Using Closed-loop Biomass to Displace Coal at Portland General Electric's Boardman Power Plant Carbon Implications

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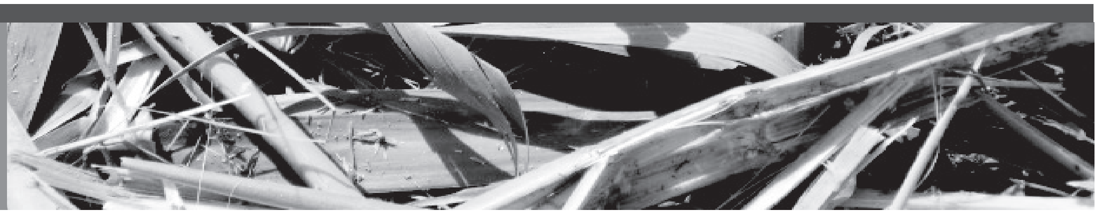

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Using Closed-Loop Biomass to Displace Coal at Portland General Electric's Boardman Power Plant: Carbon Implications

Executive Summary

Portland General Electric will cease burning coal at its Boardman, Oregon power plant at the end of 2020, at least twenty years earlier than previously expected under PGE's projected resource plans. A variety of biomass options are being researched as possible replacement fuel sources, including the high-yield biomass crop *Arundo donax,* which has the potential to serve as a significant source of locally-accessible, closed-loop biomass to power the Boardman facility after 2020. Using torrefied biomass to generate electricity would qualify Boardman for consideration as a renewable energy source under Oregon's Renewable Portfolio Standard. PGE would have the benefit of a qualified renewable energy source capable of supplying 2.6 million MWh of dispatchable baseload energy annually. In addition, repurposing the facility would allow the rural community where the Boardman facility is located to continue to receive the substantial employment and tax benefits associated with continued operation.

This study focuses on the carbon implications that accompany this fuel transition, examining in detail the impact of using torrefied *Arundo* for this purpose. It is important to note that, because of concerns surrounding reliability of supply, PGE engineers do not expect to rely on a single source of biomass if a decision is made to proceed with the fuel conversion. Potential energy crops are attractive because they would be dedicated to producing the volume of material needed, but reliance on a single energy crop could actually put reliability at risk in the event that natural occurrences – such as unseasonable weather, storms, or pests – interfered with predictable production. This study, however, focuses primarily on one potential crop. As such, it addresses one component of what would likely be a much broader biomass fuel mix. For research purposes this single component is treated as if it would supply all of the facility's fuel, understanding that in context this simplifies the task of understanding the impact and potential benefits of using *Arundo* at Boardman.

Currently, the Boardman facility uses over 2.5 million tons of coal to generate 4.3 million MWh of electricity annually, resulting in a net production of 4.6 million tons of CO_2e. In converting to a bio-mass fuel, particularly torrefied *Arundo*, a near closed-loop carbon cycle could be established, whereby the emissions from farming, transport, torrefaction and combustion balance against the above- and below-ground sequestration associated with growing *Arundo*, thereby resulting in net positive carbon sequestration.

Under this biomass scenario, it is envisioned that the Boardman facility would be run at an annualized 300 MW (2.6 million MWh per year), generating energy only when it is economically beneficial to PGE ratepayers to do so. Combustion of 100% *Arundo* to provide 2.6 million MWh of electricity will produce roughly 2.8 million tons of CO_2e. We project that torrefaction of *Arundo* will produce an additional 1.22

million tons of CO_2e annually, while farming of *Arundo* will contribute a small amount, 31 thousand tons. Transportation contributions are even smaller. Combined, the farming, transport, torrefaction and combustion will result in the emission of around 4.05 million tons of CO_2e annually. Concurrently, our study suggests the mature farming of *Arundo* would result in the sequestration of around 4.34 million tons annually, resulting in an annual net sequestration of around 0.29 million tons.

Part I: Carbon Assessment Factors

Introduction and Context

Portland General Electric (PGE) will cease burning coal at its 600 MW power plant in Boardman Oregon at the end of 2020, at least 20 years ahead of earlier projections (Figure 1). The fate of the power plant for continued use past that date could rest on the use of torrefied biomass. The use of biomass for power generation requires many critical items to be in place. First is the need for high-producing biomass sources that could meet the needs of the existing power plant. A 600 MW power plant would require large volumes of biomass, and thus potentially large acreages of dedicated biomass crops. High-yield biomass crops such as *Arundo donax* are attractive for their potential to serve as a significant source of locally-accessible biomass for a power plant of Boardman's scale, in addition to other potential closed-loop sources that could be part of the plant's fuel mix such as agricultural residues.

Coal Consumption – Boardman Power Plant

The Powder River Basin (PRB) in Wyoming is the main source of coal delivered to the Boardman power plant. At the plant, the coal is pulverized and combusted to generate electricity. The Boardman plant uses a steam turbine generator with an overall heat rate of 9,911 Btu/kWh; the heat rate represents the overall generation efficiency of the plant.[1] In 2007, over 43 trillion BTU were delivered to Boardman and used to generate around 4.3 million MWh of electricity.[2] All operations within the plant that have energy requirements, such as pulverization of coal, factor into the overall heat rate.

Powder River Basin Coal

The PRB is one of the largest coal producing areas in the United States. The Boardman power plant, the only coal-fired plant in Oregon, is supplied by coal from multiple mines within the PRB. Coal from the PRB is a low-sulfur, sub-bituminous variety. PRB coal tends to have a heat content of around 7,800-8,800 Btu/lb, a moisture content of around 20-30% and an ash content of around 5-11% wt.[3,4] Much of the coal in the PRB is close enough to the surface that surface mining operations are used to remove the coal.

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[1] Efficiency may alternatively be represented as 34.4%. See Appendix B - Calculation Examples, Boardman Efficiency

[2] Appendix B - Calculation Examples, MWh w/ coal

[3] University of Wyoming Natural Science Program website, "Coal Mines of the Powder River Basin," www.wsgs.uwyo.edu/coalweb/WyomingCoal/mines.aspx

[4] Clyde Bergman, Inc. website, "PRB Coal Properties," http://www.clydebergemann.com

Figure 1 The Boardman Coal power plant.

