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Assessing the Potential for Increased Capacity of Combined Heat and Power Facilities Based on Available Corn Stover and Forest Logging Residue in Mississippi

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By

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The amount of available biomass feedstock and associated cost components were analyzed to determine the potential increase in energy capacity of two existing combined heat and power plants in Mississippi. The amount of corn stover and forest logging residue within a 10-mile radius can satisfy the existing requirements of CHP plants in Scott (1 MW) and Washington counties (5 MW). Transporting feedstock within a smaller source area had lower transportation costs, but higher total unit cost than the two other source buffer scenarios. However, capital costs associated with higher plant capacities were significantly higher and plant expansion may not be economically advantageous. Increasing the CHP capacity from 1 MW to 2 MW in Scott county and 5 MW to 10 MW in Washington county might be a sustainable approach by drawing feedstock from a smaller area and at lower utilization rates, while keeping transportation costs low.

DEDICATION

I would like to dedicate this research project to my husband Radhakrishnan, daughter Anandi and all my family members.

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NOMENCLATURE

BTU	British thermal unit
BTU/lb	British thermal unit per pound
CS	Corn stover
CHP	Combined Heat and Power
FGB	Farm gate biomass
FLR	Forest logging residue
GW	Gigawatt
kW	kilowatt
kWh	kilowatt-hr
HHV	High Energy Heating Values
MW	Megawatt
TR	Transportation cost
TUC	Total unit cost

CHAPTER I

OVERVIEW

1.1 Introduction

The increasing demand for electricity and energy for cooling and heating is a worldwide problem. Combined heat and power (CHP) systems provide an alternative for the world to meet and solve energy-related problems (Wu and Wang, 2006; Cho et al., 2009). CHP can generate electricity and heat from any single fuel source such as natural gas, biomass, biogas and coal. CHP can apply any existing technologies for the generation of electrical and mechanical power, waste-heat recovery for heating, cooling and thermal applications.

The two most common types of CHP systems are gas turbine and steam turbine. In a gas turbine system, the fuel source is fed into a gas turbine or reciprocating engine and the CHP system produces electricity by burning fuel. A heat recovery unit captures heat from the gas turbine. In a steam turbine system, fuel and water are added to a boiler. The fuel is burned to generate steam which drives the turbine to generate electricity. Steam turbine based CHP systems typically use solid fuels like coal, biomass and waste products. CHP is cleaner method to produce power and thermal energy. The average fossil fueled power plant efficiency in the USA is 33% (Hinnells, 2008; EPA-CHP, 2007).

Combined heat and power is a concurrent process, and generates heat and power from the same location where they need to be utilized. CHP is centralized for utilizing the waste heat from the prime mover or generator driver without additional fuel firing. The steam turbine cycles are the common commercial CHP technology with solid biofuel. The boiler may be different types such as circulated or bubble fluidized bed (CFB, BFB), multi-bed combustion (MBC). The modern cycle is CFB boiler can achieve about 30% electrical efficiency and 90% total thermal efficiency. Wahlund (2003), analyzed the cogeneration plants in Sweden, the capacity of plant varies from 2MW to 39MW with the electrical efficiency of 20–30% with steam turbine and used different combustion boilers (CFB, BFB, MBC). The overall thermal efficiency varies from 70 to 80% (Mani et al., 2006).

Biomass is the one of main resource of renewable energy in the USA and, accounts for 3 percent of the total energy contribution in the USA (Perlack et al., 2005). The energy generated is in the form of heat and steam using forestry industry residue and municipal solid waste. More than 60 percent of current biomass-powered electricity generation in the United States is in the form of CHP (EPA-CHP, 2007).

Bioenergy can be produced with various biomass types such as agricultural residues corn stover, small grain straw, grains (corn, soybeans), perennial grasses and woody crops, logging residues, mill residues, and pulping liquors (Perlack et al., 2005; Walsh et al., 2000). The recovered residue generated after logging and clearing operation get about 67 million dry tons of residue annually. Forest logging residue and corn stover is used as primary feed stocks. Increased can reduce petroleum usage up to 30 percent by 2030 (Perlack et al., 2005).

