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Use of Tamarisk as a Potential Feedstock for Biofuel Production

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Use of Tamarisk as a Potential Feedstock for Biofuel Production

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Abstract

This study assesses the energy and water use of saltcedar (or tamarisk) as biomass for biofuel production in a hypothetical sub-region in New Mexico. The baseline scenario consists of a rural stretch of the Middle Rio Grande River with 25% coverage of mature saltcedar that is removed and converted to biofuels. A manufacturing system life cycle consisting of harvesting, transportation, pyrolysis, and purification is constructed for calculating energy and water balances. On a dry short ton woody biomass basis, the total energy input is approximately 8.21 mmBTU/st. There is potential for 18.82 mmBTU/st of energy output from the baseline system. Of the extractable energy, approximately 61.1% consists of bio-oil, 20.3% bio-char, and 18.6% biogas. Water consumptive use by removal of tamarisk will not impact the existing rate of evapotranspiration. However, approximately 195 gal of water is needed per short ton of woody biomass for the conversion of biomass to biocrude, three-quarters of which is cooling water that can be recovered and recycled. The impact of salt presence is briefly assessed. Not accounted for in the baseline are high concentrations of Calcium, Sodium, and Sulfur ions in saltcedar woody biomass that can potentially shift the relative quantities of bio-char and bio-oil. This can be alleviated by a pre-wash step prior to the conversion step. More study is needed to account for the impact of salt presence on the overall energy and water balance.

Acknowledgments

The authors would like to acknowledge the following for their valuable input and extensive regional expertise about tamarisk population along the Middle Rio Grande: Amy Hoy of River Brink, LLC, Valerie Williams of Bureau of Land Management Taos regional office, Carl Colonius of Rocky Mountain Youth Corps, and Walter Dunn of USDA Forest Service.

The authors would like to thank Alex Brown, Jesse Roberts, and Ben Wu from Sandia National Labs for background information on biomass conversion technologies and water consumptive use. The review comments by Geoff Klise and Todd West are gratefully acknowledged.

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Executive Summary

Tamarix spp (or. saltcedar) is classified as an invasive shrub in the western United States. Introduced in the 19th century as a candidate for riparian restoration, saltcedar has thrived under arid and semi-arid climates and replaced much of the native landscape along Western rivers. In New Mexico, saltcedar is present along rivers such as the Rio Grande, Pecos, and Gila. It is estimated that there are 900,000 acres of saltcedar, spreading across Arizona, Utah, Colorado, Texas, New Mexico, and parts of California, Wyoming, Nevada, Oklahoma, and Kansas [USGS 2009-5247]. Efforts to remove saltcedar are numerous and with mixed results. Mechanical removal is by far the most common mechanism for controlling the spread of the plant, and great effort is put into monitoring the spread of saltcedar [National Institute of Invasive Species Science; Tamarisk Coalition, 2009].

In this study, the potential of harvesting saltcedar for biofuels production is investigated in conjunction with a small New Mexico business located near Taos, New Mexico. The potential site for saltcedar harvest is assumed to be along the fluvial plain of Middle Rio Grande in northern New Mexico, downstream from the Taos Junction Bridge. The area is inclusive of the Orilla Verde Recreation area. In order to establish a system for how saltcedar can be harvested and converted to biofuels, we propose a baseline life cycle analysis that evaluates energy and water footprints of converting woody biomass to biofuels [EPA/600/R-06/060, 2006].

In a life cycle analysis, stages for harvesting, transporting, and converting tamarisk are first defined. Each stage has multiple options, but only one is chosen as a baseline. For harvesting, we calculate an annual yield of 3.71 tons per acre. There is *no* additional cultivation of saltcedar as it is assumed to be readily available and removal is part of its control strategy. The mechanical method for removal is manual cutting. Transportation of saltcedar to a biofuel processing area is assumed to be minimal. The baseline system assumes air drying of woody biomass from 50% moisture content to 30% in 8-10 weeks, then heat drying down to 10% before the biomass is chipped and fed into a pyrolysis unit.

The conversion unit is assumed to be a mobile unit capable of processing up to 200 kg/hr of biomass and co-located within 1-mile radius of the harvesting site. A mobile unit is suitable because of the large areal coverage needed for harvesting saltcedar. Thus far, the conversion technology demonstrated for a mobile unit is based on a thermochemical conversion technology for breaking down lignocellulosic biomass. The pyrolysis unit is capable of converting biomass into a combination of bio-crude, bio-char, and gas. Gas can be used as a fuel input for the conversion unit while bio-crude and bio-char can potentially be sold in the merchant market. Bio-crude still needs post-conversion treatment to purify into bio-oil.

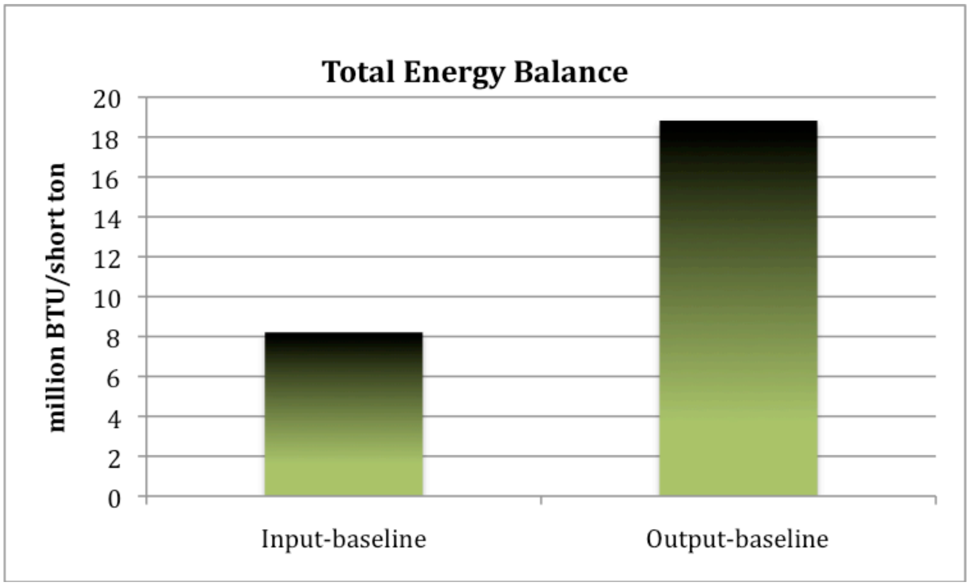

Figure ES-1 Total Energy balance of baseline saltceder-to-biocrude system.

