COALITION for SUSTAINABLE RAIL

Preserving Solid Fuel Firing in a Post-Coal World

Wolfgang A. Fengler, MSME & Davidson A. Ward

About the Coalition for Sustainable Rail

The Coalition for Sustainable Rail (CSR) is dedicated to advancement of modern steam technologies, research and development of biofuels, and educational outreach. CSR is a 501c(3) nonprofit working in collaboration with the Natural Resources Research Institute of the University of Minnesota - Duluth to advance the state of the art in these areas. A scientific and educational organization, CSR's mission is to advance biofuel research and production; to research and develop sustainable railroad locomotives; to promulgate associated sustainable technologies; and to support and conduct non-partisan educational and informational activities to increase awareness of its mission.

About CSR's White Paper Program

Working in conjunction with the University of Minnesota (U of M), the Porta Family Foundation, and other not-for-profit rail and biomass research organizations, CSR's White Paper Program brings works pertinent to biofuel, modern steam locomotive and transportation research into the public discourse. This paper was authored at the request of the Advanced Steam Traction Trust Conference for presentation at its Autumn 2017 conference.

Cover Image - *A glimpse in the firedoor of the Milwaukee County Zoo engine number 1924 burning 100% torrefied biomass fuel. The locomotive is a 15 inch gauge 4-6-2 built by the Sandley Light Railway Equipment Works, Inc., in Wisconsin Dells, Wisconsin, U.S.A. in the 1970's.*

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Abstract

Economical and environmental concerns are shifting global energy markets away from coal towards natural gas and other technologies. Indeed the last colliery closed in the UK at the end of 2015. Steam locomotive operators are already experiencing difficulties in sourcing quality steaming coal at reasonable prices. Preserving the skills associated with solid fuel firing will thus become increasingly difficult for heritage operators. The Coalition for Sustainable Rail (CSR), in association with the Natural Resources Research Institute at the University of Minnesota - Duluth (NRRI), is working to stay ahead of this eventuality by developing a direct coal replacement employing sustainable biomass.

Preliminary results and a program is herein detailed, outlining steps being taken by CSR to perform instrumented testing and refinement of this material to-date. The project is specifically designed to reduce risk associated with development of the fuel by first conducting tests in quarter scale locomotives and then systematically moving toward larger, and larger equipment.

This project and tests would not have been possible without the support of CSR donors, the Milwaukee County Zoo, New Biomass Energy, and our collaborators at NRRI.

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As timeless as the steam locomotive itself, *the art of hand firing steam locomotives is a key piece of understanding the traditional role of fireman on the railroad.*

1. Introduction

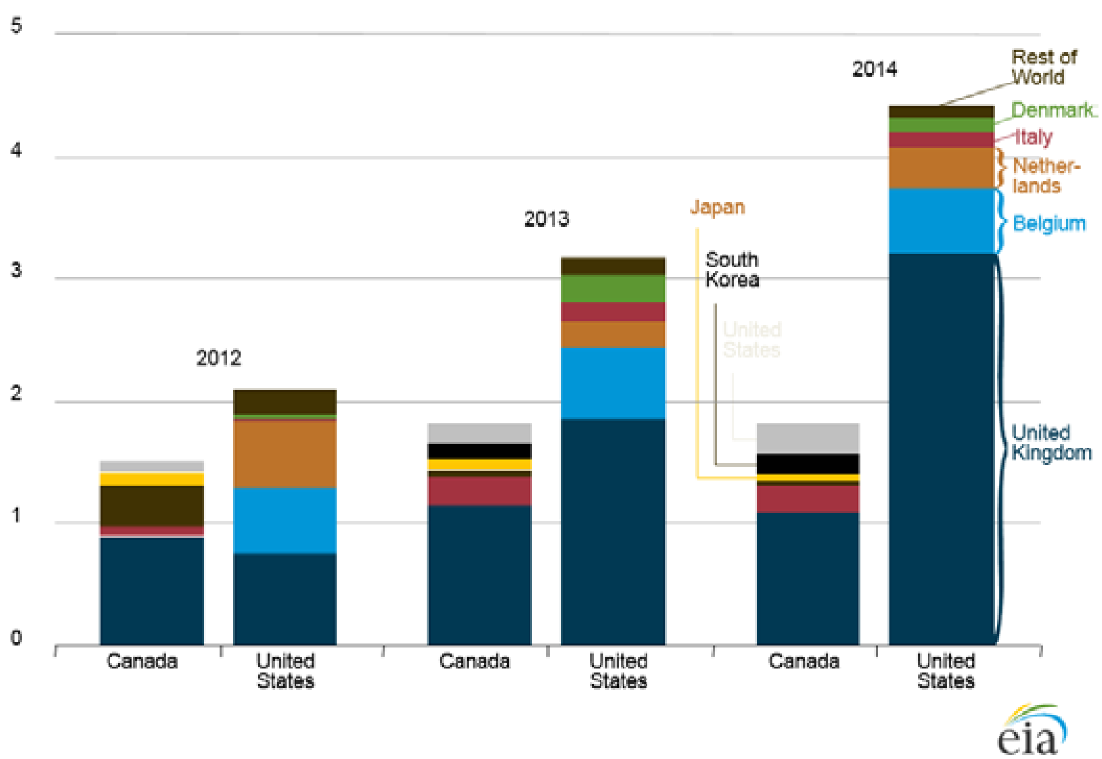
For about the first 100 years of their existence, steam locomotives relied solely on solid fuels - wood or coal - as their source of combustion energy. Indeed, even after oil firing was introduced in the late 1800s, coal was still the leading locomotive fuel and is the one most associated with steam traction. There is good reason for this. Coal is widely available around the world, fairly safe to handle, can be economically sourced, and typically has a favorable energy density. It is these later two points which account for its longevity as a fuel.