CO_2 Emissions from Boardman

The emissions intensity of generated power at the Boardman Power Plant is estimated at 2,128 lbs CO_2e/MWh. The plant produces 4.3 million MWh per year, resulting in 4.6 million tons of CO_2e from pulverizing and burning PRB coal.[5] This is by far the largest contributing factor to the plant's CO_2 emissions.

Transportation by rail of coal to Boardman is responsible for adding another 77,000 tons of CO_2e (CSX Carbon Calculator for Rail Shipments).

There is no data supporting the CO_2 emissions per ton of coal mined. Subsequent equivalents for auxiliary equipment are not used in this study (ICF International, 2008).

Arundo Donax

Arundo donax is a reed species native to southern Europe. It was introduced into North America in the late 1800s and now grows wild in California and other southern regions. Its growth area in the US is within the southern states. It is considered a weed species in California. *Arundo donax* is grown as a cultivated crop (Figure 2) for the production of musical instrument reeds.

Arundo is a member of the Poeacea family, of which corn is also a member.

Arundo has been found to produce upwards of 35 dry tons per acre per year. In comparison, plants such as switchgrass will yield 4 to 13 dry tons per acre per year (Heaton 2008). *Arundo* produces a hollow cane that is easily processed into chips and chip-like material, which handle easily.

[5] 'CO_2e' is 'CO_2 equivalent', a metric that allows for accounting of all greenhouse gases.

Figure 2 Aerial view of an *Arundo Donax* plantation.

Arundo is one of the largest herbaceous grasses, and is often mistaken for a bamboo. It is a tall, erect, perennial grass, 2 to 8 m high (Perdue 1958). Canes frequently attain lengths of 8 to 9 m in coastal California. The main stems, or culms, are hollow with walls 2 to 7 mm thick and are divided by partitions at the nodes; the culms can average 23.8 mm wide (measured between nodes one and two).

First year canes are un-branched, and in the second year single or multiple lateral secondary branches may form from the nodes (Decruyenaere & Holt 2005). The secondary branches are a much smaller diameter than the main canes (typically <10 mm versus >20 mm). In canes that are two years and older, the secondary branches bear a significant proportion of the leaves. These secondary branches can themselves give rise to third degree and even fourth degree branches, but this is uncommon (Decruyenaere & Holt 2005). Once a cane generates secondary branches these become the primary area of new growth, and continued growth of the main cane (leader) is slow to non-existent (Decruyenaere & Holt 2005).

The genus *Arundo* (of the family Gramineae, tribe Festuceae), includes six species of which *A. donax L.* is the most widely distributed and the best known. In the U.S. this species has assumed many common names. In the southwest it is called Carrizo. It is often called bamboo reed, giant reed, giant cane, music cane, nalgrass and Nile Fiber Cane, varying between commercial circles. Some of these names can be confused with species of *Phragmites communis*. In parts of the world *P. communis* is called Bara nal, or Gaba nal, thus producing confusion with “nalgrass.” In the northwest United States localized areas of what is called “giant reed” are actually *Phragmites* and not *Arundo donax*.

Part II: Carbon Assessment and Comparison

Footprint Boundary Statement

The scope of this carbon assessment encompasses activities involving transportation, planting and harvesting of *Arundo donax* and the torrefaction of *Arundo* to produce torrefied biomass or “biocoal”. It also includes a comparison of the use of the *Arundo* biocoal to the Powder River Basin coal that is currently being used by PGE. Transportation of all material is included in this evaluation; all aspects of transportation are taken into account including transportation of planting material, and the subsequent torrefied material to the Boardman Power plant.

Carbon Footprint of Energy Production from Coal at Boardman

There are approximately 4.6 million tons of CO_2e associated with the total annual production of energy from PGE’s coal burning power plant at Boardman, Oregon. Substituting coal with biocoal from *Arundo* and potentially other closed-loop sources would dramatically decrease the net CO_2e emissions associated with the plant.

Torrefaction

Biomass is the fourth largest energy supply in the world. It is mostly used in underdeveloped countries, but could be the largest supplier in developed countries. Gasification of biomass began around 1800 and was commonplace by the 1850s. During times of crisis the United States reverted back to wood gasification for fuel and other energy sources (Hewett, *et al*, 1981).

Torrefaction is a thermo-chemical treatment of biomass in the 200 to 350 degrees Celsius range. In this process the biomass partly (especially the hemicellulose) decomposes, giving off various types of volatiles. These volatiles are then used to sustain the torrefaction process. The remaining torrefied biomass (solid) has approximately 30% more energy content per unit of mass than the original dry biomass.

Torrefied biomass has excellent combustion properties; the fuel can be readily co-fired with coal, further gasified or fed to pyrolysis units. Torrefaction at the stated temperature range yields a kind of mild pyrolysis process that improves the fuel properties of the biomass. At lower temperatures, now developed between 200°C and 300°C, torrefied products and volatiles are formed resulting in hardened, dried and more volatile-free solid product. The product has a much higher energy density than the raw biomass.

As an added benefit of this higher gravimetric energy density, the distance over which the biomass can be economically transported for use or further processing is higher than that non-torrefied biomass. Earlier research into torrefied *Arundo* indicates it has a higher gravimetric BTU value (by approximately 15%) over typical PRB coal (Garcia-Perez, *et al,* 2010).

Torrefied biomass is also more hydrophobic than PRB coal, meaning it can be stored in the open for long periods without taking up water, similar to the infrastructures used for coal.

Torrefied biomass requires less energy to crush, grind and pulverize than does PRB coal. The same tools to process coal can be used to process torrefied biomas. In addition, torrefaction can reduce the energy required for size reduction by 70% to 90%.

Mass and energy Balances of a 100 t/day torrefaction plant

The following provides assessment of the mass and energy balances associated with a conceptual 100 ton per day biomass torrefaction plant for processing *Arundo*. Such a facility would yield 52.7 tons per day of torrefied *Arundo* chips, yielding 1,160 GJ of energy per day. The energy density of torrefied *Arundo* is then 22.0 GJ/ton or 10,400 BTU/lb.[6] *Arundo* offers significantly higher energy densities than other proposed bio-crops such as switchgrass (7,741 BTU/lb), wheat straw (7,978 BTU/lb) and hybrid poplar (8,178 BTU/lb) (Biomass Energy Data Book 2011).