As shown above, the total energy balance of the baseline system yields a total energy input of approximately 8.21 million BTU per short ton (mmBTU/st) and a total energy output of approximately 18.83 mmBTU/st). This does not account for the energy requirement for processing and distribution of biofuels/bioproducts post-conversion. We studied the sensitivity of energy input as a function of hauling distance. The net energy gain will be lost if the hauling distance is >20 miles. The sensitivity of total extractable energy is dependent on the technology chosen for the conversion. We have seen a range of 12 to 20 mmBTU/st depending on different conversion processes.

Water consumptive use due to evapotranspiration is expected to remain the same with saltcedar-to-biofuel operation. Nominal evapotranspiration quantity ranges from 0.8 to1.2 meter/year in New Mexico. However, approximately 195 gallon of water is needed per short ton of biomass for the conversion step to biofuels. Three-quarters of this amount makes up the cooling water for condensing hot gas from the pyrolysis process; cooling water can be recovered and recycled if needed.

Rural communities that have less access to energy can benefit from biofuels generated from this source. Nevertheless, there are a number of challenges that still need to be investigated thoroughly. Presence of salt greatly influences the rate of thermal degradation in a pyrolysis unit. There is experimental evidence of greater bio-char formation with a slight increase in salt concentration. This can be alleviated through a pre-wash step during pretreatment of saltcedar. Other considerations that need to be assessed include a detailed cost analysis as well as better understanding of the impact to river management and riparian ecology.

It is important to acknowledge that this study is purely hypothetical in its establishment of the biomass-to-biofuel cycle. The authors have not considered possible management and logistical barriers due to existing ecological and regulatory management practices and policies imposed in the area.

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1. Introduction

Saltcedar (or tamarisk) is the third most abundant invasive plant in Western United States. Introduced in the 19th century as a candidate for riparian restoration, saltcedar has thrived under arid and semi-arid climate conditions and has replaced a large amount of the native landscape along rivers in New Mexico such as the Rio Grande, Pecos, and Gila [Everitt, 1998; USGS 2009-5247]. A wealth of scientific information has been collected about its ecological impact to native plant growth, surface and sub-surface riparian hydrology, and wildlife habitat. Similarly, multiple federal, state, and local organizations have experimented with various management strategies to restore the native habitat in the region [Tamarisk Coalition, 2009; USGS 2009-5247].

As a shrub, saltcedar can reach a height up to 20 ft with woody stalks in just 5-6 years along the Middle Rio Grande in New Mexico [Everitt, 1998]. Figure 1 shows a typical saltcedar shrub.

Figure 1. *Tamarix ramosissima*, commonly known as tamarisk or saltcedar.

Tamarisk's common name suggests a tolerance for salinity, which gives it a competitive advantage for germination. Under prolonging-stressed conditions, increased salinity in the river favors germination of saltcedar relative to native plants. More importantly, a portion of the salt uptake from the plant gets deposited into the soil during winter, further impeding the growth cycle of native plants such as cottonwood [Shafroth, 1995].

Historically, control of saltcedar involves mostly mechanical removal (slash & burn) or a combination of mechanical removal with application of herbicide [Bureau of Reclamation, 2010]. The management objective of infested areas is to restore the native habitat in affected areas. Little has been done to assess its potential as a feedstock for biofuel. A study by the USDA Forest Products Laboratory analyzed the potential for converting tamarisk into wood fillers for plastics [USDA, 2007]. This study piloted a process to convert tamarisk logs into wood chips and further decompose into wood-based fillers that can be mixed with molten polymers for plastic pellet production.

There has been a long debate regarding the impact of saltcedar to the fluvial hydrology in the region. Saltcedar has a deep root system that reaches the water table of fluvial plains. The mechanical removal, in theory, should result in less water uptake, leaving more water in the river. Nevertheless, there is evidence that the impact of saltcedar removal has not resulted in significant improvement in the surface water flow because of growth of other species (native and non-native) replacing saltcedar to the area. The rate of evapotranspiration for saltcedar averages about 0.8-1.2 meter/year [USGS, 2009; Rosel, 2006].

Sandia is collaborating with a New Mexico small business to assess the use of saltcedar as a renewable energy source. The objective of this study is to investigate saltcedar's potential as a feedstock for biofuel. Rather than pursuing an analysis adopted for agricultural production of a new feedstock, tamarisk is treated as a woody-plant that is already overgrown and widespread. Specifically, areas along the Middle Rio Grande river within New Mexico would serve as the geographical location for considering such an operation.

We use this opportunity to investigate a set of questions and carry out a preliminary analysis:

1) **Would saltcedar be a suitable feedstock for small-scale biofuel production?**
2) **What are the possible technical pathways for converting saltcedar into biofuels?**
3) **What are the water and energy footprints?**
4) **What is the cost of producing biofuels from saltcedar?**

Chapter 2 focuses on defining a framework for a life cycle analysis. There are many options for creating hypothetical scenarios for use of saltcedar as a potential biomass for biofuel. Chapter 3 focuses on a baseline analysis for harvesting saltcedar and converting to biocrude. The baseline system is foundational in a life cycle analysis to establish a reference point. The assumptions applied and the parameters used are described. Categories for energy input and output are laid out for the overall energy balance. Chapter 4 addresses the results of water balance for the baseline system. Chapters 5 and 6 discuss the sensitivities and technical challenges associated with realization of saltcedar-to-fuel pathway respectively. Finally, Chapter 7 provides a summary of this work and describes additional efforts that would further substantiate the preliminary results provided in this analysis.

2. Life Cycle Analysis

2.1. Overall System Options

Figure 2 shows the a complete life cycle stages for saltcedar collection, conversion into biofuels/bioproducts, distribution, and end use. It is important to understand that the options proposed here are ones that are most applicable to saltcedar growing along river banks in high desert areas, such as the Middle Rio Grande in New Mexico.

As mentioned in Chapter 1, the life cycle of saltcedar assumes that it will be relatively abundant along riparian areas of the Rio Grande. The benefit of deriving biofuel/bioproducts from saltcedar is to control the spread of saltcedar as well as generating renewable fuels (solid or liquid) from this invasive species. The study takes account the entire life cycle energy balance to understand the energy value of saltcedar as a potential biofuel feedstock, a necessary step to consider energy and water footprints of its feasibility [EPA/600/R-06/060, 2006; Larson, 2005]. This chapter describes the various options during each step of the life cycle.

There are five broad categories: harvest, transport, conversion, distribution, and end use. Within each category, there are multiple options that are all accessible for saltcedar.