From the perspective of preserving steam locomotion, the techniques and technology associated with coal firing are important elements of the historic experience. From the perspective of advancing steam traction, coal presents unique opportunities and challenges given the current understanding of combustion including the GAS PRODUCER COMBUSTION SYSTEM. Both of these viewpoints can, however, be myopic when considered against global energy and environmental trends.

The reality of international energy and environmental trends is that there is a decided and growing shift away from coal to clean, cheap natural gas. To wit, the last colliery in the UK closed at the end of 2015. In the US, natural gas accounts for 33.8% of large-scale electricity generation while coal provides only 30.4% according to the US ENERGY INFORMATION ADMINISTRATION.

The shift to natural gas has already had huge impacts in the US. In 2016, coal shipments by rail dropped so dramatically that approximately half of the dedicated coal unit trains were sidelined. While there has been a minor resurgence in coal shipments this year, long term forecasts predict steaming coal consumption to drop by approximately 30% circa 2050 as more natural gas plants and renewables come on line. Even China is implementing policies which will see a major shift away from coal by 2040.

While the continued decline of coal may seem a long way off, perfecting, scaling up, and implementing production facilities for a coal substitute is a process for which the timeline is also measured in years. A recent article in TRAINS magazine and discussions with various operators confirm that US tourist railroads are already experiencing difficulty in sourcing reasonably priced, quality steaming coal. It is with this in mind that CSR is preparing now for a future with limited access to carbon coal.



***According to the EIA**, the graphic above represents the top five destinations for wood pellets exported from Canada and the United States. Note the significant growth in UK pellet demand - an increase of 47% from 2012 to 2014, a result, in large part, from the conversion of the DRAX plant in Northern England from coal to biomass.*

A Primer on Torrefied Biomass

Imagine a fuel with the same energy, density and material handling properties of coal, without the associated carbon footprint, heavy metal or sulfur content. The Natural Resources Research Institute (NRRI) at the University of Minnesota - Duluth is a leader in the efficient processing of cellulosic biomaterial into biocoal, has engineered such a fuel. Known as torrefied biomass (or biocoal), the fuel conversion process is a derivative of coffee roasting technology originally designed in the early 20th century in France (torrefaction = "to roast" in French).

This is not coffee roasting technology anymore. Raw biomass is heated up in a sealed, oxygenless environment to between 250 and 300 degrees Celsius, a process known as partial pyrolysis. In this temperature range, many of the volatiles in the woody biomass begin to decompose and part of the sappy lignin that binds the material together breaks down and vaporizes. This gas is captured in the sealed vessel, then returned to the original heat source to add to the combustion heat and increase the thermal efficiency of the reaction system. Research has shown that the fuel conversion process is in excess of 90% thermally efficient.

Once torrefied, the biocoal can be densified at a specific temperature into pellets, briquettes, bricks or any other shape, as requested by the end user. This permits the fuel to be of optimal size for handling and, ultimately, processing and combustion.

Why torrefaction?

Solid biomass, be it agricultural or forest product, is a readily-available, easily renewable fuel source that is easier and more efficient to combust and refine than liquid biofuels. That said, in its raw form, biomass has many attributes that make large-scale economic utilization difficult: its low density, high variability in energy content and the fact it absorbs water (hydrophilic) and will rot / offgas carbon monoxide.

The largest biomass export and utilization companies in the U.S. require large bunkers to keep the material dry, and they need to deal with combustible, poisonous carbon monoxide which, when contained in a sealed space, can be concentrated to a level that is fatal to humans.

NRRI is currently concentrating its efforts on the categorization and torrefaction of forest products, including its hybrid poplar tree population, a tree which grows to 50 or 60 feet in seven years. The raw poplar wood is roughly 6,500 btu/lb dry, contains a mix of volatiles, absorbs water, is difficult to grind and is relatively cumbersome to transport.

When torrefied, the energy density of the material increases to roughly 10,500 btu/lb, it no longer contains the mix of volatiles, it does not absorb water (hydrophobic), it is equally easy to grind as carbon coal and is very easy to transport, and the material only loses about 15% of its calorific value while being in excess of 90% thermally efficient to produce. It is, in fact, more energy efficient to torrefy certain biomaterials than it is to mechanically dry them in wood chip production.

What started as wood is transformed into a coal-like biofuel that features none of the heavy metals, sulfur, phosphorus or net carbon emissions of coal. The feedstock is also carbon-neutral, having sequestered carbon as it grew and, so long as the forest stock is sustainably managed, something in which NRRI is also a leader, will remain a carbon-neutral fuel source.

Torrefied biomass is regarded as one of the most efficient biofuel manufacturing processes available today. By recycling excess gas produced during the torrefaction reaction to optimize the manufacturing process, researchers at NRRI are able to achieve up-to 96% thermal efficiency in its production. As a point of comparison, the thermal efficiency of charcoal production is 20-40% and the production of bio-diesel and soy-diesel is often close to zero, if not negative.

Properties of Wood and Wood Drying

As with all biomass processes, the presence of water in the initial feed stock and refined product plays a huge role in the total efficiency of the torrefaction system. Standard metrics in the biomass industry to measure the energy content contained within biomass are the gross calorific value and net calorific value of the material.

In general, gross calorific value (GCV) refers to the absolute maximum energy available when the biomass is combusted. As it burns, the energy in the biomass is converted into heat and the latent heat which is necessary to liberate the water vapor from the system. The GCV minus the energy needed to liberate the water vapor is known as the net calorific value (NCV), which represents the applicable amount of thermal energy available during combustion of biomass.