<u>Suppositions for mass and energy balances:</u>

- Capacity of the unit: 100 tons/day
- Moisture content of biomass received: 6 mass %
- Biomass elemental composition (on dry basis, mass %): (carbon: 48.8, hydrogen: 5.9, oxygen: 43.7, Ash: 1.6)
- Conversion achieved in the torrefaction step: 62 % conversion
- Complete combustion of leaves and torrefaction volatile products (used as the system fuel)
- Most of the systems are considered adiabatic

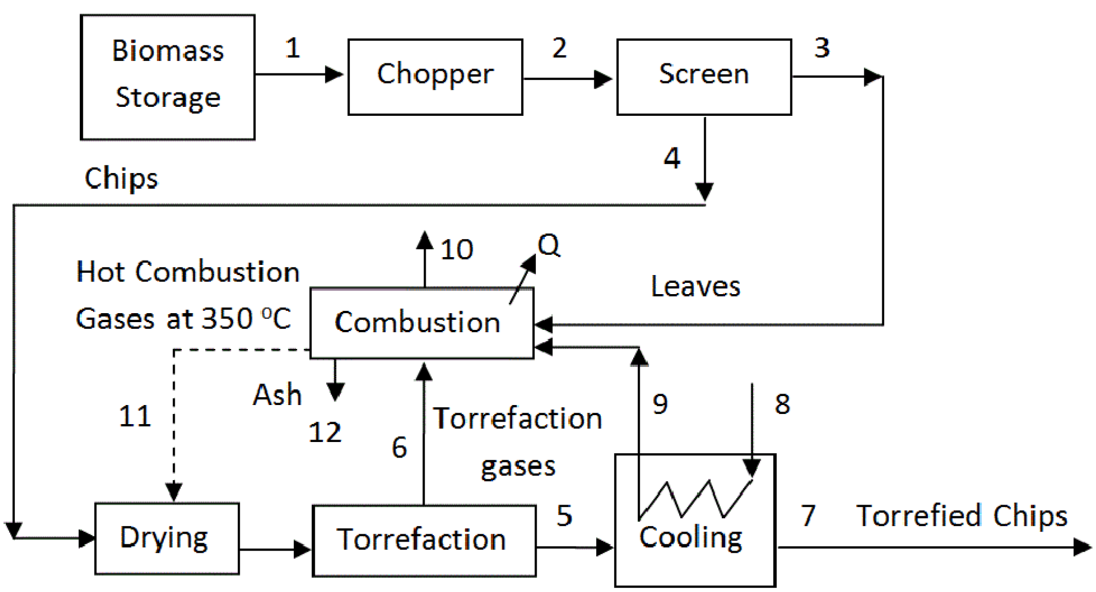

Figure 3 Conceptual design of a proposed torrefaction process proposed (Bergman et al. 2005).

[6] Appendix B - Calculation Examples, Torrefied *Arundo* in BTU/lb

Table 1 Summary of mass balances. Stream notations refer to the proposed torrefaction process shown in Figure 3.

Stream	Flow rate (Base of calculation: 100 t/day)	Composition (mass %)	Temperature (°C)
1, 2	8.1 t/d leaves	8.1 mass % leaves	25
	85.9 t/d chips	85.9 mass % chips	
	6 t/d moisture	6.0 mass % moisture	
3	8.1 t/d leaves	53.95 mass % leaves	25
	6.013 t/d chips	40.04 mass % chips	
	0.9008 t/d moisture	6.0 mass % moisture	
4	79.887 t/d chips	94.0 mass % chips	25
	5.099 t/d moisture	6.0 mass % moisture	
5	52.69 t/d torrefied chips	100 mass % torrefied chips	270
6	15.17 t/d gases of Pyrolysis	9.5 mass % gases	277
	7.69 t/d organics Pyrolysis	4.81 mass % organics	
	3.69 t/d AcA		
	3.99 t/d MeOH		
	4.29 t/d reaction water	2.68 mass % reaction water	
	5.099 t/d moisture	3.19 mass % moisture	
	30.60 t/d CO_2 carrier gas	19.15 mass % CO_2 carrier gas	
	14.60 t/d H_2O carrier gas	9.14 mass % H_2O carrier gas	
	6.00 t/d O_2 carrier gas	3.76 mass % O_2 carrier gas	
	76.27 t/d N_2 carrier gas	47.74 mass % N_2 carrier gas	
7	52.69 t/d torrefied chips	100 mass % torrefied chips	25
8	38.87 t/d O_2	Air	25
	127.97 t/d N_2		
9	38.87 t/d O_2	Air	99
	127.97 t/d N_2		
10	51.34 t/d CO_2	24.00 mass % CO_2	150
	24.49 t/d H_2O	11.45 mass % H_2O	
	10.07 t/d O_2	4.71 mass % O_2	
	127.97 t/d N_2	59.83 mass % N_2	
11	30.60 t/d CO_2	24.00 mass % CO_2	277
	14.60 t/d H_2O	11.45 mass % H_2O	
	6.00 t/d O_2	4.71 mass % O_2	
	76.27 t/d N_2	59.83 mass % N_2	
12	0.22 t/day	100 mass % ash	100

Table 2 Summary of energy balances. Stream notations refer to the proposed torrefaction process shown in Figure 3.

Stream	Flow rate (Base of calculation: 100 t/day)	Enthalpy (kJ/kg)	Hi (MJ/day)	Temperature (^oC)
1,2	8.1 t/d leaves	18400	149040	25
	85.9 t/d leaves	18400	1580560	
	6 t/d moisture	0		
	Total		**1729600**	
3	8.1 t/d leaves	18400	149040	25
	6.013 t/d chips	18400	110639	
	0.9008 t/d moisture	0		
	Total		**259679**	
4	79.887 t/d chips	18400	**1469939**	25
	5.099 t/d moisture	0		
5	52.69 t/d torrefied chips	22249.9	**1172300**	270
6	45.77 t/d CO_2	239.5	11441	277
	3.69 t/d AcA	15353	56653	
	3.99 t/d MeOH	23948.1	95553	
	23.98 t/d H_2O	2923.33	70093	
	6.00 t/d O_2	239.76	1439	
	76.27 t/d N_2	263.7	20112	
	Total		**255291**	
7	52.69 t/d torrefied chips	22015.3	**1159986**	40
8	38.87 t/d O_2	0	0	25
	127.97 t/d N_2			
9	38.87 t/d O_2	66.88	2599.6	99
	127.97 t/d N_2	76.24	9756.43	
	Total		**12356**	
10	51.34 t/d CO_2	113.02	5802.4	150
	24.49 t/d H_2O	2675.44	65521.5	
	10.07 t/d O_2	115.273	1160.8	
	127.97 t/d N_2	129.318	16548.8	
	Total		**89033.5**	
11	30.60 t/d CO_2	273.86	7329	277
	14.6 t/d H_2O	2989.37	42675.8	
	6.00 t/d O_2	273	1434	
	76.27 t/d N_2	299.2	20059	
	Total		**71497.8**	

