feedstock (Case 2b);
- If no pulpwood market is available and both pulpwood and slash is used from restoration treatments as torrefaction feedstock (Case 3).
- The hypothetical PCT case (Case 3) would produce significantly lower biomass feedstock volumes but at the same time leave more carbon in the forest. Hence, it would rank as one of the lowest carbon emissions scenarios (for further discussion, see also Note Regarding Case 3 on page 20).

These results are grounded in the assumptions that i) biomass procured for the torrefaction process would be pile-burnt in the absence of a bioenergy market and hence be labelled as “anyway emissions” and ii) no change in forest management (besides pile-burning) would be triggered by the introduction of a torrefaction plant. Case 1a does not assume pile-burn of biomass (i.e. pulpwood in this case) under the BAU scenario and therefore foregone long-term carbon sequestration in wood products (in-use and post-use) needs to be accounted for in calculating the "carbon parity" recovery date. This change in wood products carbon storage results in a carbon parity point reached after 32 years, at which point the accumulated carbon emissions of the alternative future drop below the BAU carbon emissions.

Table 5: C LCA results for all cases. Standard deviations from the average values are presented in brackets.

Case	Carbon parity (y)	Average emissions (Mg CO_2e/ $MWh_{electric}$)	Average annual biomass availability (dry Mg)[a]	Required installed capacity (MW) [b]	Total carbon emission savings (Mg CO_2e) [c]
1a (Restoration cut; existing pulp market, pulp for bioenergy)	32	0.756 (0.260)	46,902 (32,544)	15 (10)	1,644,083
1b (Restoration cut; existing pulp market, pulp and slash for bioenergy)	0	-0.223 (0.033)	263,957 (175,512)	84 (56)	6,690,769
1c (Restoration cut; existing pulp market, slash for bioenergy)	0	-0.421 (0)	217,054 (145,487)	69 (46)	8,334,852
2a (Restoration cut; pulp burnt under BAU; pulp for bioenergy)	0	-0.421 (0)	46,902 (32,544)	15 (10)	1,801,044
2b (Restoration cut; pulp burned under BAU; pulp and slash for bioenergy	0	-0.421 (0)	263,957 (175,512)	84 (56)	10,135,896
3 (PCT; pulp and slash for bioenergy)	0	-0.421 (0)	70,895 (64,393)	22 (20)	2,722,372

[a]) 0% moisture content

[b]) Assuming an 80% annual load factor

[c]) Over 40 years if all biomass available would be used for electricity generation in Japan. These emission savings are largely hypothetical since the torrefaction plant would need to be scaled to the maximum annual output under a starkly fluctuating year-to-year biomass availability (see high standard deviations of annually available biomass).

The aggregated carbon emissions of the alternative future scenario under 1a are therefore above the Japanese grid electricity footprint until year 32[1]. Biomass availability differs significantly across Cases and within years (see high standard deviations). The bulk of the average annual biomass harvest would be potentially derived from slash (82% under the restoration treatment scenario).

A sensitivity analysis demonstrated that these scenario results are largely unaffected by changes to transport and torrefied wood production emission estimates. Transport emissions hauling slash to the torrefaction site which would not occur if slash or pulpwood would be pile burnt resulted in <0.001 $MgC0_2e$/MWh electricity produced. This minuscule emission component was therefore not accounted for (assuming a 50 mi transportation route). A sensitivity analysis on pile-burning efficiency (90% to 100%; Rebain et al., 2015) resulted in no significant changes as well. If torrefied wood would offset grid emissions in Oregon, results would be affected in so far as scenario 1a would produce a substantially longer timeframe until carbon parity would be reached due to a much lower grid electricity profile for Oregon (0.164 $MgC0_2e$/MWh; EIA, 2019b, 2019a) compared to Japan (0.475 $MgC0_2e$/MWh; Table 1).

[1] Note that IPCC (2018) strongly emphasizes early/pre-2030 emissions as critical to maintaining global climate stability and managing the already baked-in adverse effects of climate change. A 32 year recovery delay extends well past this window.