As would be expected, the greater extent to which the water content of biomass is reduced prior to its combustion (i.e. dried), the higher the efficiency of combustion. It should be noted, however, that it is impossible to have GCV equal to NCV, even if there is 0% water in biomass due to the water vapor that is formed during the reaction.

That said, the drying of biomass exhibits a very beneficial trend: as biomass is dried and its mass decreases, the energy density (calorific value) increases. This inverse relationship is crucial to the overall thermal efficiency and feed / product ratio of the torrefaction process.

The Table One [BELOW] shows the effect drying has on one pound of pine chips, demonstrating the increase in GCV / NCV achieved when the pine chips are dried from 50% to 8% water content:

As can be seen, drying biomass yields a significant increase in the total NCV of the biomaterial with a loss in the overall mass, thereby effectively densifying the biomaterial on both the calorific and energy basis. In order to achieve drying, a significant amount of energy needs to be added to the system, which is used to drive off the water content (it takes about 1,000 BTUs to boil a pound of water). Unlike in a pellet mill, however, the external heat source needed to drive off vapor in a torrefaction reaction is very efficient, resulting in a minimal amount of energy needed both to drive off the water and to convert the biomass to biocoal.

Table One: Characteristics of Wood Drying

Pine Chip Biomass	Unit	Before Drying	After Drying
Water Content	% Mass	50%	8%
Mass Balance			
Water	lb	.5	.04
Dry Biomass	lb	.5	.5
Totals	lb	1	.54
Calorific Value (BTU/lb)			
GCV	BTU/lb	4385.2	8039.6
NCV	BTU/lb	3568.3	7437.7
Energy Content (BTU)			
GCV	BTU	4385.2	4385.2
NCV	BTU	3568.3	4016.4

The Basics of Torrefaction

Torrefaction is a mild pyrolysis process that takes place between roughly 225 and 300°C that improves the energy density and material properties of wood, thereby creating what is hereafter referred to as "biocoal." Essentially, cellulosic biomaterial is heated to the aforementioned temperature range in the absence of oxygen in order to drive off roughly 5-50% of the volatile materials (and only 10% of the energy content). The end product is a hydrophobic, easily-transportable fuel that, thanks to the sequestration of carbon and to the efficient process (including drying, up to 96%), is carbon-neutral.

Adding to the attractiveness of this fuel production process is the potential of torrefaction reactors to handle a variety of input feedstock, including traditional woody biomass, waste stream biomass and agricultural waste. It is important to note, however, that the primary thrust of research at the NRRI to date has focused on the "low-hanging fruit" of woody biomass thanks to its easy handling and abundant quantity in the Minnesota.

The torrefaction process results in a partial carbonization of biomass, making it moisture-free and friable, more akin to coal than biomass. Biocoal is not charcoal, however, and its manufacture results in a larger retention of woody volatiles in the material, resulting in a net higher energy availability than charcoal. In addition, the thermal efficiency of charcoal is significantly lower than that of biocoal and, thanks to the partial pyrolysis and remaining lignin in torrefied material, it may be pelletized / briquetted while the biomass is warm, making it easy-to-transport.

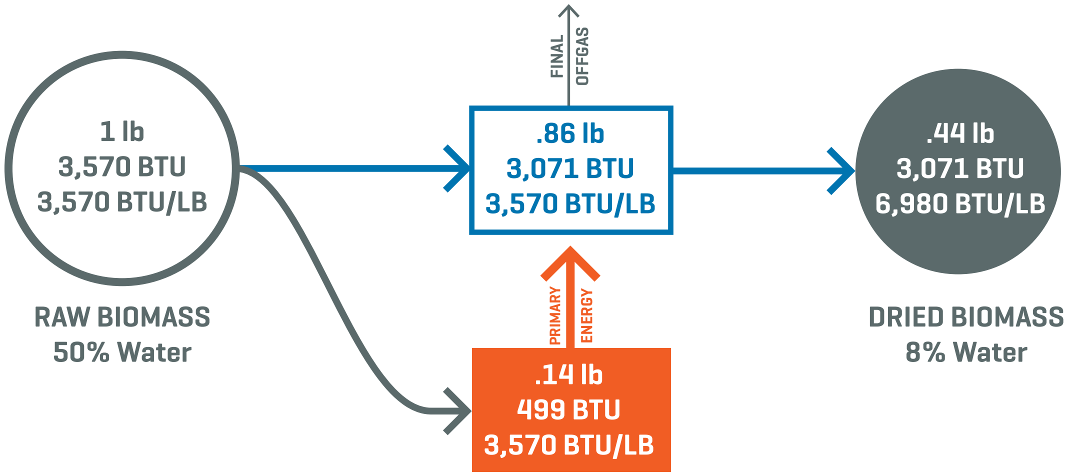
It should be mentioned that challenges remain in regards to identifying the appropriate densification technique for torrefied biomass. NRRI has on-going programs looking at rotary compaction, ram compaction and die pelleting. Preliminary findings indicate dry solids loss (DSL) plays a significant role on how well the torrefied biomass can be densified without residual binders. In addition, the resulting hydrophobic character of the material is of critical importance if it is to be stored outside while not appreciably taking on water from rain events. NRRI has ongoing trials to characterize the wetability and hydrophobic profiles across a variety of densification techniques (with and without residual binders). This is of critical importance if indeed the biocoal is stored outside--- and may be of less importance if it is not stored outside.

Table Two (BELOW) outlines general characteristics of biocoal when compared to a selection of similar solid fuels.