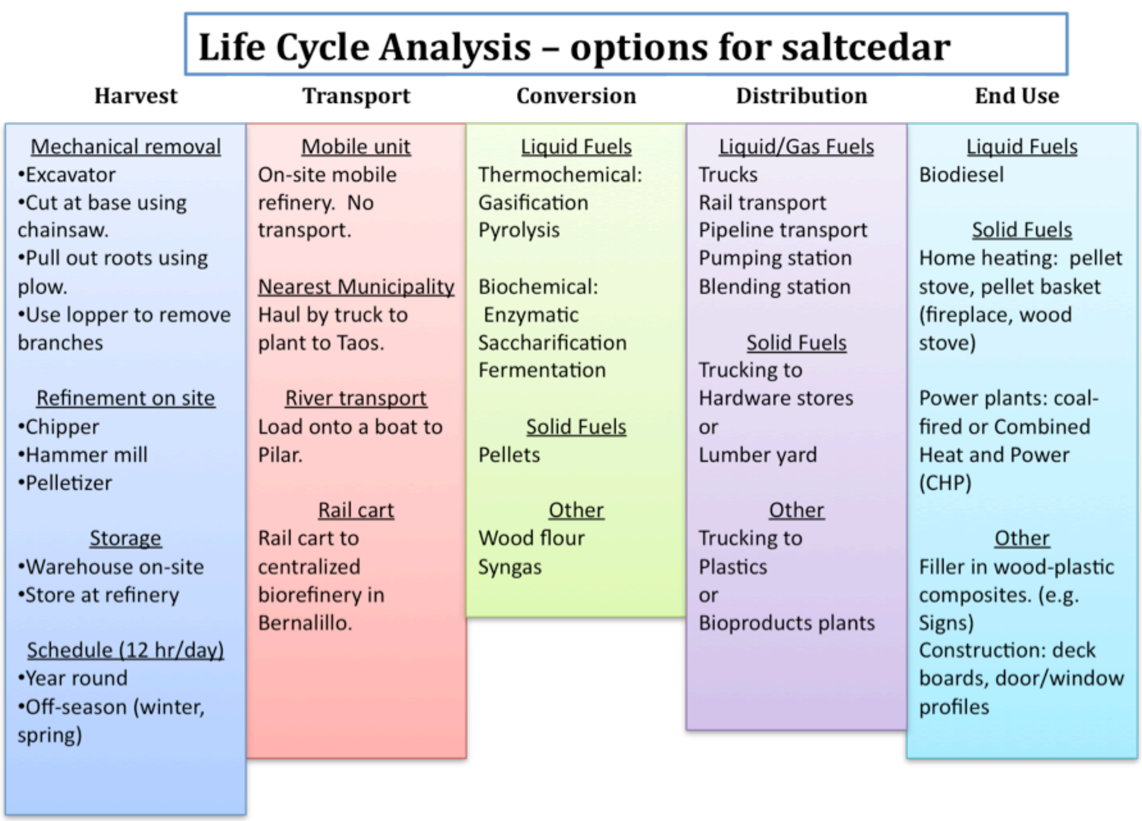

Figure 2. System options for saltcedar to biofuels or other useful bioproducts.

2.2. Biomass Harvesting

There are many existing examples for mechanically removing invasive species in the riparian zone. The factors influencing the choices include impact on soil, seeding, wildlife ecology, recreational value and fluvial hydrology. Figure 2 lists options ranging from uprooting the plant to limbing. Because saltcedar growth takes place where there are likely mixed shrubs, excavation poses the largest threat to soil and water disturbance and is unlikely to be employed successfully.

Another important factor that influences biomass harvest is its impact to wildlife ecology. One of the most important motivations behind removal of saltcedar is to restore the native wildlife ecology around an area. Mechanical removal would require careful planning.

Recreational activities along the Middle Rio Grande River will likely impact scheduling of the harvesting cycle. The Middle Rio Grande is intricately linked to New Mexico's cultural heritage and attracts tourists and sports enthusiasts to the area. Harvesting in the middle of recreational season may potentially impact the tourist industry as well as the local population who utilizes the riparian area.

2.3. Biomass Transport

There are many options to transport saltcedar once it has been mechanically removed. The woody biomass can be further broken down to be transported to the nearest processing station for conversion to biofuel. Nevertheless, having a mobile onsite unit to process the wood into useful biofuel is also an attractive option. In rural sections of the Rio Grande, the labor and fuel involved to truck the wood can be difficult to access.

River transport is also an option for transporting saltcedar to a nearby municipality. While the variability of river flow is high throughout the year, this option should not be ruled out.

Transporting wood by rail cart is also an option. This would involve a combination of trucking saltcedar to the nearest rail cart station then to the nearest biorefinery. Such an option relies on the economy of scale and is likely not attractive to small rural operation.

2.4. Conversion

The most technically challenging step for saltcedar-to-biofuel cycle involves converting woody biomass into high density fuel. Woody plants must undergo a series of chemical transformation before being isolated into biofuels. The constituents that make up the woody backbones, namely lignin, hemicellulose, and cellulose, must be decomposed. Figure 3 shows a schematic of the common steps for transforming biomass into fuel. There are two general pathways: a biochemical and a thermochemical pathway, each of which require a pre-treatment step and a chemical conversion step. Pre-treatment usually refers to mechanical/biochemical degradation of biomass into small size that can be handled more easily as well as maximizing contact area between the biomass and reactants [Kumar et al, 2009].

The biochemical pathway refers to conversion by enzymatic breakdown of lignin-containing components. This is achieved using bacteria or enzymes isolated from microorganisms. Enzymatic reactions cause saccharification of long-chain organic components into polysaccharides. The sugar components are further broken down into alcohols through the fermentation process.