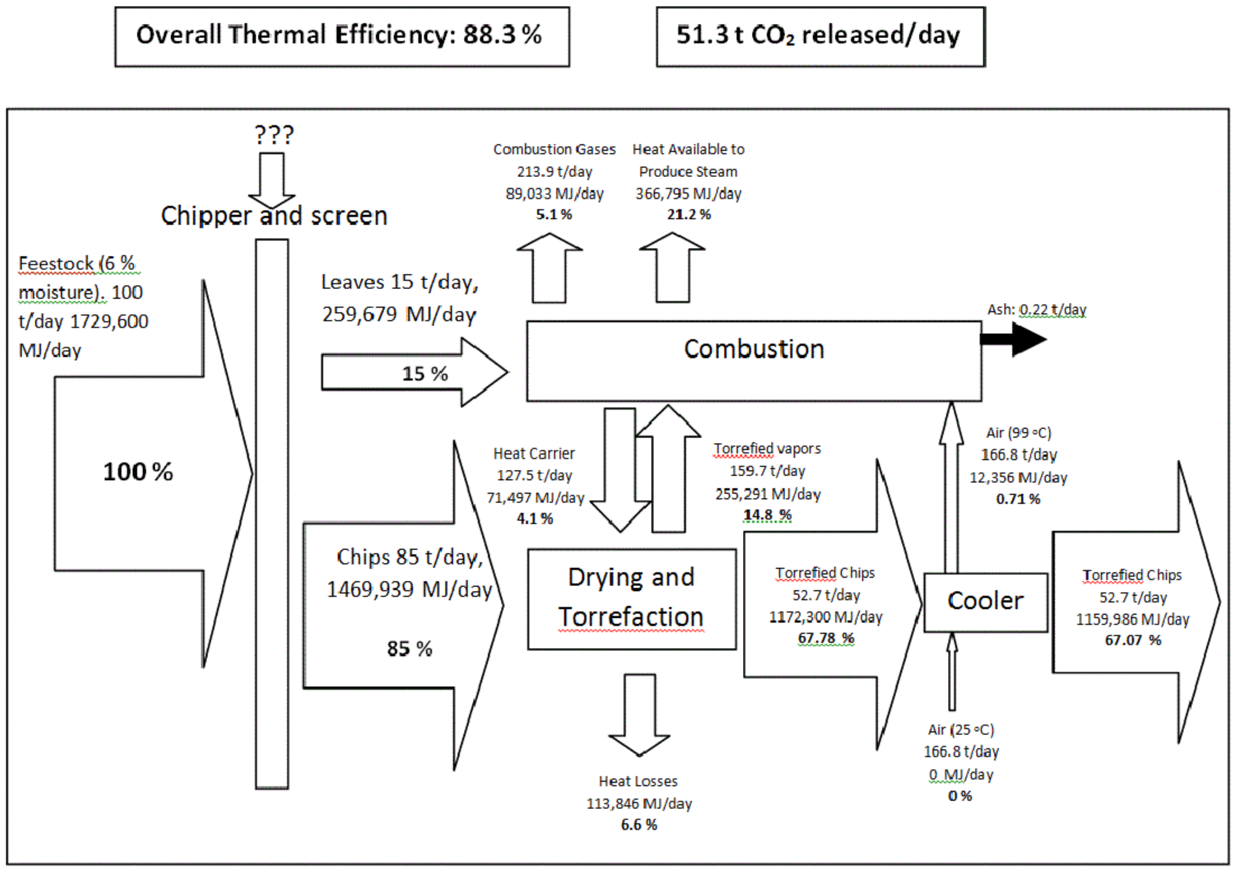

Figure 4 Overall Mass and Energy Balance of a torrefaction unit producing Torrefied Chips and steam (100 t/day torrefaction unit).

Carbon Sequestration in a Mature *Arundo* Plantation

A mature stand of *Arundo* will yield between twenty to thirty-five dry tons per acre per year. For calculations in this paper, a figure of 33 tons per acre per year is used. It has been estimated that the below-ground production in the root mass is 22 percent of the above ground production. Thus, a yield of 33 tons per acre per year will produce approximately 7.3 tons below-ground in the root mass.

Establishment of an *Arundo* plantation would require planting material being shipped to the plantation. Carbon dioxide from shipping of *Arundo* for plantation establishment is minimal when compared to the total amount of carbon dioxide involved in the whole process.

Although PGE would expect to use a mix of biomass sources if a conversion proceeds, for research purposes, this study assumes that, beginning in 2021, the Boardman facility would completely replace coal with torrefied *Arundo*. We further assume the facility would operate at an annualize 300MW (615MW with a 49% capacity factor), producing power only under optimal economic conditions. Based on the BTU content of torrefied *Arundo* (10,400 BTU/lb), 1.25 million tons of torrefied *Arundo* would be used by the Boardman power plant to provide 2.6 million MWh annually (300MW annualized) under this assumed scenario.[7] This is the BTU equivalent of 1.5 million tons of Powder River Basin coal. As of the publication of this report, PGE has not made a formal commitment to convert Boardman to a biomass-fired facility, nor has a decision been made regarding the planned capacity factor.

Arundo, specifically the leaves and torrefaction gases, would also be used to support the torrefaction process, thereby maintaining a closed-loop carbon cycle for the torrefaction process. The use of these leaves and gases is accounted in the energy balance shown in Table 2 and Figure 4.

From Table 2, 94 dry tons of *Arundo* would produce 52.7 tons of torrefied chips, so a total of 67.6 thousand acres of *Arundo* would be required to produce 1.25 million tons of torrefied chips and support torrefaction, assuming 33 dry tons per acre per year.[8] Table 3 shows a breakdown of the total annual amount of carbon dioxide sequestered in a mature plantation.