This table indicates that there is a great deal of benefit to torrefying biomass as compared to simply pelletizing wood or creating charcoal. As outlined in the previous section (see Table One), it is understood that a substantial amount of energy is required to remove water from biomass in the drying process (if the end product is 11,000 $^{BTU}/_{lb}$, and one half pound of

Table Two: Characteristics of Solid Biofuels Compared to Biocoal

Characteristic	Wood	Wood Pellets	Biocoal	Charcoal	Coal
Moisture Content (% wt)	30 - 45	7 - 10	**1 - 5**	1 - 5	10 - 15
Calorific Value (BTU/lb.)	3850 - 5100	6450 - 6850	**8600 - 11000**	8000 - 9500	8600 - 13500
Volatiles (% db)	70 - 75	70 - 75	**55 - 65**	10 - 12	15 - 30
Fixed Carbon (% db)	20 - 25	20 - 25	**28 - 35**	85 - 87	50 - 55
Bulk Density (lb/cu. ft.)	12.5 - 15.6	34.3 - 46.8	**46.8 - 53.1**	12.5	49.9 - 53.1
Vol. Density (BTU / cu. ft.)	53.7 - 80.5	201.3 - 279.1	**402.6 - 501.9**	161.0 - 171.8	493.8 - 638.8
Dust	Average	Limited	**Limited**	High	Limited
Hydroscopic Properties	Hydrophilic	Hydrophilic	**Hydrophobic**	Hydrophobic	Hydrophobic
Biological Degradation	Yes	Yes	**No**	No	No
Milling Requirements	Special	Special	**Classic**	Classic	Classic
Handling Properties	Special	Easy	**Easy**	Easy	Easy
Product Consistency	Limited	High	**High**	High	High
Transportation Cost	High	Average	**Low**	Average	Low



water was removed, then the net thermal efficiency is [11,000-500]/11,000 or 95%... just to dry the wood).

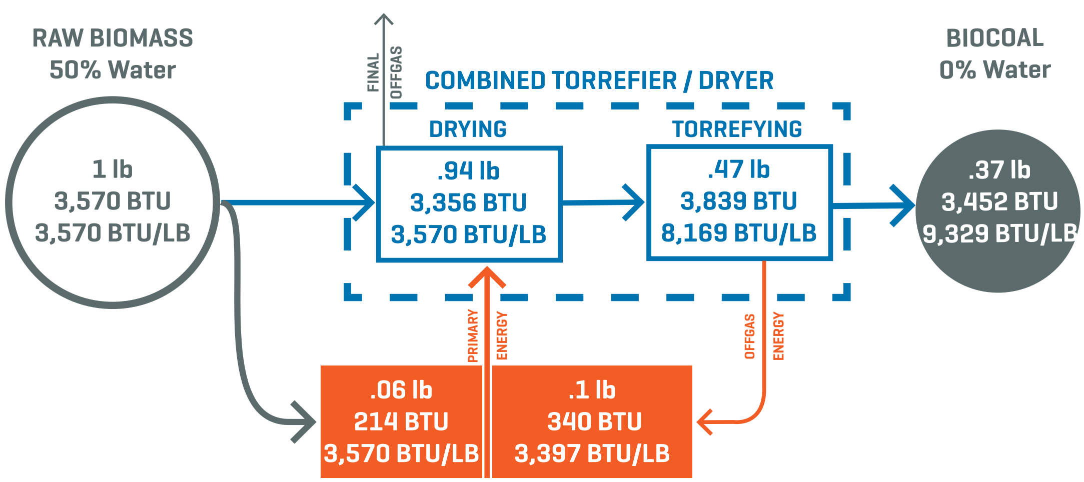
When a system becomes more efficient, however, there are many ways in which overall thermal efficiency is improved.

The diagram ABOVE is a graphic that shows the data from Table One in visual form. This shows that just under 500 BTU are required to dry the wood, resulting in a thermal efficiency of roughly 87% to create a wood substance of 8% water content and a density of 8,169 BTU/lb.

When referencing Table Two, however, it is evident that dried wood pellets do not exhibit the beneficial transportation and materials handling properties of biocoal, let alone the energy or cubic density.

Utilizing the same set of initial parameters, The diagram BELOW shows an efficient model torrefaction process in which the torrgas generated, amounting to roughly 20% of the feedstock mass and 10% of the feedstock energy, is utilized to supplement the heat provided at the dryer. In practice, the drying and torrefaction are two separate unit operations taking place in separate vessels. The diagram shows the breakdown of total energy usage.

In this case, instead of being dried to 8% water content, the torrefied biomaterial is dried to 0% water content. Interestingly enough, as much as 340 BTUs of the 514 BTUs needed to drive out the water in the feedstock is provided by the torrgas driven off in the reaction. In the end, the total net required energy for the reaction is 118 BTUs (note the loss in mass during the process), thereby resulting in a thermal efficiency of 96% in the torrefaction of the material.



The feed / product ratio in this example is 2.66. In determining what would warrant a full-scale torrefaction plant, say 100,000 tons produced per year, this would mean 266,000 tons of sustainably-harvested biomass would need to be delivered to the plant annually. Though large on paper, this equates to roughly eight railcars of biomaterial in and three railcars out of a production plant each day.

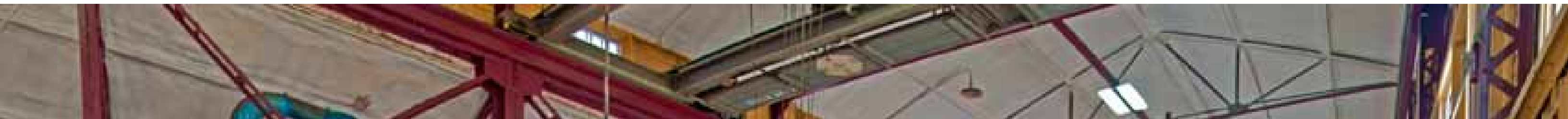
Current CSR / NRRI Research

In addition to the steam locomotive fuel testing discussed at length in the balance of this paper, current research is focusing on the development of an integrated torrefaction reactor and small-scale, distributed generation power plants.

