Emissions tradeoffs associated with cofiring forest biomass with coal: A case study in Colorado, USA

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HIGHLIGHTS

- Case study using audited fuel consumption and emissions data from a coal mine and power plant.
- Model emissions tradeoffs of cofiring forest biomass with coal up to 20% by heat input value.
- Substituting forest biomass with coal displaces fossil energy with an otherwise waste material.
- Substantially less system emissions overall are generated when cofiring forest biomass.
- Cofiring forest biomass has positive global and local greenhouse gas and human health implications.

ARTICLE INFO

ABSTRACT

Cofiring forest biomass residues with coal to generate electricity is often cited for its potential to offset fossil fuels and reduce greenhouse gas emissions, but the extent to which cofiring achieves these objectives is highly dependent on case specific variables. This paper uses facility and forest specific data to examine emissions from cofiring forest biomass with coal ranging up to 20% substitution by heat value in southwest Colorado, USA. Calculations for net system emissions include five emissions sources: coal mining, power plant processes, forest biomass processes, boiler emissions, and forest biomass disposal. At the maximum displacement of 20% of heat demand using 120,717 t of forest biomass per year, total system emissions are projected to decrease by 15% for CO_2, 95% for CH_4, 18% for NO_X, 82% for PM_{10}, and 27% for SO_X. PM_{10} and CH_4 emissions benefits are closely tied to reducing open burning for residue disposal. At maximum displacement, 189,240 t of CO_2 emissions equivalent to the annual CO_2 emissions from 36,200 passenger vehicles, 440,000 barrels of oil, or nearly 990 railcars of coal are avoided. When forest biomass is not cofired, emissions equivalent to 144,200 t of CO_2 are emitted from open burning. In addition to exploring the details of this case, we provide a methodology for assessing the emissions tradeoffs related to using forest biomass for cogeneration that incorporates the operational aspects of managing forest treatment residues, which are frequently omitted from similar analyses.

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1. Introduction

Global atmospheric concentrations of CO_2 have increased approximately 40% from pre-industrial levels of 240 ppm to about 400 ppm today [1], with the scientific evidence isolating anthropogenic-sourced emissions from fossil fuel combustion as the primary cause [2–5]. Moreover, rigorous debate persists as to which kind of greenhouse gas (GHG) emissions should be characterized as anthropogenic-sourced GHGs, particularly concerning emissions from forest biomass used for bioenergy [6–12]. A number of

authors have identified the specific factors that impact the GHG mitigation potential of biomass fuels [13] and some have identified conditions under which biomass fuels may actually be more carbon positive than fossil fuels [14]. Other authors contend that emissions from forest biomass used for bioenergy are generally considered a renewable energy alternative to fossil fuels over long rotations if the harvested land remains as forest cover [15–17]. Currently, policies in many countries, especially in North America and Europe, promote the substitution of forest biomass for fossil fuels to help mitigate climate change associated with GHG emissions [18,19].

In the United States (US), half of all biomass energy is attributable to the forest sector and 61% of biomass electricity is generated from forest biomass [20,21]. Also in the US, Zerbe [22] forecasted that up to 10% of US energy requirements could eventually be

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met with forest biomass and Tilman et al. [23] determined that bioenergy from forests could substantially diminish dependence on fossil fuels. Most of the forest biomass currently used for energy is in the form of mill residues, and residues from logging operations including tree tops, limbs and unmerchantable round-wood. A significant quantity of logging residues (hereafter referred to as forest biomass) are generated annually in the US, yet most of this forest biomass is left onsite to decompose or is burned for disposal [20] to meet state laws for fire hazard reduction, and to open growing space for regeneration. US forest managers continue to search for alternatives to onsite open burning, which is especially prevalent in the interior western US where fire risk is high and markets for forest biomass are limited [24]. An abundance of time, energy, and financial resources have been devoted to researching and demonstrating value-added alternatives to onsite open burning, most notably removal of forest biomass for energy production at facilities close to the harvest site [25]. On a national scale, Gan and Smith [26] estimated that 13.9 million dry tonnes (t) of forest biomass could be used to generate 26 TW h of electricity annually.

For several decades cofiring woody biomass with coal has been evaluated as a near term and low cost option for generating electricity from biomass [27–29], and for reducing fossil fuel GHG emissions [29–35]. Nicholls and Zerbe [36] provide an overview of the status of cofiring in the US and note that cofiring biomass with coal is easily implemented and has the potential to utilize large volumes of biomass. Hughes and Tillman [32] summarize biomass and coal cofiring experiences through the late 1990s – the heyday of industrial cofiring experimentation in the US – and Harding [37] has comprised an extensive list of over 150 worldwide cofiring demonstrations. Additionally, the Electric Power Research Institute houses a significant library containing literature addressing many aspects of cofiring wood with coal [38].

Tillman [33] describes the combustion consequences of cofiring biomass with coal as primarily based upon each fuel's volatility, ash composition and reactivity, all of which are functions of fuel chemical and physical properties. Though published details of the kinetics and chemistry of co-combustion are limited [39,40], some studies have been conducted examining the chemistry of cofiring biomass with coal, and cofiring has been shown to have both advantages and problems compared to boilers fueled entirely with coal. Cofiring wood in coal power plants achieves higher efficiency for converting wood to electric power when compared to firing wood alone [29], and cofiring can result in reduced sulfur emissions [32,41]. Mixing wood with coal also reduces the temperature for initiation of pyrolysis, an indirect measure for the ease of ignition of the fuel blend [39]. Laursen and Grace [42] conducted bench scale experiments of cofiring coal with hog fuel and sludge from a paper mill to determine coal ignition properties and limestone requirements for sulfur emission suppression. Robinson et al. [27,30] conducted ash deposition experiments from cofiring a variety of biomass materials with different coals over a range of energy equivalency blends, and found that red oak has a lesser ash deposition rate than switch grass, wheat straw, and all the US coals examined. Robinson et al. [43] found that cofiring wood with high fouling coals mitigates some fouling difficulties, and Duong and Tillman [44] and Tillman [45] reviewed literature regarding the deposition and corrosion effects from varying chlorine contents of biomass materials and coals with the intention of identifying acceptable concentrations of chlorine to reduce corrosion.