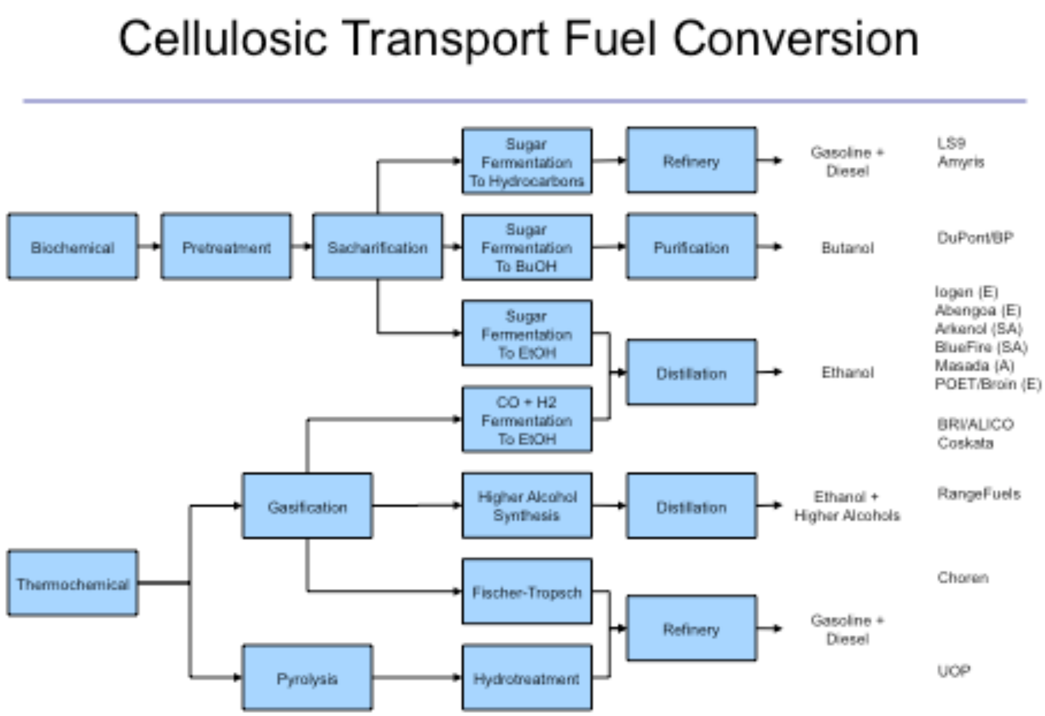

Figure 3. Pathways that lead to different types of liquid transportation fuel. (courtesy of Ben Wu, SNL-CA)

There have been numerous technical reviews devoted to detailed reaction chemistry, reaction kinetics, and process engineering to optimize production of biofuels from lignocellulosic materials. This study relies on existing literature on biofuel yield and energy/water consumptions associated with woody-biomass because a larger analysis effort is required to ascertain processing steps optimal for saltcedar conversion.

There is evidence of clear differentiation between decomposition of saltcedar relative to other woody plants. In a study conducted by the USDA Forest Service, torrefaction of saltcedar, or slow pyrolysis at low temperature yielded more minerals than Russian Olive or Pine [USDA, 2007]. It has been reported in the past that mineral content greatly impacts pyrolysis of woody mass [Serio, 1989]. This point is further elaborated in Chapter 6.

2.5. Distribution

Once biocrude is generated, it is either refined further on-site or transported to a distribution center for purification. The purpose of the distribution stage is to track the different modes of transportation and distance traveled. Distribution can be accomplished by pipeline, truck, or railway.

2.6. End Use

The last and final step in the life cycle analysis is focused on the end use of biofuel/bioproducts derived from saltcedar. The liquid fuels can be further purified and sold on the transportation fuel market (at the pump), while the solid fuel (pellets) can be sold to a power company. There are also other end use for the solids either as pelletized fuel or wood flour for blending with plastics.

2.7. Summary

Life cycle analysis is a commonly recognized practice for evaluating technological advances that have not been fully realized in large scale. In this chapter, we outline stages of saltcedar-to-biofuel life cycle to assess the net energy and water flow for use of saltcedar as a feedstock for biofuel. The life cycle is broken down into five stages: harvesting, transport, conversion, distribution, and end use. Within each step, there are numerous options that are applicable to New Mexico's river systems. This leads to multiple pathways for producing biofuels/bioproducts. The next chapter will outline a baseline system in order to establish base case for understanding the energy and water balances for converting saltcedar into a biofuel.

3. Baseline System

In this chapter, a representative small-scale biofuel production system is proposed and described for harvesting saltcedar woody biomass and converting it to biofuel. Based on the survey of saltcedar and other invasive species distribution, the geolocations are along river reach away from metropolitan centers throughout the Western U.S. [USGS, 2009]. This type of cultivation environment and the set-up for biofuel production is unlike most other fuel processing operations.

Definitions of a baseline system are necessary so that representative constants and parameters can be collected for the energy and water balances. System stages are drawn spanning from harvesting woody saltcedar to hauling and finally to conversion. The baseline system assumes one candidate technology for each category listed in Chapter 2. Note that distribution and end use categories are not included in this baseline system due to the local use of biocrude once it is generated. In a rural New Mexico community, biofuel market is targeted towards the small and local energy consumers. It is the authors' intent to consider local distribution and end use in the future.

The baseline life cycle from harvest, transport to conversion is shown in Figure 4. The default harvesting steps chosen consist of manual removal of trees by chainsaw followed by on-site storage. Cut saltcedar will be hauled by truck to a pretreatment and processing location within a one-mile radius of biomass harvest. The loose biomass is chipped before being fed into a mobile pyrolysis unit. A post-conversion treatment to generate bio-oil completes the outlined baseline system.

The next sections describe each of the baseline system process steps and their energy consumption. All woody biomass tonnage parameters reported in the baseline system assume a dry woody biomass product with 10 wt% moisture content. Freshly harvested tamarisk woody biomass is assumed to comprise of 50% moisture by weight.

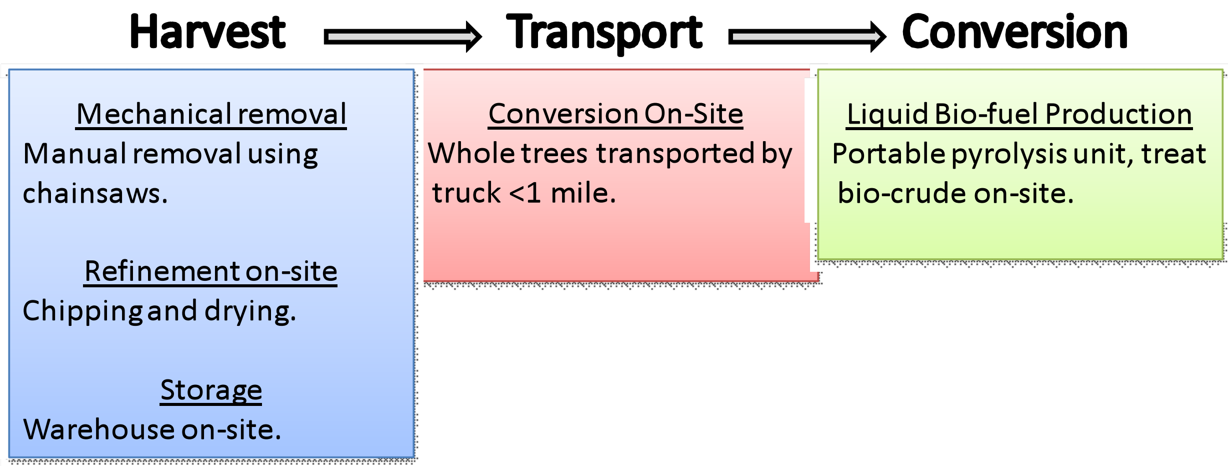

Figure 4. Baseline saltcedar to biofuel life cycle.