The benefit of easy-to-operate, easy-to-maintain steam-based electrical generation is an opportunity that has been all-but overlooked that, when combined with a fuel homogenization system like torrefaction, has the potential to generate significant benefit in both the U.S. and overseas.

Furthermore, CSR and NRRI are investigating how the torrefaction of pest plants, such as kudzu in North America and water hyacinth in Africa, can create a fuel product capable of easily powering generators on a distributed basis, or large-scale power facilities. CSR provided NRRI with kudzu for torrefaction, producing promising results. What began as RAW KUDZU with 6.8% moisture and 7,802 BTU/lb became TORREFIED KUDZU with 0% moisture and 9,868 btu/lb, a 21% increase in energy density and a fuel with greater energy density than the most-used coal in the U.S. Furthermore, CSR has been investing effort into determining the feasibility of converting used railroad ties into torrefied biomass, a process that on the laboratory scale has been achievable with near-total removal of the creosote preservative, essentially "cleaning" the railroad tie material through torrefaction.

The benefit of having NRRI as a research collaborator is that it maintains a facility capable of scaling research up from bench scale to pre-production. At its Coleraine Energy Labs, a recently-completed $2.5 million facility, NRRI is able to make up-to six tons of torrefied material per day. This is thanks to the installation of a sizeable torrefaction reactor and material handling equipment unlike any used elsewhere in U.S. higher education.

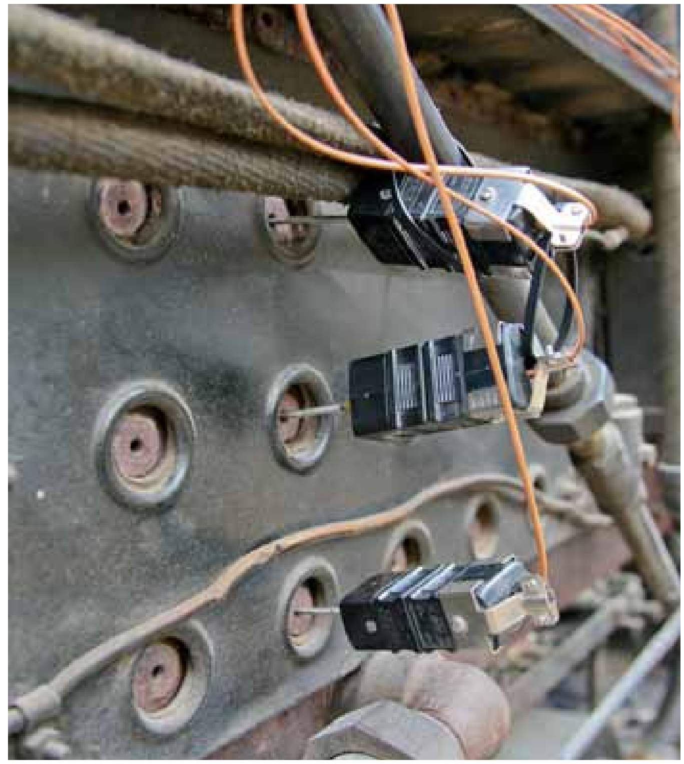


Experience Testing Biocoal

A steam locomotive burns fuel quite differently than the power plants and laboratory test equipment that NRRI researchers had previously used to gain experience with torrefied biomass. Testing on full-scale locomotives was deemed too costly and risk-laden as both the fuel and data acquisition systems would need to be validated. CSR therefore arranged to conduct initial testing on the 15 inch gauge railway at the Milwaukee County Zoo.

Locomotive No. 1924, a 4-6-2, was selected for instrumentation as its through-drilled tell-tale holes made for easy installation of Inconel-sheathed thermocouples at several heights within the firebox. The locomotive is also notable as it features a suspension not unlike Dante Porta's CARIO design. The diagram BELOW shows the general setup of the first round of testing undertaken by CSR.

RIGHT - *Thermocouples placed through staybolt tell-tale holes.*



LOCOMOTIVE Nº. 1924

MANUFACTURER:	**SANDLEY, 1977**
TRACTIVE FORCE (lbs.):	**2,070**
LOCOMOTIVE WEIGHT (lbs):	**14,000 (Approx.)**
FIREBOX GRATE AREA (ft²):	**4.375**
BOILER PRESSURE (psi):	**200**
DRIVER DIAMETER (in.):	**21.75**
PISTON W x L (in.):	**5.5 x 8**
TRACK GAUGE (in.):	**15**

Testing: Round One

The challenges of coordinating between laboratory-scale production facilities, an operating railroad, and volunteer researchers can lead to compromises. In the case of the initial biocoal tests at the Milwaukee County Zoo, NRRI researchers were unable to densify their materials in time, so CSR was graciously donated smaller, pellet sized fuel by New Biomass Energy just in time for the scheduled tests in June 2016.

While the smaller size burns well in a pellet stove, it was deemed incompatible with the ¾" openings in the locomotive's pinhole-type grates. The CSR team therefore improvised a temporary layover grate using stainless steel mesh and spacer bars. As shown in the image below, the locomotive also lacks an arch.

Data acquisition hardware from National Instruments, thermocouples from Omega Engineering, and a custom LabView program allowed second-by-second data logging and real-time display on a laptop located in the car behind the locomotive.

ABOVE *- A zoomed in view of the small pellets combusting in the firebox.*
LEFT *- The modified grates (bottom) with thermocouples sticking in (left).*

During steam-up, the biomass proved to have adequate heat and was markedly cleaner than coal. A lap around the zoo proved that the biocoal could keep steam up, but the lack of arch and small size of the pellets resulted in the fireman shoveling frequently. Furthermore, the small fuel particles became entrained in the exhaust, resulting in more burning embers being emitted from the stack than CSR found acceptable.