In addition to evaluating the operational characteristics of biomass cofiring, several studies have examined the impacts of cofiring biomass with coal on emissions of CO_2 and other GHGs. Froese et al. [46] assessed the CO_2 emission mitigation potential of cofiring biomass with coal for electricity generation in the mid-western US and found that CO_2 stack emissions are reduced

and the fossil fuel energy requirements to produce a unit of electricity are lowered for cofiring than for coal alone. Similarly, Tillman et al. [34] found that cofiring sawdust with coal in a cyclone boiler directly reduces fossil CO_2 emissions by one tonne for each tonne of sawdust burned plus an additional 1.8 t of CO_2 equivalent emissions from avoided landfill emissions. Savolainen [47] measured reductions of CO_2, SO_2, and NO_X emissions when cofiring sawdust with coal in a combined heat and power pulverized coal boiler. Galik and Abt [48] analyzed woody biomass cofiring with coal as a baseline to quantify GHG emissions resulting from various scales of forest management that generate biomass for energy based upon demand for biomass under maximum cofiring capacity. Results generally show that larger management units generate greater emissions reduction benefits.

In this paper, we draw from previous cofiring research and use facility specific data collected from the electric power production and utility industries, and other sources, to model emissions from cofiring bituminous coal with forest biomass from forest restoration treatments. The objective is to quantify and understand the emissions tradeoffs of cofiring compared to open burning of forest biomass at the individual facility scale in the context of local forest management. While many aspects of cofiring wood have been evaluated, there is little research that compares the disposal of forest biomass by open burning to utilization for energy. The new information presented here will help individual forest managers and energy providers weigh the emissions tradeoffs of cofiring at local and regional scales. As forest managers consider options for using forest biomass from forest restoration treatments, emissions from utilization alternatives are an important aspect of the decision. Results are also intended to assist decision makers when evaluating renewable energy portfolios and policies, as many individual States in the US have proposed Climate Change Action Plans to reduce GHG emissions [49].

2. Study area

To study the tradeoffs associated with emissions from cofiring forest biomass, we focused on the Uncompahgre Plateau (UP) in the western US state of Colorado (Fig. 1) because silvicultural treatments in this area produce large volumes of forest biomass that could potentially be available for cofiring at a nearby power plant. The UP faces significant land management challenges related to severe effects from fire, insects, disease, and invasive species. Approximately 70% of the 607,000 hectares (ha) of the UP are at risk of high to mixed severity fire that would result in stand replacement, alter the current vegetation mosaics, and increase the risk of permanent physical changes due to direct effects to soils and water, as well as accelerated introduction of invasive species [50–52]. Ranging in elevation from 1400 to 3100 m, forests affected by these conditions include several distinct ecosystems. Ponderosa pine (*Pinus ponderosa*) and mixed conifer forests are the primary vegetation type where wildfire is likely to result in undesirable severe crown fires accompanied by high mortality in both understory and dominant trees [53,54]. In addition, many mature aspen (*Populus tremuloides*) stands are experiencing aspen decline with associated high mortality [55] and the pinyon-juniper (*Juniperus* spp., *Pinus edulis*, and *Pinus monophylla*) woodlands that dominate lower elevations are prone to severe fire compared to historical conditions [56]. Also, the spruce fir vegetation type (*Picea* spp. and *Abies* spp.) is experiencing heavy spruce budworm infestation with increasing mortality in infected stands [57,58], and widespread forest mortality is expected to result in uncharacteristically heavy surface fuels over the next several decades [59].

Management of insect, disease, and wildfire threats on these lands often requires restoration treatments to improve ecosystem
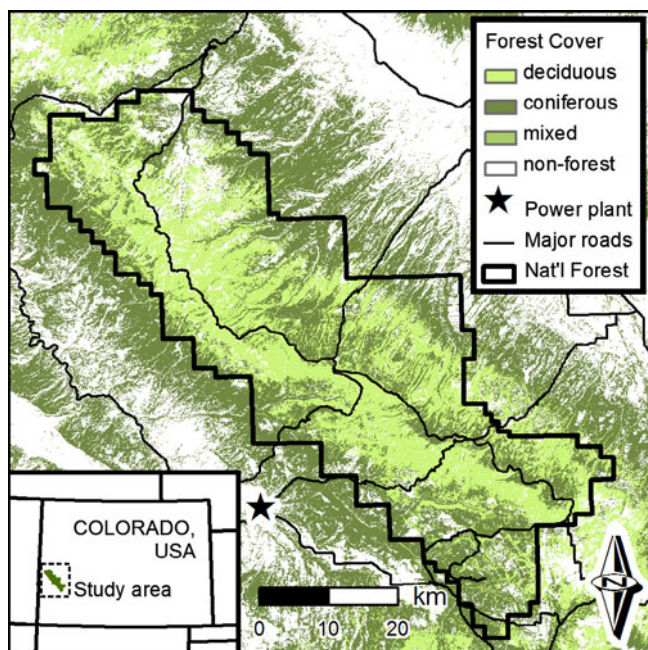
Fig. 1. The Uncompahgre Plateau region of southwest Colorado, USA.

resilience, protect watersheds, and improve forest and rangeland health. In 2010, the UP was selected as one of ten project areas in the US to receive supplemental funding from the US Forest Service under the Collaborative Forest Land Restoration Program, and over the next decade UP forest managers plan to use these funds to restore healthy forests and habitat conditions on 67,170 ha. In addition to merchantable timber, restoration treatments on the UP will generate large quantities of forest biomass from forest restoration and fuel reduction thinning, removal of invasive tree species, and salvage and sanitation cuts in beetle killed, diseased and burned stands. Currently, this material is open burned onsite for disposal to reduce fire risk and to open growing space for regeneration. However, using forest biomass to produce heat and electricity, instead of open burning, has the potential to reduce smoke from open burning and reduce GHG emissions by replacing fossil fuels with renewable forest biomass fuels, for which forests recover emissions over time [26,29,36,60,61]. The UP region does not currently have strong forest biomass markets and forest biomass utilization options are limited; however, the UP region does have large coal fired utilities, and cofiring forest biomass with coal is a potential option for forest biomass utilization.