Table 3 Breakdown of total annual CO_2e sequestered in a mature *Arundo* plantation.[9] Emitted CO_2e is noted as negative numbers, sequestered carbon as positive.

Factor	CO_2e (tons/yr/acre)	Acres ($x10^3$)	Total CO_2e (million tons/yr)
Rhizomes to field	0.40	67.6	-0.027
Plantlets to field	0.05	67.6	-0.003
Coal to Boardman (laden @ 1,000 miles)			-0.077
Return of cars			-0.002
Biocoal to Boardman (50 miles range)			-0.007
CO_2 sequestration of Arundo above ground			3.59
CO_2 sequestration of Arundo below ground			0.790
Total CO_2 Sequestered			**4.34**

Carbon Dioxide Equivalent (CO_2e) "Cost" from farming *Arundo*

Farming of *Arundo* on a large scale of tens of thousands of acres has never been attempted before so there are no hard CO_2e emissions numbers for *Arundo* agronomy. Table 4 provides estimates for *Arundo* farming based on the CO_2e for farming an acre of corn. Since *Arundo* has not had issues with insects or fungus, there are no CO_2e figures for these unit operations. The variance between the two columns of *Arundo* is based upon first year versus subsequent years, since, although *Arundo* could be cultivated in rotation with other crops, it only needs to be planted once.

[7] See Appendix B - Calculation Examples, *Arundo* Mass yield
[8] See Appendix – Calculation Examples, *Arundo* Acreage
[9] 'Coal to Boardman' and 'Return of Cars' not included in 'Total CO_2 Sequestered.'

Table 4 Estimates for annual CO_2e production for Arundo donax agronomy using corn as a surrogate comparison. Three practices for corn are noted: conventional till (CT), reduced till (RT) and no-till (NT). Data are derived from West & Marland, A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States, Journal of Agriculture, Ecosystems and Environment 91 (2002). Table 7and Table 8 show details for the machinery and agricultural inputs entries within this table.

		Corn CT[A]	Corn RT[A]	Corn NT[A]	Arundo Yr 1	Arundo Yr n > 1
		(lbs CO_2 acre^{-1} yr^{-1})				
Machinery Inputs		236	148	38.7	221	53.9
Agricultural Inputs						
	Weighted Irrigation	591	730	726	N/A	N/A
	0% Irrigation	509	655	661	N/A	N/A
	100% Irrigation	1058	1153	1091	941	871
Total Carbon (CO_2) emissions						
	Weighted Irrigation	827	878	765	N/A	N/A
	0% Irrigation	745	803	700	N/A	N/A
	100% Irrigation	1294	1301	1130	1162	925
				ΔCO_2[B]	**-10.2%**	**-28.5%**

[A] Conventional Till, Reduced Till, No-Till

[B] 100% irrigated CT corn vs. *Arundo Donax* .

Biomass Yield and Nutrient Removal Considerations

Arundo biomass yield and nutrient removal data were collected at Prosser, WA in the 4th year (2007) of growth in a drip irrigation study. The stand was not as vigorous as a previously established stand in the same location, but it still provides an idea of carbon, nitrogen, and sulfur removal in stems and leaves per unit of biomass. In 2007, the leaves and stems represented 18% and 82% respectively, of the dry harvested biomass. These numbers could be extrapolated to different biomass yield levels to determine carbon and nutrient removal rates at higher or lower yields. Note that although the nitrogen concentrations in the final harvested biomass are relatively low, the total nitrogen removed is high due to the high biomass removal. This defines a minimal nitrogen supply requirement from fertilizer and soil nitrogen sources. Since this stand was planted on an old manured field, the Nitrogen application rates were lower than the nitrogen removal rates since soil nitrogen release from the manure accounted for some of the nitrogen supply.

After this season, one root ball was excavated from one plant hill, and weighed. The root ball from a single Arundo hill or clump weighed 9.8 kg, which extrapolated out to 62 ton/acre as a preliminary estimate of root biomass production. However, this was just one sample and it was suspected to grossly overestimate the root biomass, so in the following year, two additional root samples were taken at the end of the growing season. Roots and corms were weighed and analyzed. The average root biomass was 11.8 ton/acre, representing 4.8 ton carbon/acre (17.6 ton CO_2e/acre). It is also presumed that a significant fraction of the root N (~300 lb nitrogen/acre) is decomposed, mineralized and made available again in the next growing season for the next growth cycle. Sulfur content is lower than nitrogen, but represents a significant nutrient requirement for *Arundo* as well.

Table 5 2007-8 shoot and root biomass (carbon, nitrogen, and sulfur) accumulation at Prosser, WA.[10]

Plant part	Biomass Dry (ton/acre)	Carbon (%)	Total Carbon (ton/acre)	Nitrogen (%)	Total Nitrogen (lb/acre)	Sulfur (%)	Total Sulfur (lb/acre)
2007 Stem	13.5	48.9	6.61	0.81	220	0.12	37.2
2007 Leaf	2.90	45.9	1.33	1.88	110	0.42	24.9
2007 Stem + Leaf	16.4	48.1	7.94	1.00	330	0.19	62.0
2008 Roots	11.8	40.7	4.80	1.25	295	0.27	63.7

Carbon Dioxide Equivalents (CO_2e) Comparing Torrefied Arundo to Coal

The total carbon dioxide given off from the torrefaction process to produce 1.25 million tons of torrefied material is around 1.22 million tons.[11] Total CO_2e emissions from the Boardman Plant for producing 2.6 million MWh/yr of electricity are 2.8 million tons per year, using the combustion of PRB coal as a comparable metric. Table 6 shows the total CO_2e fixed above what is generated through the unit operations surrounding the supply and consumption of coal and *Arundo* for Boardman.

Table 6 Production and Sequestration of CO_2 [12,13,14]

	CO_2 Equivalents (million tons/yr)
Torrefaction of *Arundo*	1.22
Combustion of *Arundo*	2.80
Farming of *Arundo*	0.03
Total	**4.05**
CO_2 Sequestered by Arundo	4.34
Net Sequestered CO_2	**0.29**

The initial transportation and farming required to establish an *Arundo* plantation of the required size produces over 39,000 tons of carbon dioxide; this is a one-time production value.[15] The transportation of coal from the PRB yields an annual 77,000 tons of CO_2e annually. The transportation of biocoal to Boardman results in approximately 13,000 tons annually.