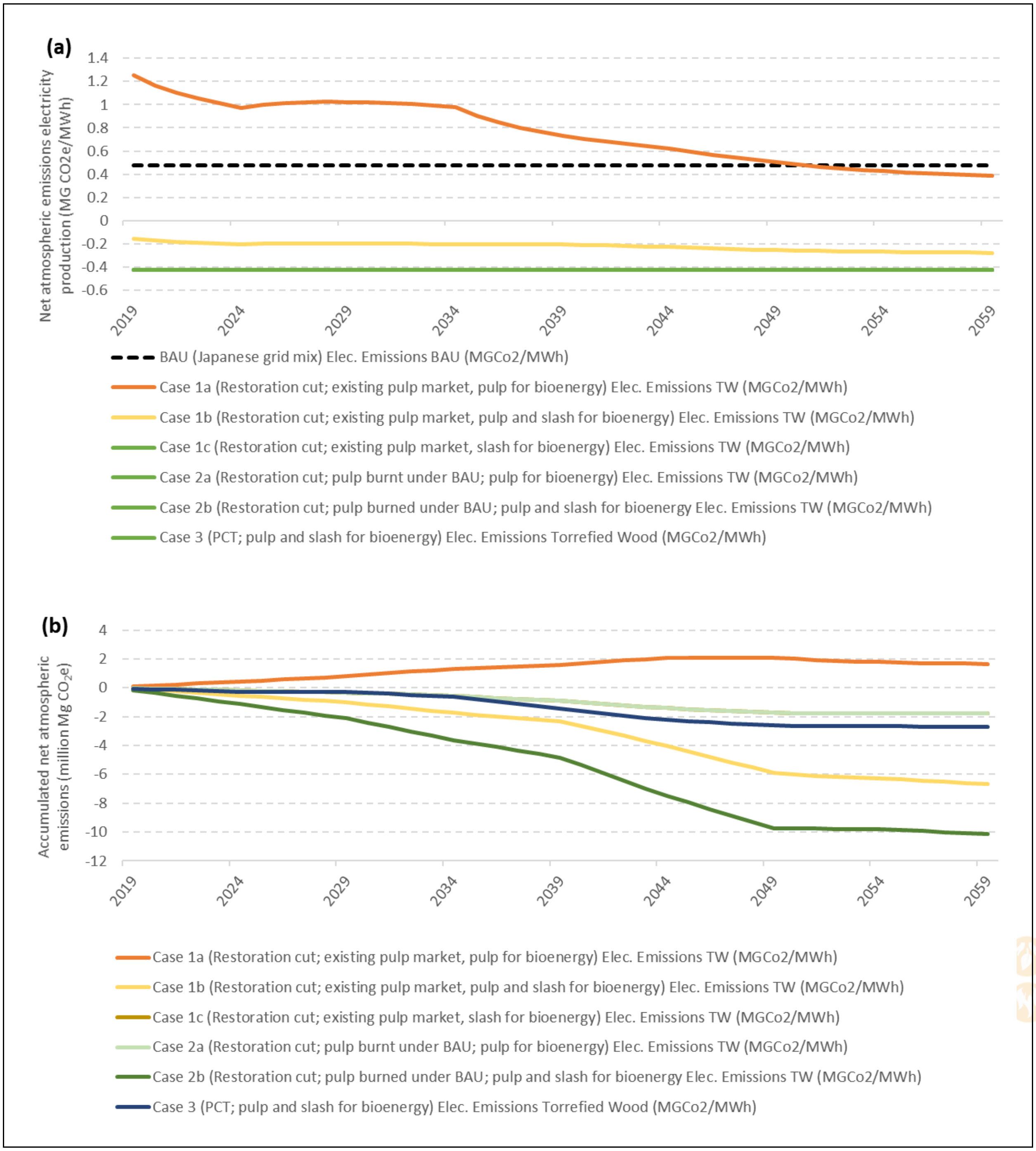

Figure 4: Aggregated case results by net atmospheric emissions per MWh electricity produced (a) and accumulated net atmospheric emissions if full potential for biomass availability would be exploited (b).

3.2 C LCA profiles by scenario

3.2.1 Forest restoration treatments

Case 1a. Restoration treatments and markets vs. using pulpwood for bioenergy.

This Case is the only one resulting in significant delays until climate benefits are realized.

Carbon parity, i.e. the time when accumulated bioenergy emissions drop below BAU emissions is not reached until year 32 (red and black dotted lines cross; red solid line drops). The driving force behind this result is the forgone carbon storage capacity of in-use and post-use wood products from pulpwood (Figure 5; green bars). For all Cases (Figure 5 to Figure 10), carbon emissions associated with transportation (orange bars) and processing (grey bars) of biomass are insignificant compared to the avoided Japanese grid electricity emissions despite the long shipping routes.

In all figures, the key metric is that represented by the "net emissions" (solid red) line as.