Tri State Generation and Transmission Association operates a bituminous coal fired electric power plant with 100 MW generating capacity in southwest Colorado, adjacent to the UP (Fig. 1). In operation since 1987, the power plant was the world's first commercial circulating fluidized bed combustion system and currently operates as coal fire only, but can be configured to cofire forest biomass. The fluidized bed combustion technology is favorable to cofiring with wood because it is fuel flexible [33] and longer residence time allows for larger fuel particles to be used [62,63] with the possibility of some wood particles being up to 7.6 cm in size [64]. The power plant currently operates approximately 8000 h per year (h yr^{-1}) with total heat input of 58.6 gigajoules per hour (GJ h^{-1}). Boiler efficiency is estimated at 85% with 32.5% and 29.5% gross and net electricity delivery efficiency, respectively. The controllable operating conditions most related to successful cofiring are the fuel fire rate, limestone feed rate, and combustion air volume. Managers at the power plant are keenly interested in the potential costs and benefits of cofiring

forest biomass with coal in light of renewable energy portfolio standards recently implemented in Colorado.

3. Material and methods

As described by van Loo and Koppejan [65], there are three basic options for cofiring forest biomass with coal: direct cofiring in which forest biomass is fed directly into the coal firing system; indirect cofiring in which forest biomass is gasified and the product fuel is fired in the coal system; and parallel combustion in which forest biomass is combusted in a separate boiler. Consistent with the majority of cofiring operations worldwide [37], in this analysis we model power plant emissions from direct cofiring forest biomass with bituminous coal. We assume a cofiring operation in which the forest biomass is stored onsite at the power plant, delivered pneumatically to a grinding and metering system, and blended with the coal prior to entering the combustion system. While cofiring wood with coal at 10% by heat value is an understood blend when using separate feed injectors [29], Tillman [33] lists several utilities which have conducted tests of cofiring, almost all of which were blended by percent mass, with blends ranging up to 50% by mass. Furthermore, Mann and Spath [66] report a life cycle analysis of cofiring 5% by heat value by blending fuels, and 15% cofiring using separate feed injectors, and Harding [37] provides a list of cofiring demonstrations that have cofired wood with coal as high as 50% by heat value. To facilitate comparison with practical substitution levels explored in previous research, in this analysis we estimate selected emissions associated with substitution levels ranging from 0% to 20% by heat value.

3.1. Fuel Calculations

In this analysis estimates of the mass of forest biomass required to achieve appropriate levels of heat substitution are based on the higher heating values (HHV) of bituminous coal and forest biomass. The HHV of the coal to be offset is divided by the HHV of forest biomass in gigajoules per tonne (GJ t^{-1}) to determine the mass of forest biomass needed for substitution. HHV is a commonly used metric for energy calculations in the US [67], and does not reflect varying boiler efficiencies or energy delivery technologies. In previous research, Tillman et al. [63] identify fuel properties and cofiring characteristics of different forest biomasses and coals, Tillman [33] and Hughes [29] describe resulting boiler efficiency changes from cofiring forest biomass with coal, and Tillman et al. [68] identify additional cofiring characteristics in both wood and coal. Furthermore, Ince [69] presents a method to estimate recoverable heat values (RHV) from wood used in boilers as a function of HHV, wood moisture content, conventional heat loss, and stack gas heat loss. Calculating substitution based on HHV as opposed to RHV is intended to allow for adjustments at any rate based upon these types of parameters.

In 2009, total coal burned at the power plant was 336,524 t, which is slightly less than the amount produced by the mine. The approximate 1% difference is due to the plant's secondary crusher and rock ejector, which inevitably removes coal from the feed system along with undesirable materials such as rock. The HHV of the bituminous coal was provided by power plant personnel and is 24.6 GJ t^{-1}; however, coal fuel properties, including HHV, are variable and present noted operational challenges that undoubtedly affect boiler efficiency and measured or estimated emissions on daily or seasonal bases. Thus, as discussed below, our application of total annual emissions captures discrete operating variations for year 2009.

Almost all of the forest biomass produced by restoration treatments on the UP is from coniferous species and aspen. Due to the

occurrence of ponderosa pine on the UP and its examination in previous studies, for this analysis forest biomass cofired is assumed to be operationally equivalent to ponderosa pine at 35% moisture content with a HHV of 13.7 GJ t^{-1} [70]. Though the UP is semi-arid and receives relatively low annual precipitation, snowfall or seasonal rainfall greater than 25 mm per month, particularly in autumn, will likely increase the moisture content of forest biomass at certain times of the year. Thus, seasonal variation in forest biomass moisture content is likely to result in variable boiler efficiency and associated emissions, with higher moisture content resulting in lower combustion efficiency. As noted with bituminous coal, estimating annualized emissions is expected to capture significant variation from the daily and seasonal operational challenges associated with cofiring forest biomass. However, our 35% threshold is above the moisture content that can be expected with proper drying in the field. We determined that up to 120,718 t of forest biomass could be cofired at 20% by heat value replacement. Proximate and ultimate analyses of bituminous coal and ponderosa pine representative of the fuels modeled in this analysis are provided in Table 1.

3.2. Emissions calculations

In this analysis the system boundary encompasses the coal mine, the power plant, and the forest supplying forest biomass. Stack emissions are generated by combustion of forest biomass and coal in the boiler, and process emissions (described as "external energy" by Spath and Mann [71]) are generated by the processes that provide fuel to the boiler and keep the plant running. Process emissions include mining and transporting the coal to the power plant, as well as emissions from harvesting, chipping and transporting the forest biomass to the power plant. Open burning emissions are produced when forest biomass is not cofired, and is burned onsite in the forest for disposal. To estimate total cofiring system emissions, emissions of carbon dioxide (CO_2), methane (CH_4), particulate matter (PM_{10}), nitrous oxides (NO_X), and sulfur oxides (SO_X) from five distinct sources are quantified:

(1) *Mining emissions*. Emissions from all fossil fuels consumed at the mine that exclusively supplies bituminous coal to the power plant. These include emissions from both the facilities and equipment (i.e. trucks, forklifts, etc.) used to mine and transport the coal to the power plant.
(2) *Power plant process emissions*. Emissions from all fossil fuels consumed at the power plant, not including boiler emissions. These include emissions from both facilities and equipment used to operate the power plant.
(3) *Forest biomass process emissions*. Emissions from all fossil fuels consumed by harvesting, chipping, and transporting forest biomass to the power plant.

(4) *Boiler emissions*. Emissions from combustion of coal and forest biomass in the boiler. Boiler emissions are divided into boiler emissions from forest biomass and boiler emissions from coal.
(5) *Forest biomass open burning emissions*. Emissions from open burning the forest biomass onsite in the forest for disposal.