The amount of agricultural crop residue and available perennial crops can potentially provide sustainable energy production in the United States (Perlack et al., 2005). The quantity of the biomass is based on the crop yield in that particular area of the land. The fraction of biomass residue can be collectable without disturbing the soil integrity, collection equipment and technology, tillage practices. With changing or new efficient technology can increase the crop yield by 50 percent. This scenario gives the potential crop yield of biomass about 998 million dry tons annually (Perlack et al., 2005). In order to decide the amount of residue to collect and how much of the fraction residue must be left on the field depend on soil characteristics and operational resources available. Tillage is the agriculture preparation of the soil, such as digging, stirring; shoveling, hoeing, and raking affect the amount of residue necessary to protect the soil. No-till process result is more residues available for removal, because the soil is less disturbed and also nutrient loss and erosion is less. To produce electric power instead of conventional coal-fired electric power plants, biomass can serve as an alternative energy source depending upon how much biomass is available within a specific radius distance from of the plant, how much it will cost to transport the biomass from the biomass source to the plant, and how much capital cost is required to build and run the plant with biomass capacities (Brechbill and Tyner, 2008).

The most promising renewable energy source is biomass. Using biomass for energy production has several positive impacts including energy cost savings (EPA-CHP, 2007), decreased fossil fuel imports and lower risk of forest fires (Dias and Azevedo, 2004), improved environmental conditions (Kaltschmitt and Weber, 2006; Lewandowski et al., 2006). Biomass energy can be useful for various energy needs such as electricity, heating homes, fuelling vehicles and providing process heat for industrial facilities (Balat, 2005).

Forest biomass resources could generate a combination of electrical and thermal energy for CHP (Viana et al., 2010). The work determined the quantities of available forest biomass residue and examined the feasibility for CHP production. The results showed that the available forest biomass could satisfy the required capacity demand using cogeneration of wood fuel. Explored potential (Kline and Coleman, 2010) of hardwood tree species to serve as feedstock for bioenergy in the southeastern United States. Hardwoods are main interest for bioenergy, because of desirable physical qualities, genetic research advances, and growth potential. Previous studies have reported potential cellulosic fuels production capacities for Mississippi State level or region-level from biomass (Eksioglu et al., 2009; Perez-Verdin et al., 2009). There is a need to determine the availability of biomass at the county specifically for CHP application in Mississippi. There are abundant quantities of biomass available in Mississippi in the form of forest logging residue and corn stover. It might be possible to increase the capacity of CHP plants is sufficient quantity of biomass is available

1.2 Objectives

The goal of this study was to assess the potential for increased capacity of two biomass-based CHP facilities in Mississippi. The specific objectives were to:

1. Assess the use of corn stover and forest logging residue as distributed feedstock sources for CHP facilities in Mississippi.
2. Determine the potential capacity of CHP plants that can run with available biomass.
3. Determine the sustainable potential biomass for an increase in capacity of biomass based CHP facilities in Mississippi, and
4. Estimate the transportation costs from biomass supply points to CHP facilities, with emphasis on using county seats as location.

CHAPTER II

POTENTIAL CAPACITIES OF TWO COMBINED HEAT AND POWER PLANTS BASED ON AVAILABLE CORN STOVER AND FOREST LOGGING RESIDUE

2.1 Abstract

Combined heat and power production using renewable energy sources is gaining importance because of its flexibility and high-energy efficiency. Biomass materials, such as corn stover and forestry logging residues, are potential feedstocks for CHP production. In this study, we collected and analyzed 10 years of corn stover data (2001-2010) and 3 years of forest logging residue data (1995, 1999, and 2002) in each county in Mississippi to determine the potential of these feedstocks for sustainable CHP energy production. We identified six counties, namely: Amite, Copiah, Clarke, Wayne, Wilkinson and Rankin, that have forest logging residue feedstock to sustain a CHP facility with a range of capacity between 8,044 kW to 9,766 kW. Using corn stover alone, Yazoo and Washington counties can produce 13,430 kW and 13,497 kW of energy, respectively. Considering both feedstocks and based on a conservative amount of 30% available forest logging residue and 33% corn stover, we found that 20 counties have adequate supply for a CHP facility with a capacity of 8,257 kW to 19,564 kW. Forest logging residue accounted for the highest percentage of biomass to the total available feedstock in these counties. We also analyzed the amount of available biomass feedstock that can sustainably support the potential increase in energy capacity of two existing CHP plants. Three biomass source buffer distance scenarios were considered in this study. The

amount of corn stover and forest logging residue within a 10-mile radius can satisfy the existing requirements of CHP plants in Scott (1 MW) and Washington counties (5 MW). Increasing the radial distance of biomass utilization to 30 miles can potentially produce 24.5MW and 27.6MW in Scott and Washington counties, respectively. Furthermore, if adjacent counties were considered as biomass supply areas, the available feedstock can produce 49.4MW and 61.6MW in Scott and Washington counties, respectively.