Note that forest carbon stocks and where applicable sawtimber in-use and post-use carbon stocks are not shown since they remain unchanged between BAU and alternative future (i.e. treatments remain the same when comparing the baseline to the bioenergy scenario and only the fate of pulpwood and slash changes). This presentation is accurate since slash (and pulpwood in scenario 2a, 2b, and 3) would be immediately released (within e.g. 12 months) through either pile-burning or energetic use. The leveling-off of avoided electricity emissions (black bars) in the last ten years analyzed under the restoration treatment scenarios (Figure 5 to Figure 9) is due to a reduced harvest volume in later years when a full cycle of restoration treatment has been implemented and low-quality/small-diameter volumes therefore drop.

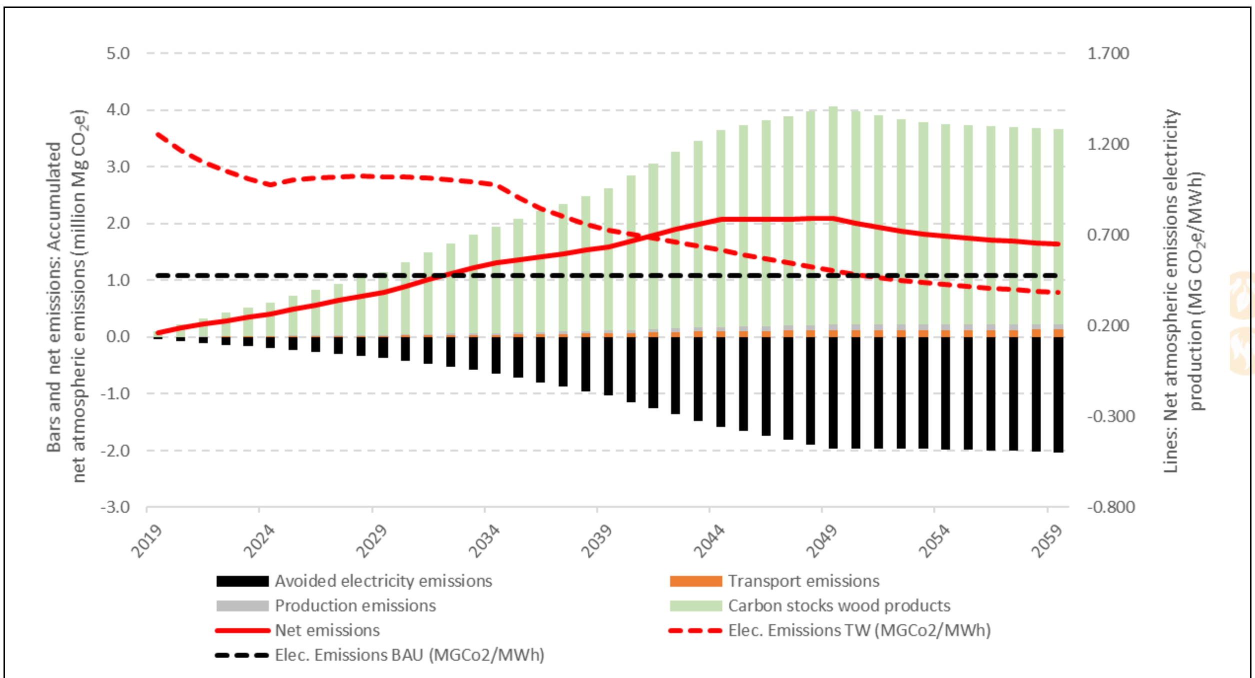

Figure 5: Conventional treatments and markets vs. using pulpwood for bioenergy (Case 1a).

Case 1b. Restoration treatments and markets vs. using pulpwood and slash for bioenergy.

When slash is removed and processed into torrefied wood along with pulpwood, climate benefits are instantaneously realized (Figure 6).

This considerable change in outcomes compared to Case 1a (Figure 5) can be explained by the sheer quantity of biomass feedstock volume added when also extracting slash (see Table 5) instead of pile-burning it. While lost carbon storage capacity in wood products still needs to be accounted for, the carbon emissions associated with electricity production from torrefied wood (red dotted line) replacing grid emissions in Japan (black dotted line) are substantial.