Other than emissions from open burning forest biomass and coal boiler emissions, emission factors for all other fuel sources were obtained from the US Environmental Protection Agency (EPA) [72]. EPA emission factors are recommended for use in the US Voluntary Reporting of Greenhouse Gases Program, as established in the US Energy Policy Act of 1992. EPA emissions factors are used for "developing emission control strategies, determining applicability of permitting and control programs, ascertaining the effects of sources and appropriate mitigation strategies, and a number of other related applications by an array of users, including federal, state, and local agencies, consultants, and industry" [72]. EPA's general equation for emission estimates is:

$$E = A * EF * ((1 - ER)/100) \tag{1}$$

where E equals emissions, A equals activity rate, EF equals the emission factor, and ER equals the emission reduction efficiency. While emissions estimates from individual facilities are appropriate when available, the use of nationally derived forest biomass boiler emissions factors in this analysis establishes a methodology that allows for application of the results across many potential cofiring entities, and compliments the coal emissions factors obtained from the power plant.

3.2.1. Mining emissions

The coal burned at the power plant is supplied exclusively by a single surface mine located 10.5 kilometers (km) away. Unlike the national convention in which coal is transported long distances by rail [73], the coal is transported from the mine to the power plant in trucks with a maximum payload of 22.7 t. Approximately 70 truckloads per day are transported to the power plant. Mining activities include uncovering, mining, preparing, cleaning, and transporting coal, as well as mine site reclamation. The mine has been in operation since 1993 and approximately 10 ha yr^{-1} are uncovered, mined, and reclaimed. Total coal produced at the mine in 2009 was 339,074 t (Table 2); however, as discussed below, the power plant consumes slightly less than the amount of coal mined.

Total fossil energy consumed while mining was provided by the mine manager following an internal review of the mine's utility and fuel bills. Fossil energy sources consumed are diesel fuel for mining, mine reclamation, loading and transporting coal; natural gas for heating mine facilities; and electricity for powering offices, shops, and irrigation pumps (Table 2). We further determined that the energy portfolio of the company that supplies electricity to the mine is approximately 76% coal, with the remainder comprised of renewable and purchased power from undetermined sources;

Table 1
Proximate and ultimate analyses of bituminous coal and forest biomass.

	Bituminous coal	Forest biomass
Proximate analysis (% wt) (dry)		
Ash	28.15	1.07
Volatile matter	27.84	84.58
Fixed carbon	44.01	14.35
Ultimate analysis (% wt) (dry)		
Carbon	58.84	52.95
Hydrogen	4.48	5.93
Oxygen	6.66	39.85
Nitrogen	0.94	0.20
Sulfur	0.93	<0.01

Table 2
Coal and other fossil fuels consumed at the mine and power plant in 2009.

Fuel	Units	Bituminous coal mine	Coal fired power plant
Bituminous coal[a]	t	339,074	336,524
Diesel fuel (on-site)	l	1,734,310	58,830
Diesel fuel (haul)	l	268,788	–
Gasoline fuel	l	–	1124
Natural gas	GJ	205	–
Propane	l	–	1,373,970
Electricity	GJ	463	44–52

[a] The difference between coal mined and coal burned is due to coal lost during cleaning at the power plant using a secondary crusher and rock ejector.

therefore, 76% of the mine's electricity consumption are converted to coal emissions. Emission factors for the fuels consumed at the coal mine are listed in Table 3, as are references to the sources of the emission factors. Table 4 displays total coal energy and quantities required for incremental levels of forest biomass substitution.

3.2.2. Power plant process emissions

The power plant generates emissions from two general sources: emissions from fossil energy used to operate the plant and emissions from burning coal to produce electricity. Total fossil energy consumed at the power plant for operation was provided by the plant manager following an internal review of the plant's utility and fuel bills. Fossil energy sources consumed are diesel fuel for rolling stock (i.e. vehicles and mobile equipment), coal crushing, rock separation, and rejected rock transportation; gasoline for trucks and forklifts; and propane for startup fuel, auxiliary heating, and limestone drying (Table 2). Additionally, the power plant consumes approximately 11–13 MW of electricity that is generated onsite; thus, emissions from the power plant's electricity consumption are captured by the stack emissions discussed below. Table 4 displays the total process energy in the fossil fuels required to produce quantities of coal for incremental levels of forest biomass substitution.

3.2.3. Forest biomass process emissions

Forest biomass process emissions include emissions from diesel engines used in the equipment for harvesting, chipping, and transporting forest biomass to the power plant. Diesel fuel requirements to harvest forest biomass using a feller buncher, skidder, and loader are found in Pan et al. [70] and estimates for chipping forest biomass are derived from the Forest Residue Trucking Simulator [74]. Diesel fuel used to harvest, skid and load forest biomass was estimated at 4.12 liters (l) t^{-1}, and diesel fuel required to chip the forest biomass was estimated at 1.36 l t^{-1}, at 35% moisture content. Diesel fuel used to transport processed forest biomass to the power plant is based on the average road transportation distance within the UP, which was calculated using spatial analysis

of the public road network including gated forest roads in the Uncompahgre National Forest. Spatial analysis was performed using ESRI's ArcGIS 10.0 and determined that the average transportation distance for 2085 forest biomass origination points (i.e. landings and roadside locations) to the power plant is 116.5 round trip km. Assuming a chip van with a forest biomass payload of 22.7 t [75], a 1.98 km l^{-1} fuel consumption rate reflecting low average speed from the UP to the power [76], and an average round trip transportation distance of 116.5 km, diesel fuel consumption for transporting forest biomass is estimated at 2.59 l t^{-1} at 35% moisture content.

Diesel fuel emissions for harvesting, chipping and transporting the forest biomass were derived by applying emission factors from US EPA [72], and energy contents from US EIA [77] to the quantities of diesel estimated. Table 4 displays total forest biomass energy and quantities, and total process energy in the fossil fuels required to produce forest biomass for incremental levels of substitution. Table 5 displays forest biomass quantities and diesel fuel consumed to harvest, chip, and transport the forest biomass for cofiring with coal at these levels.