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[10] From: Supplemental report on shoot/root biomass production of *Arundo donax*, W. L. Pan
[11] See Appendix – Calculation Examples, CO_2 from Torrefaction
[12] See Appendix – Calculation Examples, CO_2 from Farming *Arundo, year n > 1*
[13] CO_2 from farming *Arundo* for years n > 1.
[14] See Table 3 for specific details regarding sequestration.
[15] See Appendix – Calculation Examples, CO_2 from Farming *Arundo, year n = 1*

Part III: Summary Conclusions and Discussion

Renewable Portfolio Standards and Boardman Production Using Biomass

Beginning in 2021, the Boardman facility has the potential to convert from PRB coal to 100% torrefied biomass. Currently, Boardman operates at 615MW with an 80% capacity factor, generating 4.3 million MWh annually. After a conversion, the plant would be expected to operate at an annualized 300MW capacity (this may be alternatively viewed as operation at 615MW with a 49% capacity factor). Under these conditions, the plant would generate 2.6 million MWh annually.

Using torrefied biomass to generate electricity would qualify Boardman for consideration as a renewable energy source under Oregon's Renewable Portfolio Standard, so PGE would have the benefit of a qualified renewable energy source capable of supplying 2.6 million MWh of dispatchable baseload energy annually. In addition, repurposing the facility would allow the rural community where the Boardman facility is located to continue to receive the substantial employment and tax benefits associated with continued operation.

Carbon Sequestration and Its Limits

Our analysis suggests that the benefits described above would be further enhanced by the fact that farming and use of *Arundo donax* for 100% replacement of coal from the Powder River basin would generate net positive carbon dioxide sequestration. Currently, the Boardman facility uses over 2.5 million tons of coal to generate 4.3 million MWh of electricity annually, resulting in a net production of 4.6 million tons of CO_2e. Combustion of 100% *Arundo* to provide 2.6 million MWh of electricity annually would produce roughly 2.8 million tons of CO_2e. We project that torrefaction of *Arundo* would produce an additional 1.22 million tons of CO_2e annually, while farming of *Arundo* would contribute a small amount, 32 thousand tons. As noted in Table 6, farming, torrefaction and combustion would result in the emission of 4.05 million tons of CO_2e annually. Concurrently, mature farming of *Arundo* would result in the sequestration of around 4.34 million tons annually, resulting in a net sequestration of around 0.29 million tons, at least until soil organic content (SOC) becomes saturated. This scenario is illustrated in Figure 5. Net CO_2e savings are consistent with findings reported by other researchers studying the replacement of coal with biomass resources (Lemoine 2010).

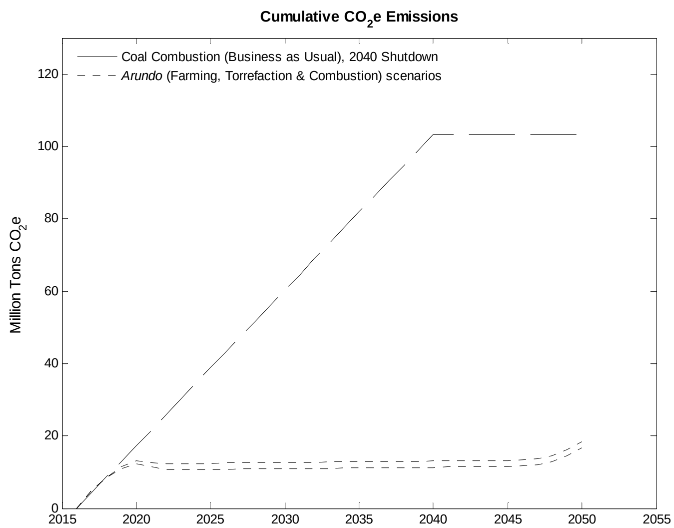

Figure 5 For illustrative purposes, this figure depicts the cumulative CO_2e emissions from a business-as-usual approach (coal combustion) at the Boardman facility compared to emissions that could result from combustion of 100% torrefied *Arundo*. Farming of *Arundo* starts ramping up in 2017, prior to the conversion to combustion of 100% torrefied *Arundo* in 2021. Uncertainty in the amount of CO_2e that can be sequestered within soil results in uncertainty regarding cumulative emissions for the *Arundo* case. Below-ground sequestration of carbon eventually saturates, but this saturation limit is not well understood nor are agreed-upon methods uniformly established. This uncertainty is illustrated by the divergence of the two dotted lines, which depict two different sets of saturation limits and saturation rates. The positively-sloped tails at the far right of the *Arundo* projections arise due to continued combustion of *Arundo* as farming (and thereby sequestration) tails off in anticipation of a 2050 shutdown. Between 2018 when farming of *Arundo* starts, and 2050 when Boardman shuts down, between 16 and 18 million tons of CO_2e may be emitted, the bulk of which (18.5 million tons) occurs between 2017 and 2021 due to coal combustion during the initial farming phase and prior to the conversion of Boardman to 100% *Arundo*. The difference between 16/18 million and 18.5 million is due to the uncertainty regarding below-ground carbon sequestration of carbon.

Perennial grasses grown in cool temperate environments have been observed to sequester carbon below ground, as soil organic content (SOC), particularly on previously-cultivated agricultural land (Post 2000). Riffaldi, et al demonstrated *Arundo* cultivation within a Mediterranean climate increases the amount of SOC due to its large underground rhizome structure and the low-tillage nature of the cultivation (Riffaldi 2010). However, below-ground sequestration is limited by several soil mechanisms (Six 2002). Consequently, accumulation of SOC cannot continue indefinitely, as discussed in a meta-analysis by Groenigen, et al, and as noted by Oren, et al, specifically regarding sequestration in forest ecosystems (Groenigen 2006, Oren 2001). Further, there is uncertainty regarding the amount of carbon soils can sequester as well as the duration required before SOC is saturated. For instance, Diaz-Hernandez questions the sample depth used to measure SOC density, which is critical to estimating the amount of below-ground sequestered carbon (Diaz-Hernandez 2010). Diaz-Hernandez suggests current methods to do not sample to sufficient depth, thereby underestimating the amount of sequestered carbon. *Arundo* has been observed to produce deep root masses within short time frames. For instance, Sher, et al observed root growth of *Arundo* beyond 100 cm within three month (Sher 2002).