The cylindrical shape and small size (packing factor) of the pellets when coupled with the thicker firebed found by the fireman to be needed to maintain steam did, however, tend to lead more smoky combustion in actual service as compared to hostling. Both the ember and smoke problems were thought to be correctable with biocoal sized similarly to that of the coal normally used - approximately 1.25" to 2".

Before and after the biocoal trials, additional data with coal was recorded, during the normal operating day, to provide a baseline for comparison. Results of the baseline comparison is shown on page 19 of this report.

Zoo officials and train operating staff were sufficiently impressed with the cleanliness of the fuel that they agreed to another round of testing once a batch of larger sized fuel could be acquired. CSR reported its findings back to NRRI, and the two organizations set to work identifying a means to refine the pellet.

ABOVE *- This was the darkest the smoke became during these tests, shown here just in preparation to depart the servicing facility. The small particle size lead to a very tight packing of the fuel, promoting smoke.*

ABOVE RIGHT *- A view showing the size of the pellets used.*

RIGHT *- Wolf Fengler cranes his head to observe the stack, with the data recording laptop logging second-by-second temperature data.*

BELOW *- An overview image of the 1924 as set up for its tests, including sensor wiring and thermocouples.*

Testing: Round Two

By late summer of 2016, NRRI was nearly ready to provide a batch of the larger sized fuel, so arrangements were made for another series of tests in October. NRRI had refined the manufacturing process of the large biofuel reactor, though the densification, and scalability of said densification, was still in development.

NRRI generated two, 55 gallon drums of torrefied biomass fuel for CSR to use in tests at the Zoo. As it turns out, this was the very first batch of fuel manufactured in the Coleraine Energy Labs' then-new industrial scale torrefaction reactor.

Instead of using a smaller, extrusion-style pelletizer as was employed in making the first batch of fuel, two dedicated NRRI researchers spent nearly a week using a cylindrical ram briquetter, which densified approximately 32 cubic inches of loose biomass into a 2 cubic inch puck, to create the approximately 500 pounds worth of fuel. These new pellets were cylinders approximately 1-1/2" in diameter and up-to 2" in length. Instead of using any after market binder to hold the pellet together, NRRI employed bag house fines, the torrefied biomass dust captured during manufacture, as a binding agent.

As with the previous tests, locomotive No. 1924 was again equipped with the same test equipment and the locomotive was fired up. Thanks to the larger torrefied biomass pieces, the fuel packed less densely, allowing for better air circulation. Right away, the fuel showed itself to be significantly cleaner than the coal it replaced, not to mention burning with much less smoke than the smaller pellets burned in the first test. Even with a heavy layer of biocoal shoveled, the stack rarely indicated more than a translucent gray haze.

We fired up the engine with the torrefied biomass fuel and, again, undertook laps around the railroad. The fuel exhibited good steaming potential and similar firing temperatures to coal, but still showed slightly too much spark entrainment, something deemed unacceptable by the CSR test crew.

The culprit for the spark entrainment is theorized to be the lack of uniform densification. Due to the densification technology and binder used, CSR and NRRI determined that the fuel was not homogeneously dense throughout each piece. While the outside edges of the fuel were found to be quite dense, the inside of the cylinder was noticeably less dense. This, combined with the binder used, resulted in pellets that would flake apart into small fines when heated up during combustion.

Note in the image above the readily crushed (by hand) biocoal pieces. A close examination of the combustion process showed that the biocoal was expanding during combustion and quickly decomposing into its smaller constituent fibers. This difference in density and surface area also account for the faster lightoff and burnout of the material, as was noted in the data.

While not optimal, the results were again encouraging and pointed the research team to focus on densification and binding techniques as key to the success of the fuel.

ABOVE *- Wolf Fengler crumbles one of the test pellets in his hand.*

OPPOSITE TOP *- Coal burning 1916 [L] with biocoal burning 1924 [R]. Pictured are [L to R]: Davidson Ward (CSR); Ken Ristow (Zoo); Rob Mangels [CSR]; and Wolf Fengler (CSR).*

RIGHT *- These two images compare the combustion characteristics of coal vs. torrefied biomass during fireup. The coal was typically smoky, while the biomass, even upon significant stoking, seldom made smoke.*


1916
1924

With full steam and throttle, *No. 1924 lugs its 10 car train up the 3% grade leading from the shop to the Zoo mainline, burning 100% torrefied biomass. This was the darkest we saw the stack all day burning biofuel.*


1924

Comparing Tests 1 and 2

The results of both biocoal/coal comparison tests, one in June with small pellets and one in October with large pellets, are shown BELOW and in the charts on PAGE 19. It is interesting to note the difference in maximum temperatures between the tests, a function most likely of the difference in grates and the impact they had on the coal firebed. Both graphs took data recorded on two runs and synced them up, shifting the data along the "x-axis" to relate to similar segments of the railroad.

Note that the torrefied biomass fuel is quicker to ignite than coal and, similarly, that it is quicker to fall off in temperature than coal. This is particularly evident when comparing the findings of the October tests, wherein fuel of analogous sizes were burned. The densification of the fuel certainly caused a difference in combustability, since the less compacted torrefied biomass tended to fray apart, enabling quicker combustion.

Given the differences in the energy content and bulk density of the fuels, these are logical results. Since the torrefied biomass pellets were of lower bulk density and of higher porosity, the increased surface area enables them to ignite quicker. The lower bulk density also means that the fuel reacts and burns quicker, resulting in a more rapid dropoff in temperature. That said, torrefied biomass burned with similar heat to coal on average, but the peak coal temperature was approximately 100 degrees hotter than the torrefied biomass.