3.2.4. Boiler emissions

Emissions from cofiring were estimated using a combination of measured stack emissions provided by power plant personnel, emission factors from forest biomass boilers obtained from US EPA [72] and wood energy content from Pan et al. [70]. Power plant personnel provided 2009 total measured stack emissions from firing coal for CO_2, PM_{10}, NO_X, and SO_X; CH_4 emissions from firing coal were estimated using [72] (Table 3). Emissions calculated for the boiler account for emissions control technologies in place at the power plant. The boiler is a low temperature, atmospheric circulating fluidized bed combustion boiler that provides greater than 78% capture of sulfur dioxide emissions and reduces the formation of nitrogen dioxide compared to other types of boilers [78]. Emissions control devices also include limestone that is introduced to the boiler, which further controls sulfur emissions, and a selective noncatalytic reduction control method to further limit formation of NO_X.

Table 3
Emission factors used to determine power plant stack emissions from cofiring forest biomass with coal.

Fuel	Units	CO_2	CH_4	NO_X	PM_{10}	SO_X	Refs.
Bituminous coal[a]	kg t^{-1}	2252.97	0.03	4.36	0.10	3.16	[72,78]
Forest biomass–boiler	kg t^{-1}	1149.65	0.12	1.29	0.44	0.15	[70,72]
Forest biomass–open burn	kg t^{-1}	1010.73	3.52	1.95	3.83	1.18	[50,79,80]
Diesel fuel	kg l^{-1}	2.73	0.0	0.07	0.01	0.01	[72,77]
Gasoline fuel	kg l^{-1}	2.29	0.0	0.02	0.0	0.0	[72,77]
Natural Gas	kg GJ^{-1}	50.86	0.0009	0.0009	0.0035	0.00	[72]
Propane	g l^{-1}	1497.99	0.02	1.56	0.08	0.01	[72]
Electricity[b]	kg GJ^{-1}	100.62	0.0	0.09	0.22	0.48	[72,78,90]

[a] Emission factors derived from total 2009 emissions and coal consumption provided by the power plant. Methane emissions are not measured by the power plant and are estimated using EPA (1995).
[b] 76% Of the electricity consumed at the mine is produced from coal; therefore 76% of electricity is converted to coal emission factors.

Table 4
Forest biomass and coal quantities and energy, and process energy at varying levels of cofiring.

Forest biomass cofire (%)	Coal (t)	Total coal energy (GJ)	Total coal process energy (GJ)	Forest biomass (t)	Total forest biomass energy (GJ)	Total forest biomass process energy (GJ)
0	336,524.0	8,270,011.2	115,409.0	0.0	0.0	0.0
5	319,697.8	7,856,510.6	109,638.5	30,179.5	413,500.6	9,408.9
10	302,871.6	7,443,010.0	103,868.1	60,358.9	827,001.1	18,817.8
15	286,045.4	7,029,509.5	98,097.6	90,538.4	1,240,501.7	28,226.6
20	269,219.2	6,616,008.9	92,327.2	120,717.8	1,654,002.2	37,635.5

Table 5
Forest biomass fuel and associated diesel fuel consumed for forest biomass production for incremental cofiring levels.

Forest biomass cofire (%)	Forest biomass (t)	Diesel fuel (l)		
		Feller, skidder, loader	Chipper	Transportation
0	0.0	0.0	0.0	0.0
5	30,179.5	124,403.1	40,922.1	78,066.7
10	60,358.9	248,806.2	81,844.1	156,133.4
15	90,538.4	373,209.2	122,766.2	234,200.1
20	120,717.8	497,612.3	163,688.3	312,266.8

The limestone is 62.47% $CaCO_3$, 1.28% $MgCO_3$, 35.92% acid insoluble matter, 0.20% free moisture, and is fed into the boiler at an average rate of 3,230 kg h^{-1}. The facility also has a fabric filter baghouse that collects 90% of all particulates. The forest biomass emission factor for PM_{10} during cofiring assumes the same control device currently in place at the power plant. Table 3 displays forest biomass emission factors for cofiring with coal as 'Forest biomass – boiler.'

3.2.5. Forest biomass open burning emissions

Restoration treatments on the UP will generate large quantities of forest biomass which are most often open burned onsite for disposal, and Jones et al. [61] showed that higher emissions of CH_4 and PM_{10} are generated from open burning forest biomass than if the forest biomass is processed and transported to a boiler. At all levels of cofiring, the balance of forest biomass that is not burned in the boiler, up to the equivalent mass of 20% by heat value, is assumed to be open burned onsite for disposal and the associated emissions are included in total system emissions. In our accounting, we include the emissions from open burning up to the maximum value of 120,717 t, which is the total amount of forest biomass open burned for disposal in the 0% forest biomass cofire scenario. CO_2, CH_4, and PM_{10} emissions from open burning forest biomass are derived from Hardy et al. [50], and NO_X and SO_X emissions are derived from Urbanski [79] and Yokelson et al. [80] (Table 3). In calculating emissions associated with open burning, 5% of the mass of forest biomass is assumed to be incompletely combusted and left onsite in the form of charcoal and unburned wood.

3.3. Fixed versus variable fuel requirements and emissions

Process emissions at the mine, power plant and forest biomass harvest site include both fixed and variable emissions which are partitioned appropriately at all levels of substitution, depending on the mix of coal and forest biomass. Under the 0% forest biomass cofire scenario, emissions estimates are based upon total fossil fuels consumed by the mine and power plant. When forest biomass is cofired, fossil fuel emissions from the fixed energy requirements at the power plant (e.g. electricity for offices and shops, and natural gas for heat) remain the same, but the variable energy requirements associated with coal are adjusted downward to account for reduction in coal production and use in cofiring scenarios. All fossil energy requirements and associated emissions for forest biomass are considered variable, and are directly related to the quantity of forest biomass harvested, chipped and transported for cofiring.

4. Results

Table 4 displays the amount of energy produced from forest biomass and coal for incremental levels of cofiring, all of which achieve the power plant's total 2009 heat input of 8.27 million GJ. Table 4 also shows the mass of forest biomass and coal that corresponds with total heat input values, and the process fuel energy requirements for the coal and forest biomass. Logically, when substituting forest biomass for coal, fossil fuel requirements to achieve maximum power plant energy output are reduced. Forest biomass heat input directly displaces coal heat input; however, more than 1 t of forest biomass is required to displace 1 t of coal. This is because at 35% moisture content, 1 t of forest biomass has approximately 55% of the energy content of 1 t of coal. In 2009 slightly more than 336,500 t of coal was burned at the power plant to produce 8.27 million GJ of energy. Cofiring coal with 10% forest biomass would require 60,350 t of forest biomass to yield the equivalent gross heat contained in the nearly 33,700 t of coal displaced. Of the total heat requirement at the 10% level, coal contributes 7.44 million GJ while forest biomass contributes 0.83 GJ. While the forest biomass process energy requirement is 10% less than the coal process energy requirement on a mass basis, on an energy basis the forest biomass process energy requirement is approximately 40% greater than the coal process energy requirement. However, at the 20% substitution level the total forest biomass process energy required to produce 120,700 t of forest biomass, which substitutes for 67,300 t of coal, represents approximately 2% of total fossil energy in the displaced coal (Table 4).