Greenhouse Gas Reduction using Electricity from Biomass

There has been much discussion recently concerning the use of biofuels as a substitute for liquid petroleum products for motor vehicles. The heavily-subsidized nature of biofuels calls into question their cost-effectiveness in achieving both reductions in net greenhouse gas emissions and decreases in fossil-fuel use (Jaeger 2011). Further, focusing on biomass strictly for the production of liquid biofuels limits the impact biomass resources can play in achieving these policy objectives (EPA 2005, EO 13149). In light of the policy objectives of promoting electric vehicles penetration over the coming years, using biomass as a means for generating electricity provides a renewable energy resource with the flexibility to provide energy for multiple markets, particularly vehicles (EO 13541 2009, Jaeger 2011). A biomass-fired Boardman facility, together with the extensive hydroelectric and wind power resources throughout the region, would provide the Pacific Northwest with substantial renewable energy resources. Coupled with innovative demand response mechanisms and energy market dynamics, these resources could help achieve significant reductions in net greenhouse gas emissions and decreases in fossil fuel use.

Appendix A

Table 7 summarizes annual CO_2e production, accounting for machinery inputs and agricultural inputs. Machinery and agricultural inputs are detailed in Table 8 below. The sources from which West & Marland derive these data are listed in the references section of this report.

Table 7 Carbon Dioxide emissions from agriculture machinery for different corn tillage practices in the United States, circa 1990 (West & Marland 2002) and projected agricultural machinery practices for *Arundo donax*. Beyond Year 1, machinery inputs decrease due to the perennial nature of *Arundo*.

	Corn CT[A]	**Corn RT**[A]	**Corn NT**[A]	**Arundo Yr 1**	**Arundo Yr n > 1**
	(lbs CO_2 $acre^{-1}$ yr^{-1})				
Moldboard Plow	87.6	N/A	N/A	87.6	N/A
Disk[B]	56.9	56.9	N/A	56.9	N/A
Planting	22.2	22.2	22.2	22.2	N/A
Single Cultivation[C]	15.0	15.0	N/A	N/A	N/A
Harvest	54.0	54.0	54.0	54.0	54.0
Total	**236**	**148**	**76.2**	**221**	**54.0**

[A] Conventional Till, Reduced Till, No-Till

[B] Double pass over the field

[C] Applied only to row crops like corn.

Table 8 Annual average agricultural inputs and associated carbon dioxide emissions for corn using three different tillage practices (conventional, reduced and no-till) in 1995 (West & Marland 2002) and projected agricultural inputs for *Arundo donax*.

	CT Corn (lbs CO_2 $acre^{-1}$ yr^{-1})			RT Corn (lbs CO_2 $acre^{-1}$ yr^{-1})		
		%[A]			%[A]	
Herbicide	50.0	93	46.5	53.8	96	51.7
Insecticide	24.3	24	5.82	22.0	27	5.94
Fungicide[C]	–	–	–	–	–	–
N	342	93	318	455	98	446
P_2O_5	30.3	83	25.1	35.7	81	28.9
K_2O	29.1	71	20.7	37.1	81	30.0
$CaCO_3$	444	5	22.2	444	5	22.2
Seed	70.3	100	70.3	70.3	100	70.3
Irrigation Water	550	15	82.4	498	15	74.7
Total (weighted irrigation)			**591**			**730**
Total (0% Irrigated)			**509**			**655**
Total (100% Irrigated)			**1058**			**1153**

	NT Corn (lbs CO_2 $acre^{-1}$ yr^{-1})			Arundo [D,E,F] (lbs CO_2 $acre^{-1}$ yr^{-1})	
		%[A]		Yr 1	Yr n > 1
Herbicide	64.1	99	63.5	0	0
Insecticide	19.3	22	4.24	0	0
Fungicide[C]	–	–	–	–	–
N	462	98	452	274	274
P_2O_5	33.9	79	26.8	24.2	24.2
K_2O	33.5	65	21.8	23.3	23.3
$CaCO_3$	444	5	22.2	0	0
Seed	70.3	100	70.3	70.3	0
Irrigation Water	429	15	64.4	550	550
Total (weighted irrigation)			**726**	N/A[G]	N/A[G]
Total (0% Irrigated)			**661**	N/A[G]	N/A[G]
Total (100% Irrigated)			**1091**	**942**	**872**

[A] Percent of planted hectares treated in 1995.

[B] Weighted against percent of planted hectares treated

[C] Fungicides are applied on less than 1% of crop lands

[D] Assuming fertilizer application on *Arundo Donax* is 80% that of CT corn. 100% of all acres fertilized (N, P, K). Lye excluded.

[E] Assuming emissions related to *Arundo Donax* rhizome preparation is equivalent to that of seed preparation for CT corn.

[F] Assuming irrigation of *Arundo Donax* is equivalent to that of CT corn.

[G] 100% of all *Arundo Donax* acres irrigated.

Appendix B – Example Calculations

MWh w/ coal, 615 MW and 80% Capacity Factor:

$$E_{Boardman} = (615\ MW)(0.80)(365\ days/year)(24\ hours/day)$$

$$\boxed{E_{Boardman,coal} = 4.3\ MWh/year}$$

MWh, w/ Arundo, 300 MW annualize:

$$E_{Boardman} = (300\ MW)(1.0)(365\ days/year)(24\ hours/day)$$

$$\boxed{E_{Boardman} = 2.6\ MWh/year}$$

BTU, 615 MW and 80% Capacity Factor:

$$T_{Boardman,coal} = E_{Boardman,coal}\ (9911\ BTU/kWh)$$

$$\boxed{T_{Boardman,coal} = 43\ trillion\ BTU/year}$$

BTU, 300 MW annualize:

$$T_{Boardman} = E_{Boardman}\ (9911\ BTU/kWh)$$

$$\boxed{T_{Boardman} = 26\ trillion\ BTU/year}$$

Torrefied Arundo in BTU/lb:

$$\rho_A = \frac{1{,}159{,}986\ {}^{MJ}\!/_{day}}{52.69\ {}^{ton}\!/_{day}}$$

$$\rho_A = \frac{\left(22{,}015\ {}^{MJ}\!/_{ton}\right)\left(947.8\ {}^{BTU}\!/_{MJ}\right)}{2000\ {}^{lb}\!/_{ton}}$$

$$\boxed{\rho_A = 10{,}430\ {}^{BTU}\!/_{lb}}$$

Boardman Efficiency:

$$\eta = \frac{1}{9{,}911 \,{}^{BTU}\!/\!_{kWh}} \left(3412 \; BTU / kWh\right)$$

$$\boxed{\eta = 34.4\%}$$

Arundo Mass:

$$M_A = \frac{T_{Boardman}}{\rho_A \left(2000 \; lb/ton\right)}$$

$$\boxed{M_{A,torrified} = 1.25 \; million \; tons \left(short, U.S.\right) torrefied \;\; Arundo \;\; per \;\; year}$$