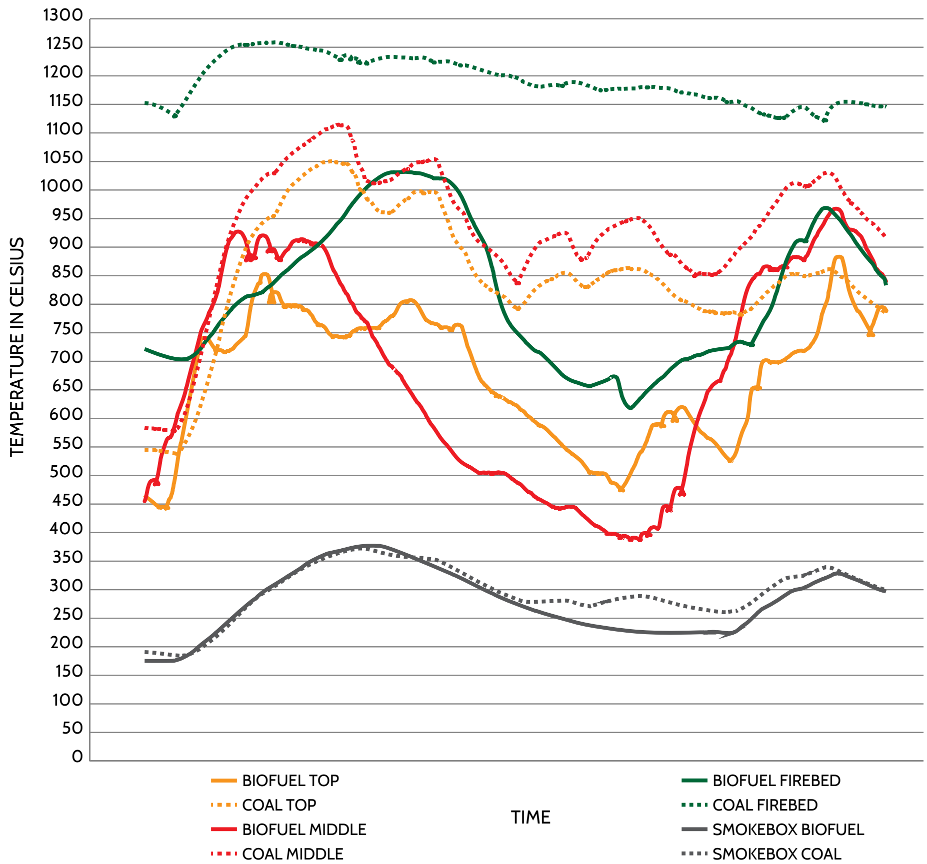
The foregoing combined with the lack of ideal densification binder on these tests resulted in the fuel tending to break apart prematurely when combusted, leading to fuel particles becoming entrained in the exhaust stream. This has led CSR and research collaborator NRRI to focus primarily on ensuring the fuel is densified more uniformly.

We should note that, due to the scale of the locomotive, with 22" driving wheels, the tests were undertaken over a "scale" distance of 6 miles of railroad and a top scale speed of approximately 40 miles per hour.

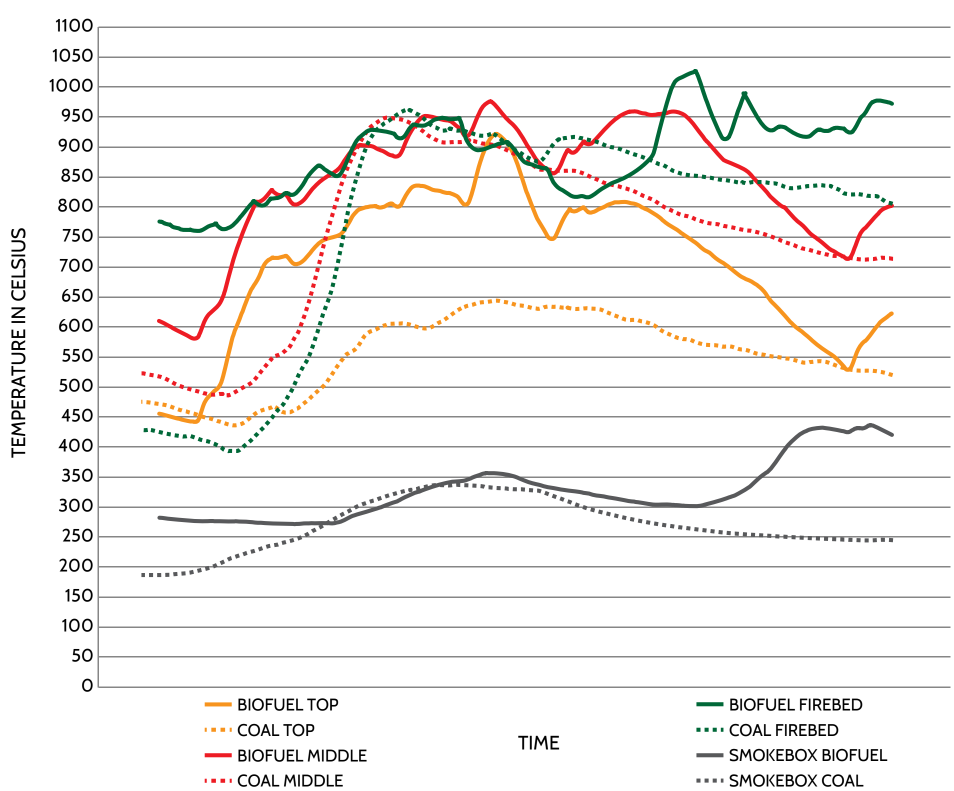
***Test One** - Fuel and flame pattern while hostling.*

***Test Two** - Fuel and flame pattern while hostling.*

June Tests - Small Pellets vs. Coal



October Tests - Large Pellets vs. Coal



Future Research

The results of the first two tests of the torrefied biomass in No. 1924 has helped significantly in identifying the next areas of research, primarily improvement to the densification process. As noted, the expansive firing properties of the fuel produced using the current production process led to challenges with combustion in locomotives. Fortunately, there are two new treatment processes being scaled up by NRRI that appear to solve these issues.