Using the total fuel consumptions displayed in Tables 2 and 5, and the emission factors displayed in Table 3, we compared emissions associated with alternative levels of cofiring forest biomass with coal ranging from 0% to 20% by heat value. Table 6 displays results for incremental cofiring percentages. Emissions estimates for all five types of emissions are significantly less when forest biomass is cofired with coal, rather than open burned onsite for disposal. For example, when 10% of the coal demand is displaced with forest biomass, total system CO_2 emissions decrease by 8%, CH_4 emissions are decreased by 47%, NO_X emissions are decreased by 9%, PM_{10} emissions are decreased by 41%, and SO_X emissions are decreased by 14%. The 10% threshold is notable because it is considered the level of substitution that can be made without significant changes in boiler operation and performance compared to coal only operation [27].

This trend holds across the range of forest biomass substitution from 0% to 20%. Table 6 displays values for emissions associated with cofiring forest biomass with coal at 5% increments and Figs. 2–6 displays emissions tradeoffs across the entire cofiring range. When forest biomass is substituted for coal, total system emissions decrease. At the maximum displacement of 20%, total system CO_2 emissions decrease by 15%, CH_4 emissions decrease by 95%, NO_X emissions decrease by 18%, PM_{10} emissions decrease by 82%, and SO_X emissions decrease by 27%. Although cofiring 20% forest biomass in the power plant generates more forest biomass CO_2 than would have been produced by open burning due to more complete combustion, the displacement of coal results in a net decrease in total system CO_2 emissions. CH_4 emissions from forest biomass and coal production are not included in Fig. 3 because modern diesel engines used in equipment to harvest, grind and transport forest biomass, and mine and transport coal, produce very low CH_4 emissions (Table 3).

Of the emissions analyzed here, CO_2 and CH_4 are notable GHGs and significant reductions of these emissions are realized through the avoidance of open burning. This is important because GHGs

Table 6
System component and total emissions from cofiring forest biomass with coal at incremental levels.

| Forest biomass cofire (%)	System component	CO$_2$	CH$_4$	NO$_X$	PM$_{10}$	SO$_X$
		t				
0	Coal	835,067.8	11.1	1,616.0	37.2	1,171.0
	Mine & power plant process	8,529.6	0.0	169.0	12.0	11.2
	Forest biomass	0.0	0.0	0.0	0.0	0.0
	Forest biomass process	0.0	0.0	0.0	0.0	0.0
	Open burn	134,386.6	468.4	258.8	509.4	156.4
	Total	977,984.0	479.5	2,043.8	558.6	1,338.6
5	Coal	793,314.4	10.6	1,535.2	35.3	1,112.5
	Mine & power plant process	8,106.3	0.0	160.6	11.4	10.7
	Forest biomass	38,214.5	4.1	42.9	14.5	4.9
	Forest biomass process	731.3	0.0	19.7	1.4	1.3
	Open burn	100,789.9	351.3	194.1	382.1	117.3
	Total	941,156.4	366.0	1,952.5	444.7	1,246.6
10	Coal	751,561.0	10.0	1,454.4	33.5	1,053.9
	Mine & power plant process	7,683.0	0.0	152.1	10.8	10.1
	Forest biomass	76,429.0	8.2	85.9	29.0	9.8
	Forest biomass process	1,462.6	0.0	39.3	2.8	2.6
	Open burn	67,193.3	234.2	129.4	254.7	78.2
	Total	904,328.9	252.5	1,861.2	330.7	1,154.6
15	Coal	709,807.6	9.5	1,373.6	31.6	995.4
	Mine & power plant process	7,259.6	0.0	143.7	10.2	9.6
	Forest biomass	114,643.5	12.3	128.8	43.5	14.7
	Forest biomass process	2,193.9	0.0	59.0	4.1	3.9
	Open burn	33,596.6	117.1	64.7	127.4	39.1
	Total	867,501.3	138.9	1,769.8	216.8	1,062.6
20	Coal	668,054.2	8.9	1,292.8	29.8	936.8
	Mine & power plant process	6,836.3	0.0	135.2	9.6	9.0
	Forest biomass	152,858.0	16.5	171.8	58.0	19.6
	Forest biomass process	2,925.2	0.0	78.7	5.5	5.2
	Open burn	0.0	0.0	0.0	0.0	0.0
	Total	830,673.7	25.4	1,678.5	102.9	970.6
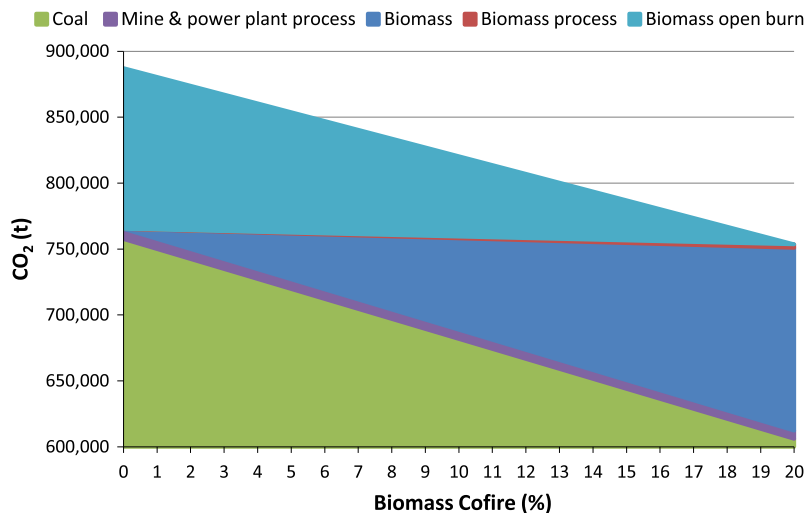
Fig. 2. CO$_2$ emissions from cofiring by source across the range of substitution.