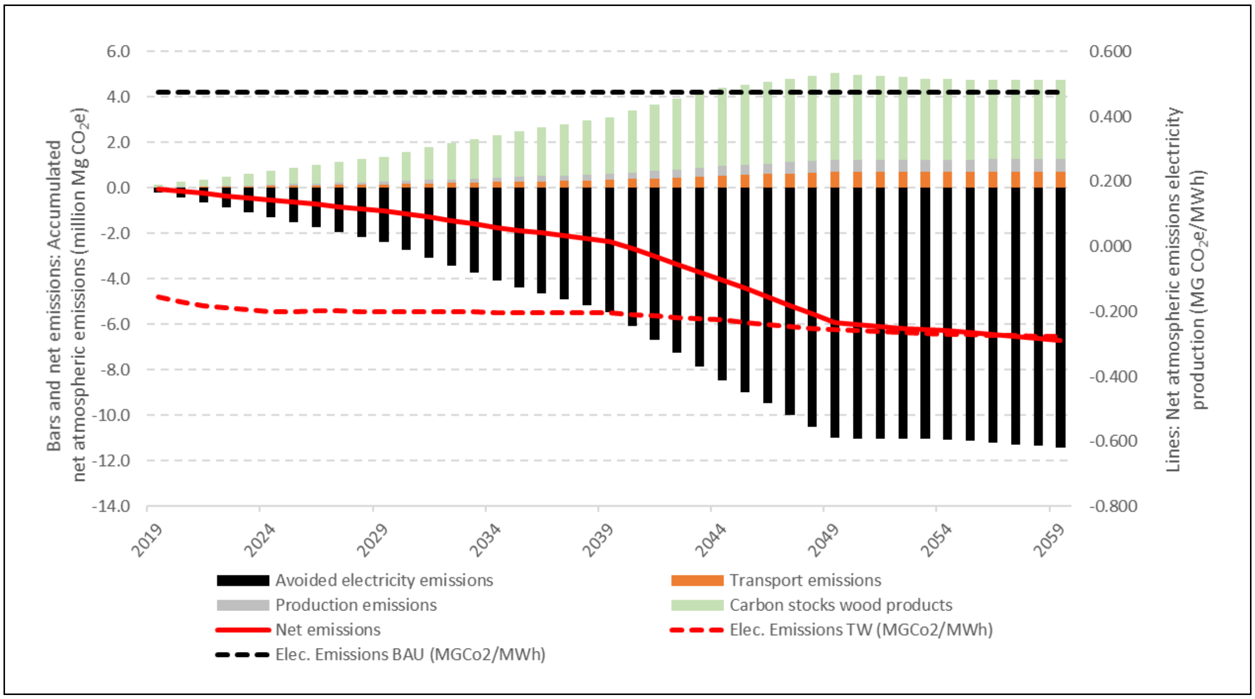

Figure 6: Conventional treatments and markets vs. using pulpwood and slash for bioenergy (Case 1b).

Case 1c. Restoration treatments and markets vs. using slash only for bioenergy.

When only slash is used for torrefied wood production under the restoration treatment scenario, no wood product storage pools are affected.

The emissions associated with electricity production from torrefied wood (red dotted line) are therefore lower in Case 1c (Figure 7) then in Case 1b (Figure 6).