3.1. Baseline Tamarisk Harvesting Cycle

For riparian environments such as the riparian area along Orilla Verde State Park (co-located to RiverBrink, the small business collaborating on this project), tamarisk harvesting requires methods that are amendable to plants that grow along the fluvial plain of shallow river systems. In addition to being non-intrusive to the river system, the harvesting system must have a high degree of mobility to be practical for harvesting acreage with ~25% tamarisk coverage. As shown in Table 1, the harvesting process chosen for the baseline system that meets these requirements is manual removal of trees. For the baseline system, harvested trees will be sent to a processing location within a one-mile radius to eliminate the need for harvest storage.

An alternative for tamarisk removal is mechanical extraction via excavator. Tamarisk shrubs can be pulled out of the ground using an extractor, a grapple-like bucket on an excavator [Tamarisk Coalition, 2005]. Excavators pull the entire tree, including root crown, directly out of the soil. Racher Resource Management (RMM) in Corona, NM and Boss Reclamation, LLC in Ruidoso, NM are two local companies that specialize in the mechanical excavator method of removing invasive species such as tamarisk.

While excavator extraction of tamarisk is likely to be more energy efficient and cost effective than manual chainsaw removal, mechanical extraction results in significant soil disturbance that could destabilize embankments. Tree removal via excavator might be more amenable to tamarisk elimination in sites with dense tamarisk thickets where soil disturbance is less of a concern. Chainsaw removal is considerably less invasive by comparison, and is better suited for use on riverbanks or in unstable soil locations that are inaccessible by heavy equipment. Given the terrain and ecological sensitivity of the acreage under considerations along the Rio Grande in New Mexico, utilizing a manual chainsaw is the most practical method of harvesting tamarisk [Young, 1982].

Values and assumptions used for estimating the available harvest and the associated harvest energy costs are listed in **Error! Reference source not found.**. Average tamarisk coverage of

25% is assumed [Bureau of Reclamation, 2010], with a growth density of 106 trees per acre. Tamarisk harvesting is intended for growth control, and no intentional cultivation is required due to its wide spread presence in New Mexico [USGS, 2009]. Similarly, no tamarisk eradication or permanent removal methods are considered. Assuming tamarisk trees are maturing on a continual basis, their yield as a biofuel feedstock is fairly constant year round. The potential woody biomass yield from tamarisk harvesting has been estimated using the yield obtained from hybrid poplar trees that grow 9.7 m in 6 years and produce 20.5 kg of biomass every 6 years [Felix, 2008]. Chainsaw fuel use for manual removal of the estimated available tamarisk is assumed to be 15.7 gal/ton [Young, 1982]. The energy required for removal of tamarisk by chainsaw in Orilla Verde Park is estimated to be 1.96 mmBTU/st.

Table 1. Harvest yield and energy input.

Harvest Parameters	
Tamarisk coverage	25%
Total site acreage	40 acres
Growth density	106 trees/acre
Tree height	9.7 m
Crop rotation	6 years
Per acre yield	3.71 tons/acre/year
Total yield	148 tons/year
Chainsaw fuel	15.7 gal/ton
Chainsaw energy use	1.96 mmBTU/st

3.2. Baseline Transportation and Hauling

The transportation portion of the baseline system involves hauling tamarisk biomass to a conversion plant. As discussed in Chapter 2, there are several possibilities including trucking, boating, and a conveyance system. In this small-scale operation, the baseline system uses a mobile conversion unit that is capable of processing chips on-site and therefore does not require long-distance hauling. The baseline transportation process assumes hauling loose trees not more than one-mile in distance. Co-location of a conversion process minimizes transportation and hauling costs.

Table 2 lists the main assumptions used when estimating transport energy parameters. Small trucks with a 5 ton hauling capacity and 8 miles/gallon fuel consumption were chosen given the variable terrain and entry and egress requirements of hauling in a riparian zone. Trees are loaded in whole or loose format and are estimated to have 50% moisture content. Using an estimated yearly harvest of 148 tons/year from location like Orilla Verde Park, the average daily harvest will be 0.74 tons/day. One mile distance is assumed in calculating the energy input for transportation.

Table 2. Whole tree hauling parameters for a 40-acre site.

Transport Assumptions	Value	Unit
Number of trucks	2	
Hauling Capacity	5	tons/truck
Gas Mileage	8	miles/gallon
Harvest Days	200	days
Harvest	0.74	tons/day
Hauling distance	1	mile
Trips to Mobile Unit	1	per day

3.3. Baseline Storage Considerations

The tamarisk harvesting baseline scenario assumes temporary storage in loose tree format on-site for 8-10 weeks. Freshly harvested tamarisk biomass is assumed to contain 50 wt% moisture and must be dried to 10 wt% before pyrolysis conversion. A unit of short ton (st) is referred to biomass with not more than 10 wt% of moisture. Transpirational drying on the ground open on-site for 8-10 weeks is assumed to reduce the moisture content to 30 wt% in New Mexico's arid climate. While biomass storage adds additional capital cost and logistical considerations, transpirational drying will significantly reduce the overall drying energy cost. It is assumed in the baseline case that there is no additional energy input for drying from 50 wt% to 30 wt% by leaving the wood on-site.

3.4. Pretreatment: Size Reduction and Drying

The pretreatment method used for the baseline system is chipping. Chipping is used for coarse mechanical size reduction of woody biomass to an average size of 30 mm by 30 mm by 10 mm. Chipping of woody biomass is reported to require 0.155 mmBTU/st [Zhu, 2010].

The pyrolysis conversion process chosen for the baseline system requires chips with no more than 10 wt% moisture content. Drying of green chips from 50 wt% to 10 wt% moisture gives an energy cost of 3.10 mmBTU/st [Fagernas, 2010]. Transpirational drying, while ineffective in reducing the moisture content to 10 wt%, should be able to reduce the moisture content to 30 wt% moisture after 8-10 weeks of storage in an arid environment. The addition of transpirational drying is estimated to halve the drying energy required to 1.55 mmBTU/st. Table 3 summarizes the energy input for both steps.

Table 3. Pretreatment energy consumption.

Pretreatment Energy (mmBTU/st)	
Chipping	0.155
Drying	1.55

3.5. Conversion: Pyrolysis

The baseline system conversion method chosen is fast pyrolysis in a mobile pyrolysis unit. There are few small scale pyrolysis units that are commercially available, and potential compatibility concerns remain to be resolved. Nevertheless, a representative one, such as the one manufactured by Agri-Therm, may be suited for this type of remote area operation. Dry chipped woody biomass may be fed at a rate of up to 200 kg/hr into the pyrolysis unit to produce bio-crude, bio-char and gas. Table 4. lists the reported energy output of the pyrolysis unit based on herbaceous biomass (Agri-Therm Inc., London, Ontario, Canada).