2.2 Introduction

Combined heat and power is the process in which electricity and heat are produced concurrently. CHP can produce heat from any fuel source such as natural gas, biomass, biogas and coal. CHP can be applicable for various types of existing technologies for the generating electricity, power, and waste-heat recovery for heating, cooling and thermal applications (Hinnells, 2008). The two most common types of CHP systems are gas turbine and steam turbine. In a gas turbine or reciprocating engine system, the CHP system produces electricity by burning fuel and a heat recovery unit is used to capture heat from the gas turbine. In a steam turbine system, the CHP system produce stream by burning a fuel and water and this steam is used to generate electricity in a turbine. Steam turbine based CHP systems typically use solid fuels like coal, biomass and waste products that are readily available to fuel the boiler unit (EPA-CHP, 2007).

CHP is an efficient and clean way to producing power and thermal energy from a single fuel source. The total CHP system efficiencies are from 60 to 80 percent for producing electricity and thermal energy, which are higher than the average efficiency of conventional power plants (33%) in the United States. These CHP efficiency gains improve the economics, as well as have other environmental benefits (EPA-CHP, 2007).

There are 22 CHP facilities in the state of Mississippi that generate a total of 570,382 KW (EEA-Inc, 2010). The applications of these units range from dairy facilities (capacity: 50 kW) to oil refineries (capacity: 146,900 kW). There are 8 CHP facilities with lower capacities (< 5,000 kW) that are fueled by either wood, wood waste or other biomass sources. The biomass based CHP facilities are using the technology of boiler/steam turbine and wood based CHP facilities are using the reciprocating engine technology.

Currently, Mississippi utility companies rely heavily on fossil fuels and other non-renewable sources to produce electricity in the state. Current sources of electricity in this region are coal (42.5%), nuclear (27.2%), natural gas (23.6%), petroleum (4.1%), and renewable (2.5%). (EIA Data, 2007; www.southeastcleanenergy.org)

Forestry is the biggest source for Mississippi's economy (Munn and Tilley, 2005). It covers 18 million acres or 62% of the total land area in Mississippi. Several studies have examined the use of woody biomass as an energy source in Iowa (Mueller et al., 2008), Ohio (Jeanty et al., 2004), and Texas (Jianbang et al., 2007). In Mississippi, about 4 million dry tons of woody biomass is available for energy production, distributed into four major types namely, logging residue (70%), small diameter trees (20%), urban waste (7%), and mill residue (3%) (Perez-Verdin et al., 2009). Logging residue represents a significant feedstock that can be utilized for energy production, and it is less expensive than small diameter trees. Perez-Verdin et al. (2008) analyzed the economic impacts of woody biomass utilization for bioenergy conversion in Mississippi. The economic impacts were categorized into three levels: 1) recoveries of logging and thinning residues, 2) electricity generation from co-firing systems, and 3) construction and operation of biofuel facilities. Results showed that the recovery of all available logging and thinning residues would create a considerable number of jobs and stimulate the rural economy.

Forestry residues, woody biomass gained main focus for energy because of their relatively low-cost production, and environmental benefits over fossil fuel (Cook and Beyea, 2000; Bartuska, 2006; Gan and Smith, 2006). Gan and Smith (2006) quantified the logging residues and their potential utilization for electricity and carbon displacement value across the USA. They also identified the maximum power plant using logging residue in each state and compared the carbon value with coal. The distribution of logging residues are located mainly in southeast and south central regions of the United States. Mississippi is among the top three states along with Alabama and Georgia, in terms of available logging residue.

According to a National Renewable Energy Laboratory report (NREL and Milbrant, 2005), Mississippi has the potential amount of forest residue available for energy about 3,825 thousand dry tons /year and total biomass resources available about 15,956 thousand tons / year (Milbrant, 2005). In addition to forest residue, Mississippi has other types of biomass feedstock such as corn that can be used for CHP production. According to the National Agricultural Statistics Service (NASS, 2011) corn production in Mississippi increased significantly from 35,750,000 bushels in 2006 to 134,680,000 bushels in 2007. In Mississippi, large historical production acreage, increased productivity, recent rise in corn acreage, farmers' switch from cotton to corn in recent years, and favorable climate and soil conditions for corn production in the state suggest that a large area is potentially available for corn stover-based ethanol production (Eksioglu et al., 2009). Corn acreages and corn productivity grew dramatically from 1940-2010 (NASS, 2011; Woli and Paz, 2011). According to Mississippi Agricultural and Forestry Experiment Station report (MAFES, 2012), Mississippi farmers have grown about 694,000 acres of corn and produced 131 bushels per acre or 91 million bushels over the last five years. In the past 20 years corn yield doubled and are increasing faster than any other crop grown in Mississippi. Corn acreage should be sustained in Mississippi due to many significant agronomic benefits it produces in rotation systems and advantages of the regional corn market. Corn grown in crop rotation significantly increases productivity of all crops in the long run. Reports consistently indicate 10-25 percent yield advantages for cotton or soybeans grown in rotation with corn on Mississippi farms.