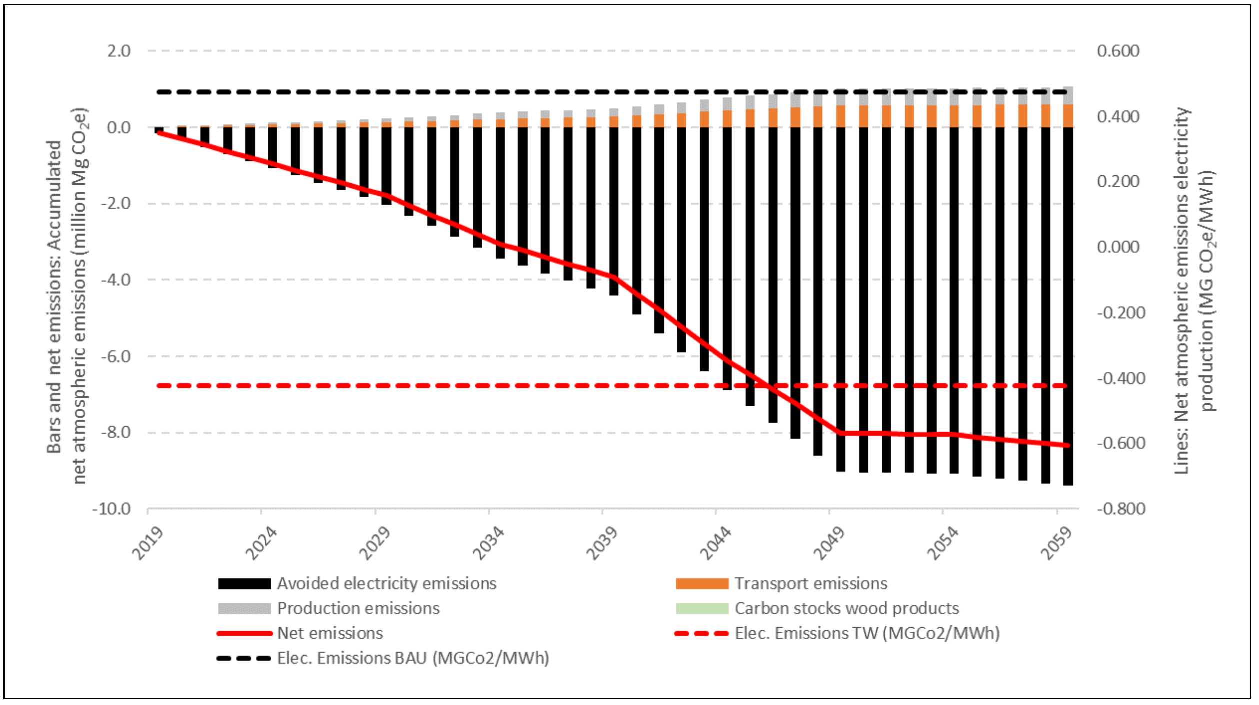

Figure 7: Conventional treatments and markets vs. using only slash for bioenergy (Case 1c).

Case 2a. Restoration treatments in absence of pulp market vs. using pulpwood for bioenergy.

When pulpwood that cannot be marketed otherwise is used for torrefied wood production under the restoration treatment scenario, no wood product storage pools are affected and climate benefits are instant.

Similar to Case 1c (Figure 7), Case 2a (Figure 8) does not have to account for wood product carbon storage since the assumption is that cost-effective extraction of pulpwood would not be feasible and hence pulpwood would be pile-burnt. Biomass electricity emissions per MWh are therefore the same as in Case 1c (red dotted line) and show a substantial climate benefit compared to BAU electricity emissions (black dotted line). Since only pulpwood is used for electricity generation, total carbon savings are reduced (red solid line) compared to Case 1c.