The first was the installation of a new pelletizing machine at the Coleraine Energy Lab. With this pelletizer, the researchers are able to generate upwards of 1,500 pounds of densified material per hour with a uniform, half-pill-shaped product [shown below]. This product, combined with an industry-standard biomass binder at 1% mass, has shown significant increases in durability and lack of friability. During tests completed in September 2017, this new fuel burned nearly smoke free and with a very similar decomposition process as coal.

The second new process is known as Hydrothermal Carbonization (HTC). This technique converts biomass while suspended in a liquid, typically water, by subjecting it to elevated temperatures and pressures (on the order of 500 degrees Fahrenheit and 1,000 PSI). These temperatures and pressures result in the carbonization of the woody biomass, resulting in biomass that features improved energy density. In essence, the product is nearly identical to that made in the traditional torrefaction reactor, but the process preserves some of the lignins of the feedstock, which otherwise would be usually liberated in the traditional torrefaction reactor. The lignin of certain plant species has been found to have better binding properties than others. Thereby a biocoal producer can optimize the fraction and species of biomass sent to a torrefaction reactor or HTC reactor to balance processing costs, energy density, and the binding characteristics of the final product.

ABOVE *- A view of the larger fuel pieces made in the newly-acquired pelletizing machine at NRRI's Coleraine Energy Lab.*

CSR personnel conducted a hardware review of the scaled up HTC reactor at the NRRI facility in March 2017. The reactor is set to be online in Q4 of 2017.

CSR is scheduled to return to the Milwaukee County Zoo to test the optimized fuel in November 2017. NRRI has agreed to make multiple blends of fuel, including fuels using commercial binders, HTC binder, and a blended torrefied biomass / pulverized coal fuel. Assuming all goes well, CSR will undertake testing on a standard gauge 2-6-0 on the Everett Railroad in Pennsylvania. Several other steam operators have also expressed interest in testing the fuel, so subsequent tests will see the product being evaluated in larger locomotives up to mainline, stoker-fed machines.

GPCS Operation

CSR has also designed a stationary boiler-reciprocating steam engine-based power generation system as part of a large research grant it was awarded with NRRI. The boiler fabrication of this 100 kW power plant should begin in late 2017 or early 2018. Of specific note to this research is that the boiler has been designed specifically to test the biocoal in a firebox purpose-built for the Gas Producer Combustion System. The boiler features a deep firebed that should support the evolution of high calorific value producer gas. Inlet air preheating is also provided for both primary and secondary air.

An automatic firing system with clinker grinding grate has also been conceived, although the low ash content of the fuel and provision for steam injection under the grate should mitigate any clinkering tendencies. That unit should be under test sometime late in 2018.

This opportunity allows CSR to push the state-of-the-art as it pertains to advanced, locomotive-boiler-based steam engineering, albeit in stationary form. It also provides a test platform, to be located directly adjacent to the biocoal manufacturing facility in Coleraine, in which to continue perfecting this fuel research.

ABOVE *- Everett Railroad No. 11 will serve as the testbed for the next scale of tests, thanks to the generosity of the railroad. This photograph, by Oren B. Helbok, nicely shows the scale of this standard gauge 2-6-0.*

Conclusions

Our tests, in both the laboratory and the first two rounds at the Milwaukee County Zoo, have proven that the torrefied biomass fuel has sufficient heating energy to generate steam. These tests have also illustrated the need to focus significant effort into optimizing the densification of the material.

We remain confident that our research collaborators at NRRI will be able to develop an ideal blend of fuels / binders to sufficiently replicate the carbon coal used by the operators of solid fuel-fired steam locomotives and other historic Rankine cycle-powered equipment. The softer, wood-based torrefied biomass has been shown to be less abrasive to the boiler surfaces (e.g. less cinder cutting), and the lower ash and moisture content results in a more efficient combustion process overall. We are confident this will lead to a fuel that will allow historic rail operators to continue to use their equipment as originally designed and benefit from a fuel that is less damaging to the locomotives and the environment.

What this research process has reinforced, above nearly all else, is that developing an experienced, and skilled, collaborative research team is key to undertaking such an effort. CSR has been fortunate to work with NRRI, the Zoo, New Biomass Energy, and other organizations to advance this cause, and we look forward to the opportunity to take our testing to the next level, thanks to the generosity of the Everett Railroad. It was through an interdisciplinary approach, one that brought together researchers from multiple backgrounds, that we were able to develop the torrefied biomass fuel, instrumentation plan, and overall research approach.

Perhaps the single biggest conclusion is the fact that research is iterative, and persistence is key to achieving a reliable, new product. We have been able to refine our research needs following each of the tests, and NRRI has reacted in kind, providing new blends of fuels that have responded to our needs.

We are passionate about the history, and future, of steam locomotion, and it is something we want to share with our children and grandchildren for years to come. The preservation of the art of hand firing in the face of decreasing availability of coal is a key component of keeping the history of steam alive.

The use of 100% torrefied biomass fuel, or a blend of torrefied biomass and coal, could very well be a viable solution to keeping historic steam locomotives on the rails for the next century. CSR looks forward to addressing these challenges over the coming few years, and we welcome those interested in supporting our research, be it through collaboration or contribution, to contact CSR to see how to get involved.

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