have different global warming potentials and atmospheric lifetimes, and the impacts of increasing GHGs are not just a local phenomenon, but are evaluated on a global scale. CH$_4$ has 21 times the global warming potential of CO$_2$ and resides in the atmosphere for approximately 12 years [81]. Consequently, the overall reductions of these emissions are especially significant. Table 7 displays the CO$_2$ equivalent (CO$_2$e) of the GHGs CO$_2$ and CH$_4$ calculated from the global warming potential of these gases. At maximum displacement, 189,240 t of CO$_2$e emissions are avoided, 97% of which is

from the coal fuel. For reference, 189,240 t of CO$_2$ is equivalent to the annual CO$_2$ emissions from 36,200 passenger vehicles, 440,000 barrels of oil, or nearly 990 railcars of coal. When forest biomass is not cofired, 144,200 t of CO$_2$e are emitted from open burning.

Furthermore, PM$_{10}$, SO$_X$ and NO$_2$ (a species contained in NO$_X$ estimates) emissions have the greatest impacts relatively close to the emissions source. The reduction of point source PM$_{10}$ and SO$_X$ from cofiring are important at the local scale because these
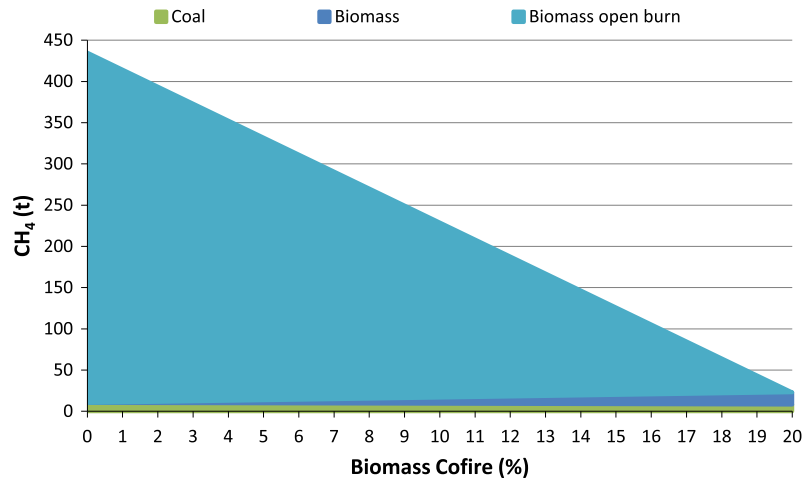
Fig. 3. CH_4 emissions from cofiring by source across the range of substitution. Biomass process and mine and power plant process emissions not included due to the extremely small amount emitted.
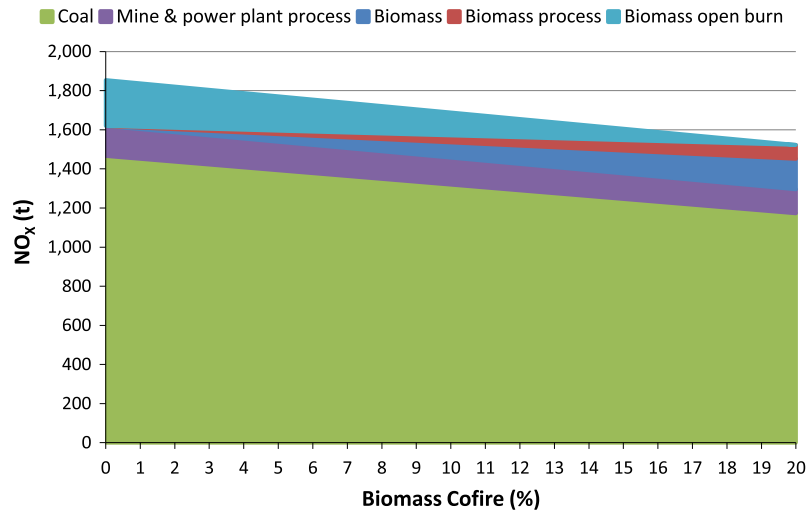

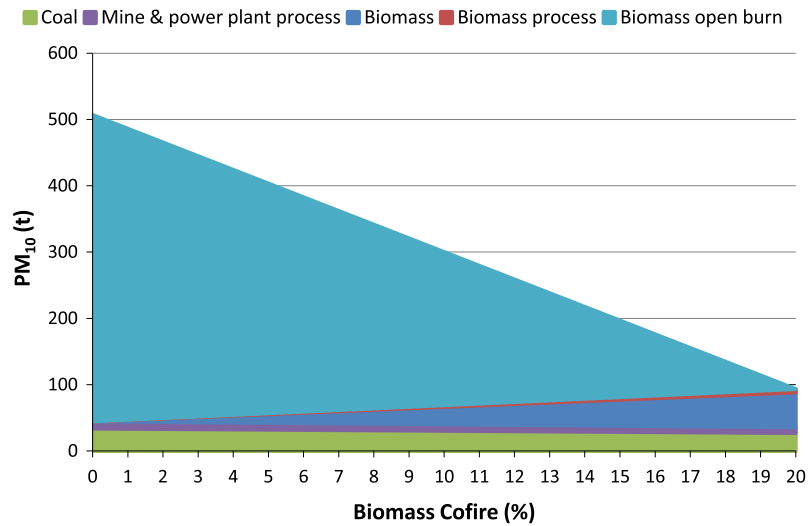**Fig. 4.** NO_X emissions from cofiring by source across the range of substitution.

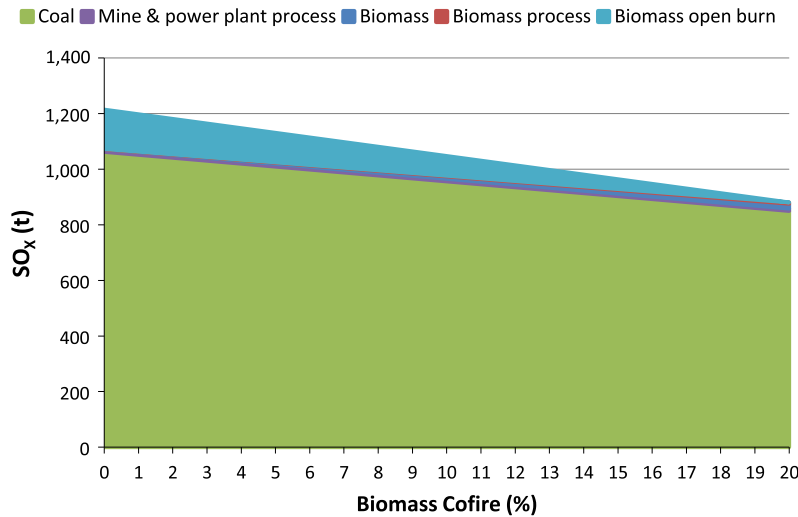**Fig. 5.** PM_{10} emissions from cofiring by source across the range of substitution.