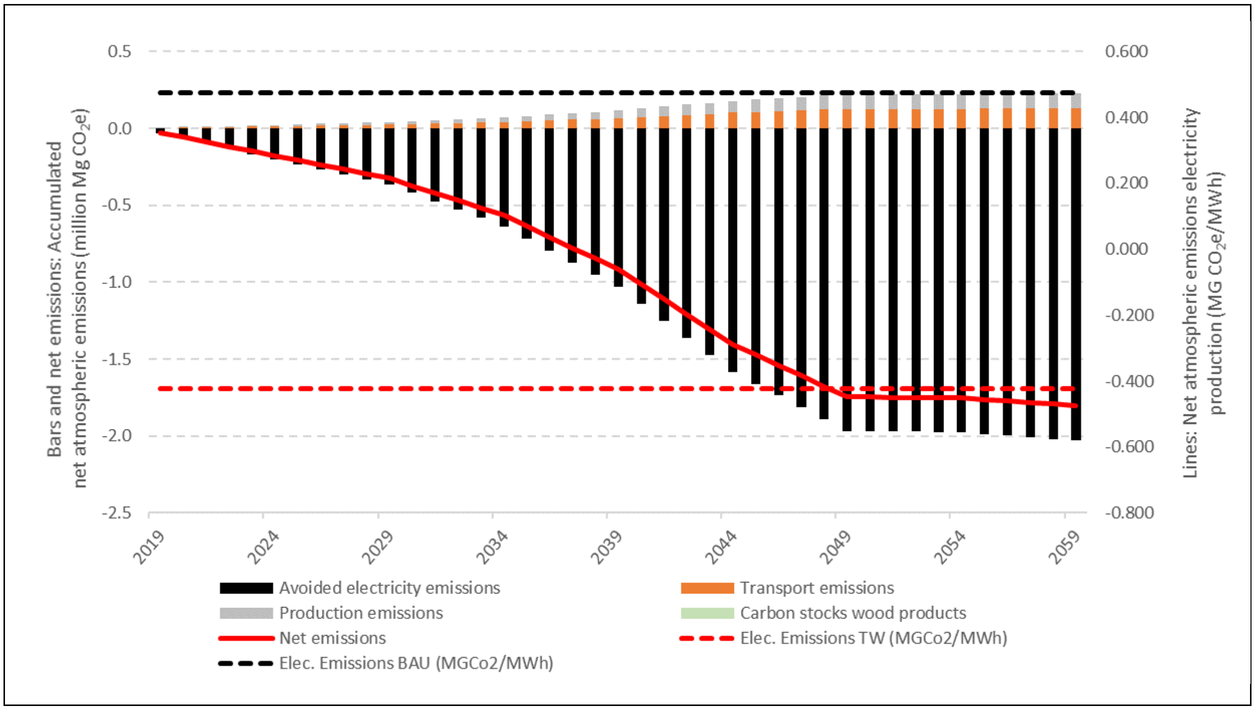

Figure 8: Conventional treatments in absence of pulp market vs. using pulpwood for bioenergy (Case 2a).

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Case 2b: Restoration treatments in absence of pulp market vs. using pulpwood and slash for bioenergy.

When pulpwood that cannot be marketed otherwise is used for torrefied wood production under the restoration treatment scenario plus all available slash, no wood product storage pools are affected and climate benefits are instant and further scaled up compared to Case 2a.

This Case is identical to Case 2a. However, slash is also used for electricity generation in addition to pulpwood (Figure 9). Hence, the additional availability of biomass provides a substantial boost to overall emission benefits (red solid line).

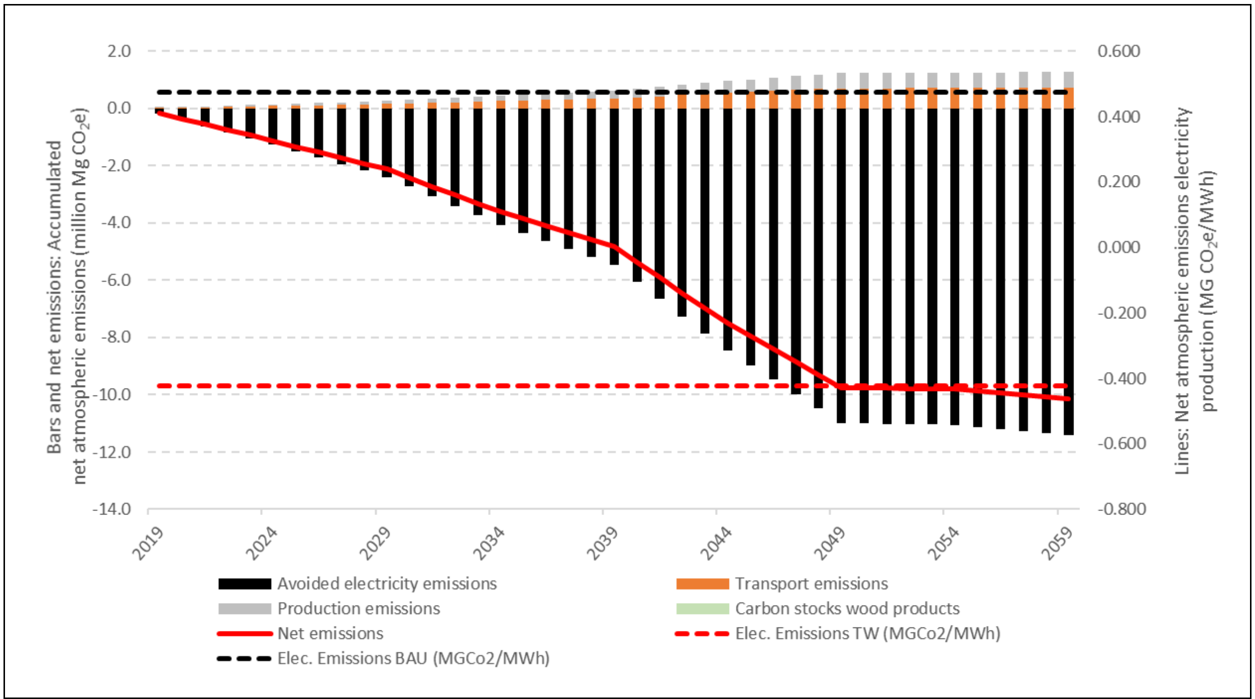

Figure 9: Conventional treatments in absence of pulp market vs. using pulpwood and slash for bioenergy (Case 2b).

3.2.2 Case 3. Pre-commercial thinning treatments.

Climate benefits would be instant if only pulpwood dimensions would be removed (i.e., no commercial-grade sawtimber), could not be marketed, and be used as feedstock for the torrefaction process along with all slash.