One short ton of 10 wt% woody biomass chips is estimated to generate bio-crude with an energy content of 11.5 mmBTU and bio-char with an energy value of 3.82 mmBTU. The total energy output for a portable pyrolysis unit is estimated to be 15.3 mmBTU/st. The portable pyrolysis unit can run in a self-sustaining mode, requiring only the pyrolysis gas output (3.5 mmBTU/st) for fuel. In this conversion process the pyrolysis gas output is entirely consumed, giving a total process energy input of 3.50 mmBTU/st. The energy input and output values do not include any efficiency losses from reactor start-up or shut-down. The bio-crude must undergo a post-conversion treatment to yield the final bio-oil end product. This process is estimated to require 1 mmBTU/st.

Table 4. Portable pyrolysis energy input and output.

Conversion (mmBTU/st)	
Bio-oil	11.50
Bio-char	3.82
Bio-gas	3.50
Total Energy Output	18.82
Post-conversion treatment	1.00
Pyrolysis energy requirement	3.50
Total Conversion Energy Input	4.50

3.6. Overall Energy Balance

The baseline system energy balance for portable pyrolysis of tamarisk to bio-oil is summarized In Table 5. The harvest to plant gate energy input is 2 mmBTU/st, the majority of which is from chainsaw removal. Minimal transport energy costs are the result of co-location of storage, treatment and conversion processes on-site. In Chapter 5, sensitivity relative to the distance is assessed. The energy input required for biofuel conversion is 2.71 mmBTU, and includes chipping, drying, pyrolysis, and post-conversion treatment to bio-oil. The total energy input required for the baseline saltcedar to bio-oil process is 4.71 mmBTU/st. The energy value of the output bio-oil is 11.5 mmBTU/st and the char energy value is 3.82 mmBTU/st. If the bio-char produced is sold or otherwise utilized, the total energy output rises from 11.5 mmBTU/st to 15.3 mmBTU/st. The gas generated from pyrolysis (3.50 mmBTU/st) is the sole source of energy input for pyrolysis conversion.

Table 5. Portable pyrolysis energy balance (mmBTU/st).

Total Energy Input		**8.21**
Harvest to plant gate		**2.00**
Tree Removal	1.96	
Transport	0.0352	
Conversion at mobile unit		**6.21**
Pretreatment - chipping	0.155	
Pretreatment - drying	1.55	
Conversion	3.50	
Post-conversion treatment	1.00	
Total Energy Output		**18.82**
Bio-oil		11.50
Bio-char		3.82
Bio-gas		3.50

4. Analysis of Water Consumption

In this chapter, the water footprint for the baseline system is described. Tamarisk evapotranspiration and the potential individual process contributions to the overall baseline system water footprint are considered.

4.1. Water Consumptive Use – Evapotranspiration

Saltcedar is viewed to have negative ecological and economic effects in riparian environments including streamflow depletion from increased evapotranspiration rates, displacement of native vegetation, and increased soil salinity [Shafroth, 2005]. Nevertheless, riparian restoration efforts following tamarisk removal have led to minimal water recovery as evapotranspiration rates of native vegetation are often similar to that of tamarisk [Shafroth, 2005; Tamarisk Coalition, 2009]. Control of tamarisk is considered a practical approach to realizing restoration goals rather than total eradication due to cost and ecological concerns.

The current estimates of tamarisk evapotranspiration are in the range of 0.8-1.2 m/yr [Rosel, 2006; Barz, 2009; USGS2009-5247]. The tamarisk to biofuel baseline system defined in this report uses a 6-year crop rotation approach to tamarisk harvesting; it assumes a harvesting approach that would not affect the tamarisk population in the area. As such, no net reduction of evapotranspiration rate is expected. Tamarisk harvesting as outlined in the baseline system would have a negligible impact on consumptive use of water in the harvesting step.

4.2. Water Consumption – Pretreatment

The baseline system pretreatment process consists of chipping whole trees followed by transpirational and forced drying. Neither process contributes to the baseline system water footprint. However, chipped tamarisk may require a pre-wash to reduce the salt content as it impacts the pyrolysis fuel product energy yield [Clemons, 2007]. Analysis of saltcedar logs has indicated tamarisk hardwood contains ~1 wt% of sulfur and calcium, and 0.2-0.3 wt% of sodium, potassium and magnesium. Chapter 6 looks at the additional energy and water implications of salt handling.

4.3. Water Consumption – Conversion

Conversion to biofuel from dried woody biomass chips via pyrolysis requires approximately 195 gal/st for conversion and post-treatment processing [Jones, 2009]. Cooling water constitutes the largest portion (77% or 150 gal/st) of that water use. Water is also used as a cooling medium to condense the bio-oil vapor after it exits the pyrolysis reactor. This water is recoverable after it passes through the condenser. The coupling of heating and cooling cycles can efficiently cut down on water loss during the conversion process. The likely candidate for cooling water would be from the river or a nearby well.

Post-treatment processing to generate a final bio-oil end product utilizes the remaining 23% of total water use. This rate of water consumption is required regardless of the conversion unit type. Water is used as a solvent for purification step.

4.4. Summary

There will be no significant impact to evapotranspiration of saltcedar from harvesting mature plants based on the default scenario for this study. Because the proposed harvesting method for the study is cutting, saltcedar will be allowed to grow back (unless herbicide treatment is applied, the likelihood of saltcedar returning to the area is high). The conversion step in the proposed saltcedar to bio-oil process is the only contributor to the baseline scenario water footprint. Approximately 195 gal/st is used for a combination of cooling and purification. Cooling water, which constitutes about ¾ of the total water use, is recoverable and recirculated in the conversion unit.

5. Sensitivity Analysis

In this chapter, we evaluate the energy footprint associated with different options for transportation, pretreatment, and conversion. Options for different energy inputs are described first, followed by consideration of different scenarios.

5.1. Sensitivity to Hauling Distance

While the baseline scenario assumes tamarisk conversion within a one-mile radius, estimates are also given for loose transport to an off-site plant. Table 6 shows the energy used to transport as a function of distance. Note that these estimates include hauling from the point of harvest to nearest metropolitan areas where a stationary conversion plant may exist to process different types of biomass.

Typically, biomass transportation costs are a function of hauling distance, moisture content, and vehicle capacity and utilization. Transport costs to an off-site plant can be reduced by using larger trucks or by densification via size reduction. Size reduction of whole trees to chips or wood flour should be considered if hauling off-site as a high density product can often be transported more efficiently than bulky whole trees or branches [Johnson, 1989]. Drying should also be considered if hauling greater distances as the reduction of water mass transported can reduce the overall hauling energy expenditure.