Arundo Acreage:

$$A_A = \frac{\left(\frac{94 \; dry \; tons}{52.69 \; torrified \;\; tons}\right) M_{A,torrefied}}{33 \,{}^{dry \; tons}\!/\!_{acre}}$$

$$\boxed{A_A = 67.6x10^3 \,{}^{acres}\!/\!_{yr}}$$

CO₂ from Torrefaction:

$$M_{CO2,torrefaction} = M_{A,torrified} \left(\frac{51.34 \,{}^{tons \; CO_2}\!/\!_{day}}{52.69 \,{}^{tons \; torrefied \;\; chips}\!/\!_{day}} \right)$$

$$\boxed{M_{CO2,torrefaction} = 1.22 \; million \; tons \; CO_2 \;\; per \;\; year}$$

CO₂ from Farming Arundo, year n > 1:

$$M_{CO2,\, farm,n>1} = \frac{\left(925 \; lbs \; CO_2 / acre \cdot yr\right)}{2000 \; lb/ton} A_A$$

$$\boxed{M_{CO2,\, farm,n>1} = 32x10^3 \,{}^{tons \; CO_2}\!/\!_{yr}}$$

CO_2 from Farming Arundo, year n = 1:

$$M_{CO2,\,farm,n=1} = \frac{\left(1162 \, {}^{lbs\ CO_2}\!/_{acre \cdot yr}\right)}{2000 \, {}^{lbs}\!/_{ton}} A_A$$

$$\boxed{M_{CO2,\,farm,n=1} = 40x10^3 \ \ {}^{tons\ CO_2}\!/_{yr}}$$

Biographies

Mark Lewis

Mark Lewis is the Director of the Paper Science Center at the University of Washington. He has over 30 years of experience in the pulp and paper industry with the last 14 in the Paper/Bioresource Science and Engineering Department at the University of Washington. He has been involved with Arundo donax as a fiber and chemical raw material. His research led to the first ever major commercial non-wood pulp run in North America using Arundo at the Samoa Pacific mill in Arcada, CA. He worked with Bill Pan and Bob Stevens from Washington State University to establish research stands of Arundo donax at a WSU experiment station. Mark continues to work with ag-residue as a bioresource for fiber and biopolymers; the Paper Science Center pilot plant facility produces straw pulp, paper, and biopolymers on a routine basis.

Manuel Garcia-Perez

Manuel Garcia-Perez is an assistant professor in the Biological Systems Engineering Department at Washington State University. He was hired to establish a program in biomass thermochemical conversion (torrefaction, pyrolysis, gasification and combustion) as part of the university's vision to develop integrated capabilities in biomass processing and bio-products. Dr. Garcia-Perez is developing systematic methods to design thermochemical reactors, rural bio-oil refineries and modified petroleum refineries for the production of transportation fuels, chemicals and electricity from lignocellulosic materials. In the last 13 years he had been working with several thermochemical technologies: Vacuum pyrolysis, Auger Pyrolysis, and Fluidized bed pyrolysis in Australia, Canada and the United States and has published more than 40 peer reviewed papers on the thermochemical conversion of several lignocellulosic and lipid rich materials (sugarcane bagasse, softwood and hardwood bark, pine chips, palm oil mill residues, poultry litter, Oil Mallee, DAF skimmings, Arundo Donax and wheat straw). Dr. Garcia-Perez has recently published a comprehensive review on the evolution of pyrolysis technologies.

Bill Pan

The Green Revolution, Earth Day and rural life were early influencing factors that lead Dr. William Pan to pursue a career in the agricultural sciences. He earned his B.S. in Biochemistry at the University of Wisconsin, an M.S. in Agronomy at the University of Missouri, and a Ph.D. in Soil Science at North Carolina State University. He joined WSU in 1984 focusing on soil fertility management and soil-plant-rhizosphere processes. Dr. Pan is currently Professor in Crop and Soil Sciences at Washington State University. His recent interdisciplinary collaborations are leading to emerging commercial integrations of agriculture with the pulp/paper, medical and renewable fuel industries. Dr. Pan is a Fellow of the American Society of Agronomy, Director of WA State Biofuel Cropping Systems Program, Co-director of the USDA-funded PNW STEEP Program, and Board of Directors member of Far West Agribusiness Association and Pacific Northwest Direct Seed Association. His work has culminated in over 40 refereed publications, 7 book chapters and numerous invited conference papers and presentations.

Don Wysocki

Don is an Associate Professor within the College of Agricultural Science at Oregon State University. His research projects are concerned with improving management of soils under dryland farming systems in relation to soil and water conservation, crop rotation, nutrient management, and tillage.

Don Horneck

Don is an Extension Agronomist Associate Professor with Oregon State University's Department of Crop and Soil Science. His research focuses on soil fertility/crop production, potatoes, onions, alfalfa, cereals. Don offers expertise on a wide range of topics to the general public, growers and fieldmen in the area. He also represents agriculture's interests on committees. He is responsible for providing educational pesticide and CCA licensing opportunities for local growers and fieldmen. His primary concerns are profitability and environmental sustainability of local cropping systems.

Robert Bass

Dr. Bass is an associate professor in the Department of Electrical and Computer Engineering at Portland State University. His research is focused on electrical power systems, particularly distributed & renewable generation resources, electric vehicle charging, demand-responsive loads, optimization methods for multi-unit generation and the overlaying smart grid methods that link them together. Dr. Bass specializes in teaching undergraduate and graduate courses on electric power, electromechanical energy conversion, distributed energy resources and power systems analysis. His academic contributions include developing power engineering degree programs; ABET accreditation, undergraduate laboratory development and novel engineering course design.

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