The PCT Case looked at the carbon emission impacts if only small-diameter trees (<7” DBH) would be removed across the Malheur National Forest and the absence of sawtimber from the harvest mix would also prevent a cost-effective extraction of pulpwood for the traditional pulpwood market. Hence, both slash and pulpwood would be pile-burned under BAU in this Case. As an alternative, the Case 3 analyzed the carbon impact if slash and pulpwood would be rerouted towards torrefied wood destined for the Japanese electricity market (Figure 10). Similar to Cases 1b to 2b (Figure 6 to Figure 9), this Case results in immediate and substantial climate benefits. The available feedstock volume shows a comparable levelling off past the first 30 years of analysis as observable in the restoration treatment when a full cycle of restoration treatments has been implemented and low-quality/small-diameter volumes drop as a consequence.

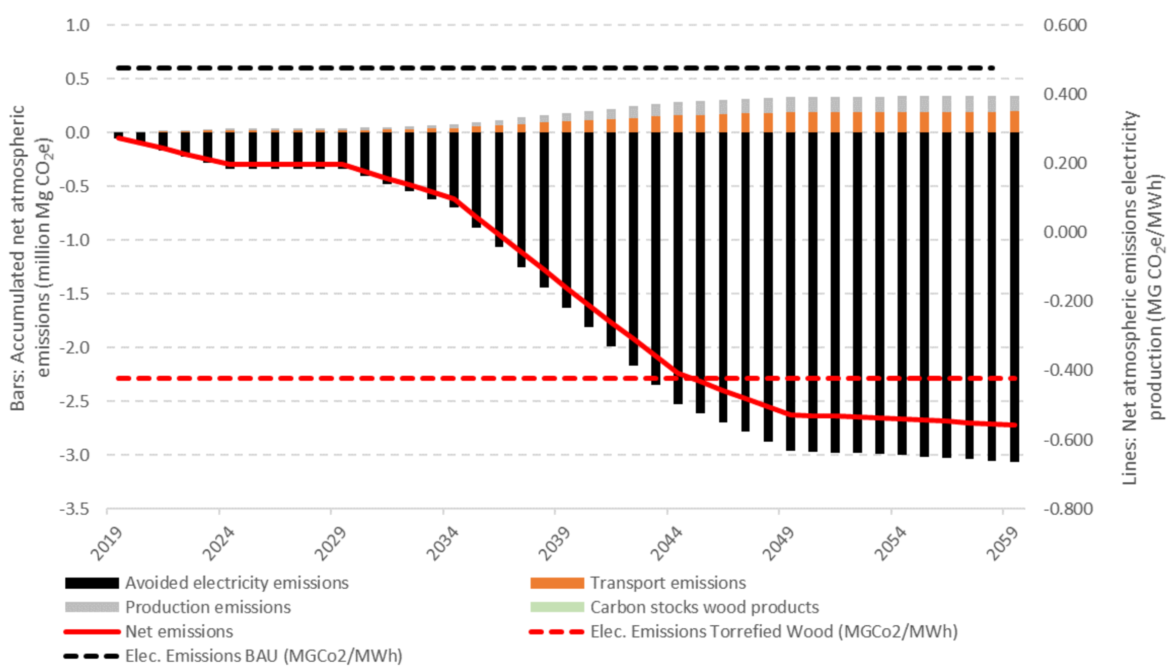

Figure 10: Pre-commercial thinning treatments in absence of pulp market vs. using pulpwood and slash for bioenergy (Case 3).

3.2.3 Landscape carbon forecast across scenarios

We compared the forest carbon stocks for both treatment scenarios as currently practiced by the USFS in the Malheur National Forest through restoration treatments (USFS Rx) with the hypothetical treatment scenario of removing small-diameter trees only (PCT) and with no-harvest scenario (let grow, Figure 11). While the forest carbon stocks are not relevant for the C LCA provided above (since both BAU and alternative future scenarios do not assume a change in forest management in each Case), this assessment is still insightful. It shows that forest carbon stocks are only marginally reduced over a no-harvest scenario when compared with the PCT scenario and experiences a 13% reduction over the 40-year timespan analyzed when comparing the no-harvest scenario with the currently practiced restoration treatment scenario.

The forest carbon stock projection in Figure 11 does not take into account the potential change in carbon forest stocks under each scenario if stochastic events (e.g. wildfire) would occur in the Malheur National Forest as frequently experienced in past decades. Restoration treatments as practiced in the Malheur National Forest stabilize forest carbon stocks over the medium to long-term as proven for other fire-adapted forested ecosystems (e.g. Hurteau et al., 2016; McCauley et al., 2019).