Table 6 Energy input as a function of distance for hauling loose tamarisk.

Hauling Distance (mmBTU/st)	
1 mile (on-site)	0.0352
3 miles to Pilar	0.282
17 miles to Santa Fe	1.24
53 miles to Albuquerque	3.81

5.2. Storage Considerations

Instead of allowing tamarisk to dry in open space and then transporting it to the mobile conversion unit, it can be stored in chip form and then allowed to dry in an offsite storage unit. The storage space requirement will be considerably less for chips and the drying time (by transpiration) will decrease as well. Densification of tamarisk can reduce storage space by a factor of two. The advantages of decreased storage volume must be balanced with long-term storage concerns of chipped woody biomass; examples include excessive energy value loss from microbial activity and the risk of self-ignition [Johansson, 2006; Nurmi, 1999].

5.3. Pretreatment Options

There are candidate processes for size reduction of woody biomass other than chipping. These include mechanical comminution using hammer mills and using steam explosion. The energy consumption values for the various pretreatment processes considered are listed in Table 7. As in the baseline calculation, chipping of woody biomass is requires 0.155 mmBTU/st [Zhu, 2010]. Milling of chipped woody biomass to a particle diameter of 10 mm (or even 2 mm if required) can be accomplished using a hammer mill at an additional energy cost of 1.70 mmBTU/st, which is significantly higher than the default.

While steam explosion is not the most viable size reduction method for woody biomass pyrolysis, it is a very competitive method for generation of biofuels that are produced via saccharification, a step under biochemical pathway [Zhu, 2010; Hamelinck, 2005]. Steam explosion achieves the physical size reduction and chemical pretreatment necessary for viable saccharification processes in one step. The alternatives to steam explosion are more energy intensive as they require separate physical size reduction and chemical pretreatment in two separate steps.

Table 7 Pretreatment energy consumption.

Pretreatment Energy (mmBTU/st)	
Chipping	0.155
Milling	1.70
Steam Explosion	1.70
Drying	1.55

5.4. Mobile vs. Plant Conversion

Table 8 compares the proposed baseline mobile pyrolysis system to a designed large scale pyrolysis plant capable of processing 2000 dry mt/day of hybrid poplar woody chips [Jones, 2010]. As noted in Table 5, the energy content of woody biomass chips is 16.1 mmBTU/st [Spath, 2005]. The mobile pyrolysis unit in the baseline system requires 2.71 mmBTU/st input process energy plus 3.5 mmBTU/st of generated gas consumed in the process. The plant design consumes both the bio-char and bio-gas streams during processing; the total energy input is 7.94 mmBTU/st: 4.85 mmBTU/st from biomass and 3.09 mmBTU/st from other energy sources.

Table 8 Energy consumption and output for two types of pyrolysis of tamarisk (mmBTU/st).

	Mobile pyrolysis	Plant pyrolysis
Bio-oil	11.50	7.57
Bio-char	3.82	3.14
Bio-gas	3.50	1.71
Process energy input	2.71	3.09
Biofuels consumed	3.50	4.85
Total energy input	6.21	7.94
Total energy output	18.82	12.42

The total energy used in generating bio-oil from pyrolysis of woody biomass chips in the proposed baseline system is similar but slightly lower than energy input in a large scale plant. The stationary plant design likely accounts for efficiency losses during all processes, whereas the baseline system does not account for these factors. More work is needed to understand the discrepancy.

Figure 5 shows the difference in energy output between the two platforms. The mobile unit energy output is 50% higher than that of large-scale plant unit. Again, the advantage of the mobile unit is unexpected and may reflect the uncertainty in energy yield from various conversion technologies. The difference is attributed to the contribution from extractable bio-oil between these two platforms. Again, we believe that the energy estimate from plant design likely accounts for efficiency losses during all processes, whereas the baseline mobile system does not account for these likely losses. Since we have not analyzed the assumptions associated with each platform and normalizing them, one should treat the difference between these two energy outputs as within the uncertainty range of extractable energy available from woody biomass.

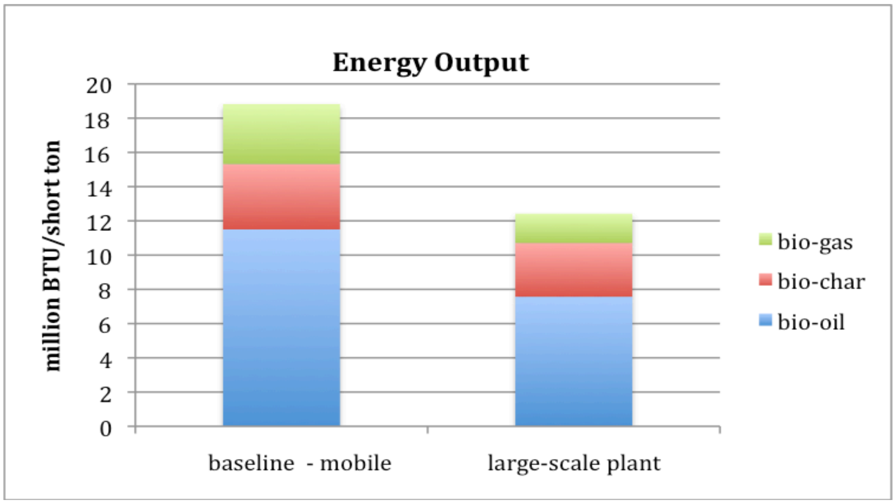

Figure 5. Output energy based on mobile unit and plant unit. The mobile unit estimation is based on Agri-Therm's woody biomass energy output. The large-scale plant output is based on PNNL's technoeconomic study [Jones et al., 2009].

5.5. Case Study #1 – Effect of transportation

We assess the impact for hauling tamarisk to a metropolitan site for processing. The energy input for this case replaces only the energy input in transportation while the assumptions for harvesting, storage, and drying remain at their default levels. This also changes the conversion characteristics since a plant-based conversion platform is likely to process the biomass. Figure 6 shows the total energy input as a function of plant location.