Fig. 6. SO_X emissions from cofiring by source across the range of substitution.

Table 7
System component, total and avoided fossil CO_2 equivalents (CO_2e) at incremental levels of cofiring.

Forest biomass cofire (%)	Coal	Mine and power plant process	Forest biomass process	System total[a]	Avoided fossil
	CO_2e (t)				
0	920,746.8	9,403.0	0.0	930,149.8	0.0
5	874,709.5	8,936.3	806.1	926,670.7	47,310.1
10	828,672.1	8,469.6	1,612.2	923,191.6	94,620.3
15	782,634.8	8,002.9	2,418.3	919,712.5	141,930.4
20	736,597.4	7,536.2	3,224.4	916,233.4	189,240.6

[a] System total includes CO_2 equivalents from forest biomass fuel.

emissions have been clearly linked to adverse human health and environmental effects [82–84]. For PM_{10}, emissions avoided from open burning forest biomass are far greater than total emissions from cofiring forest biomass with coal (Fig. 5). At 20% forest biomass cofire, NO_X and SO_X emissions avoided from open burning forest biomass are less than avoided coal emissions (Figs. 4 and 6). Consequently, not only are NO_2 and SO_X emissions from open burning avoided, but total system emissions are lower as well. The reduction of PM_{10} and SO_X is primarily attributable to emissions controls at the power plant and the avoidance of open burning forest biomass all but eliminates the adverse impacts on local airsheds associated with PM_{10}, NO_2, SO_X emissions.

5. Discussion

In this analysis we provide estimates of CO_2, CH_4, NO_X, SO_X, and PM_{10} emissions resulting from cofiring forest biomass with coal up to 20% substitution by heat value. Results show that overall system emissions are decreased when forest biomass is burned in a controlled boiler setting and offsets fossil coal. Emissions reductions represent benefits that may support forest biomass utilization in some areas, and in previous efforts that evaluated emissions from using forest biomass for energy, several system component emissions were overlooked or misunderstood, notably emissions from open burning forest biomass and emissions associated with forest operations equipment. In many parts of the world, the current practice for handling forest biomass from silvicultural treatments is to burn in place as a site preparation to open growing space for regeneration and reduce fire risk. When this is the case, it is critically important to include emissions from open burning when evaluating tradeoffs between current practices and alternative utilization options for the forest biomass that would otherwise be burned in place for disposal.

Though research efforts have characterized forest biomass energy as expediting a near term increase in levels of atmospheric carbon, this is due primarily to indirect land use change [8–12,85,86]. However, an empirical worldwide evaluation of land use patterns and commodity grain imports by Kim and Dale [87] found that biofuel production in the US through 2007 has not, in all probability, induced indirect land use change. Fargione et al. [12] also note that indirect land use change is not likely to occur when biofuels are produced from waste forest biomass, including residues from forest restoration operations. For National Forests in the US, including the UP, land use change, especially for development and agriculture, is highly unlikely. In this context, this work shows that cofiring may have significant emissions benefits to both local airsheds and global atmospheric GHG emissions.

Furthermore, US Forest Service land managers operate under a range of directives that require them to consider climate change adaptation and mediation in their management activities and forest biomass utilization for bioenergy would help meet these objectives. Stack emissions from forest biomass harvested from forests that remain in forested land use over long rotations can be generally characterized as recycling carbon between the atmosphere and biosphere (i.e. repetitive solid to gas recycling). In contrast, emissions from fossil fuels release permanently sequestered carbon into the atmosphere. As Lemus and Lal [88] and Obersteiner et al. [89] note, until more permanent atmospheric carbon reduction solutions are identified, reducing atmospheric carbon emissions is best addressed by substituting forest biomass for fossil fuels and thereby leaving carbon sequestered in materials outside the biosphere.

Although there are many aspects of forest biomass utilization that forest managers and power companies must consider, cofiring

in this case appears to have significant emissions benefits. Specifically on the UP, there appears to be a good opportunity for forest biomass utilization because Collaborative Forest Land Restoration Project treatments on 64,750 ha are expected to generate significant quantities of forest biomass over the next decade. However, we have not yet incorporated other important utilization aspects into our analysis, such as determining the financial feasibility of utilization and the potential impacts that renewable portfolio standards, subsidies, nonmarket economic impacts, carbon credit markets, long term fuel supply agreements, and forest level management decisions can have on the feasibility of cofiring and the benefits identified in this study. For example, the power plant's proximity to the UP requires short haul distances leading to favorable transportation logistics, but many other variables will impact supply and costs in this case. In cooperation with a broad group of stakeholders, the authors are currently engaged in a number of ongoing projects to provide integrated economic analysis that will assist these stakeholders in making decisions about options for forest biomass utilization, including cofiring and other bioenergy applications.

6. Conclusions

Forest restoration treatments that produce forest biomass as a byproduct are generally prescribed to meet a broad range of objectives including managing insects, disease, and fire risk to improve ecosystem resilience, protect watersheds, and improve forest and rangeland health. In this study we have demonstrated that because open burning of forest biomass contributes significant quantities of emissions to the atmosphere, these emissions can be reduced when the forest biomass is cofired with coal under controlled combustion conditions in a boiler. In the case of methane, a notably abundant and powerful GHG, emissions are almost entirely avoided. In addition, emissions from fossil coal are offset, reducing total system emissions and perpetuating permanent sequestration of fossil carbon. We further demonstrate that while all component emissions are relevant, emissions resulting from diesel fuel associated with forest biomass production are rather small relative to total system emissions. In considering emissions tradeoffs with biomass utilization, it is important to consider the fate of biomass associated with forest management, in addition to stack and process emissions.

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