Note regarding Case 3: Restoration treatments currently practiced in the Malheur National Forest are designed to provide ecological long-term benefits. Pursuing this goal requires considerable initial reductions in forest carbon stocks. If instead the goal would be to achieve a change in fire behavior through the removal of small-diameter trees (PCT cuts; assuming that these cuts would be effective as a fuel treatment), this goal could be achieved at a lower 'carbon cost'. If we further assume, that a switch from restoration cuts to PCT cuts could be achieved by providing (torrefaction) markets for slash produced during the PCT cuts, forest carbon could be retained at a higher level, at least initially for the next climate-relevant 20 years (IPCC, 2018). In this case, a change of forest management triggered by the torrefaction facility would require a carbon LCA that also incorporates changes in forest carbon stocks. As a consequence, torrefied wood chips from PCT cuts under this scenario would outperform all other cases in terms of climate benefits by several magnitudes. For instance, while this study suggested carbon emission savings of 0.421 Mg CO_2/MWh electricity produced, this new scenario would potentially suggest carbon emission savings of over 6 Mg CO_2/MWh electricity produced.

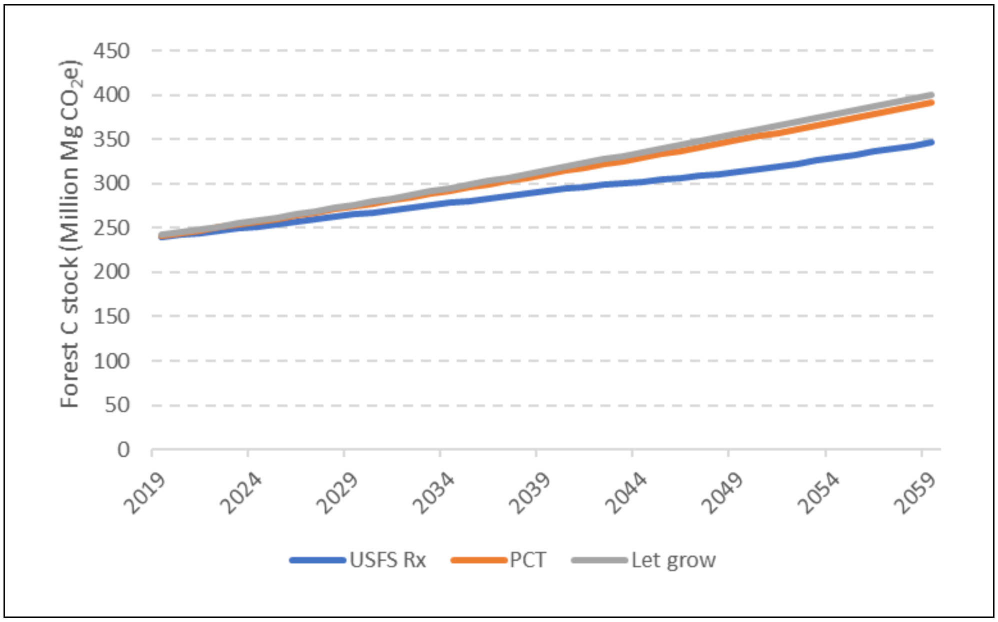

Figure 11: Total forest carbon stocks for conventional restoration treatments (USFS Rx) as currently practiced, pre-commercial thinnings (PCT) and no harvest (let grow) scenarios.

4 POTENTIAL NEXT STEPS

To further elaborate on results and fine-tune the analysis, we recommend the following steps:

- Account for avoided wildfire emissions when comparing different forest management scenarios against each other (Hurteau et al., 2016; McCauley et al., 2019). This analysis would include forest carbon stock changes in the LCA (Figure 2, Figure 11);
- Compare results to forward looking grid electricity emission profiles by either comparing the torrefied wood electricity scenario with declining grid electricity emission profiles over time as anticipated with an increasing global shift to renewables (Macintosh et al., 2015; UK Committee on Climate Change, 2015);
- Results strongly indicate that any diversion of pulpwood away from traditional pulpwood markets and towards energetic use can result in significantly delayed climate benefits. In any case, using feedstocks that would be pile-burnt in the absence of a torrefied wood market is climate beneficial;
- Increasing efficiencies at the end user is a promising alternative to boost climate benefits of bioenergy systems. This can be achieved by shipping torrefied wood from John Day to combined heat and power plants rather than electricity-only plants.

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