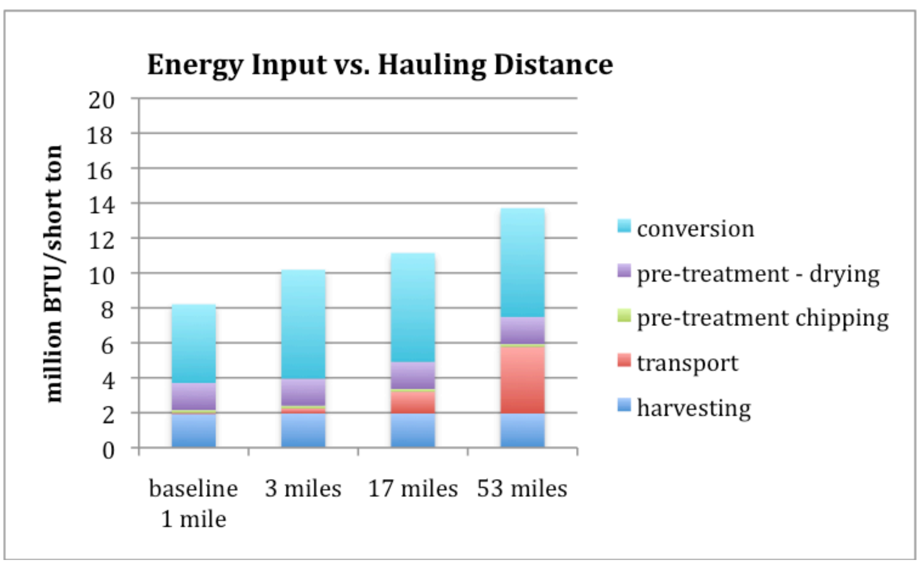

Figure 6. Sensitivity of total energy input as a function of hauling distance

5.6. Case Study #2 – Effect of pretreatment

The sensitivity with respect to the type of pretreatment method is shown in Figure 7. If steam explosion were the method of choice for pre-processing the biomass, after chipping, this would increase the energy consumption for pre-treatment by a factor of two.

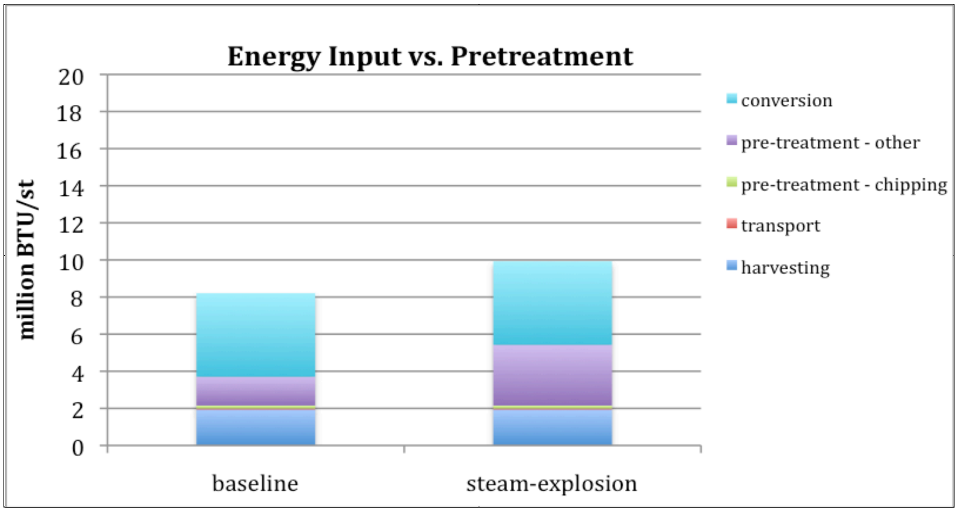

Figure 7. Sensitivity of total energy input as a function of pretreatment options.

5.7. Summary

This chapter focuses on the sensitivity of the energy balance on the various assumptions used in the baseline study. The additional energy required for longer hauling distances shifts the total energy input by 50%. Alternative pretreatment processes can also double the energy input of that step alone. There is uncertainty associated with the potential extractable bio-energy based on the assumption of a mobile unit versus a large-scale, centralized plant. The difference can be significant if different assumptions on feedstock and process efficiencies are used.

6. Technical Challenges

There are additional challenges associated with implementation of this technology that we have identified during this study. This chapter outlines some of the potential technical barriers that warrant further investigations.

6.1. Impact of salt

The authors anticipate salt to be one of the biggest technical barriers that needs to be addressed. Past salcedar biomass profile analysis has yielded high salt concentrations compared to woody biomass derived from plants such as pine or juniper. Presence of sulfur, calcium, sodium, potassium, magnesium have been detected by mineral profiling [USDA, 2007]. Mineral content can significantly impact the rate of thermal degradation of woody biomass and the characteristics of char during pyrolysis [Serio, 1970; Williams and Horne, 1994]. A study of pyrolysis of cellulose with varying concentrations of metal salts by Williams & Horne (1994) found bio-char formation increased by a factor of two to five relative to pyrolysis products from cellulose containing no salts.

In order to eliminate salt in woody biomass, a washing step prior to drying and conversion needs to be considered to extract the minerals. A 4-hour water extraction step needs to be incorporated in the life cycle logistics in order to adequately address the overall energy and water balance. There is a tradeoff between the relative gain of bio-energy versus the energy input for the water extraction step. An additional washing step may also increase the overall consumptive use which has not been considered to date.

The sensitivity of thermal decomposition under pyrolysis conditions would need to be assessed experimentally and theoretically in order to close the knowledge gap for use of saltcedar as a potential biomass.

6.2. Other Uncertainties

Some concerns are listed below as potential areas for future studies.

- Distribution and end use of biofuels.
- Capital investment and incentives.
- Impact to recreational use in the area.
- Impact to wildlife.
- Coordination with land and water management personnel.

7. Summary

This study was originally set up to investigate a set of questions introduced in Chapter 1. While there was not enough time to address all of them in detail, the results are summarized.

1) Would saltcedar be a suitable feedstock for small-scale biofuel production?
Saltcedar is a woody invasive plant that is prevalent in New Mexico such that control of its spread is underway along the Middle Rio Grande. Harvesting this woody plant for conversion to biofuels is feasible for small-scale operation in rural New Mexico. The salt content, however, poses a technical challenge that has not been addressed thoroughly in this study. It is recommended that future study be focused on salt handling as well as an economic assessment.

2) What are the possible technical pathways for converting saltcedar into biofuels?
Like other woody biomass, saltcedar can be converted to biofuels via thermochemical or biochemical pathways. The presence of salt significantly impacts the decomposition characteristics, however.

3) What are the water and energy footprints?
The study of the energy and water footprint for a small-scale saltcedar–to-biofuel is constructed. We have shown that a local operation with a mobile unit can present a favorable set-up that will have a net energy gain. There will be no impact to the existing evapotranspiration pattern based on this operation. There will be additional water use for converting saltcedar to biofuels, most of which comes from water needed to extract bio-oil from pyrolysis products.

4) What is the cost of producing biofuels from saltcedar?
There was not enough time to assess the cost of biofuels in this study. However, the capital investment and operating and maintenance costs will be a natural extension to the existing life cycle analysis.

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