There are many advantages for using biomass over fossil fuels to meet energy demand. Specific benefits depend upon the use and fuel source, greenhouse gas, air pollutant reductions, energy cost savings, local economic development, waste reduction, and the security of a domestic fuel supply. In addition, biomass is more flexible and can generate both power and heat, and reliable as an energy option than many other sources of renewable energy. Biomass fuels are typically used most efficiently and beneficially when generating both power and heat through CHP (EPA-CHP, 2007). Forestry biomass from poor quality trees and logging residues is a feasible option for energy production. Several researchers estimated that an abundance of forest materials is available in the southeastern United States and can be economically converted into energy.

The main objectives of this study were to a) assess the use of corn stover and forest logging residue as distributed feedstock sources for combined heat and power facilities in Mississippi, b) determine the potential capacity of CHP plants that can run with available biomass, and c) quantify the sustainable amount of feedstock that can support two biomass based CHP facilities in Mississippi.

2.3 Materials and Methods

2.3.1 Study Area

The analysis of available biomass feedstock for CHP application focused on existing CHP facilities or plants in Mississippi. There are 22 CHP facilities in the state of Mississippi that generate a total of 570,382 kW (EEA-Inc., 2010). The applications of these units range from dairy facilities with a capacity of 50 kW to oil refineries with a capacity up to 146,900 kW. There are 8 CHP facilities with lower capacities (< 5,000 kW) that are fueled by either wood, wood waste or other biomass sources. The biomass based CHP facilities use the boiler/steam turbine, and wood based CHP facilities use the reciprocating engine CHP technology. Two biomass based CHP plants in Mississippi were selected for this study. The capacity of CHP plants in Scott county and Washington county is 1000 kW and 5000 kW, respectively.

2.3.2 Available Biomass

Ten years of corn production data (2001-2010) in each county in Mississippi were collected and analyzed to determine the potential of these feedstocks for sustainable CHP energy production. Corn production values were obtained by averaging the county production of corn in terms of total bushels produced for the years 2001-2010 (NASS, 2010). Corn production was summed across all Mississippi counties and converted from bushels to tons (Larson et al., 1978). Dry weight of corn grain is 56 pounds per bushel (Perlack et al., 2002). For this study, one ton of corn stover was produced for every ton of harvested corn grain, based on values reported by Lang (2002) and (Perlack et al., 2002).

The amount of corn stover that can be collected in a sustainable way depends on different factors such as type and sequence of collection operations, the efficiency of the collection equipment, environmental restrictions, such as the need to control erosion, maintain soil productivity and soil carbon levels. There is no consensus on the sustainable rate of utilization. Wyman and Hinman (1990) stated that 58% of the corn stover could be collected on a sustainable basis. Scechinger and Hettenhaus (1999) suggested lower rates ranging from 40 to 50% while Brechbill et al. (2011) noted that 53.5 % utilization rate was sustainable. A conservative value of 33% collection rate of stover was used in this study, similar to the value used by (Perlack et al., 2002). The moisture content of corn stover was assumed to be 47 percent (WSU, 2005). The available corn for energy production was calculated using equation 2.1:

$$\text{Corn stover (dry tons)} = \text{Corn production (in wet tons)} \times 0.33 \times 0.53 \qquad [2.1]$$

County level dry logging residue data from 1995, 1999, and 2002 were obtained from the Department of Forestry, Mississippi State University courtesy of Dr. Donald Grebner. The data were part of an inventory conducted by Periz-Verdin et al. (2009) who drew from two main sources, namely, the Mississippi Institute for Forestry Inventory (MIFI) satellite imagery-based data, and Forestry Inventory Analysis (FIA) Timber Products Output database (TPO) forest inventory data. The MIFI data provides land cover information such as timber volume, size, age and different type of the forest area by covered region available at [http://www.mifi.ms.gov/mission.htm]. The online system also helps users analyze the potential biomass utilization for bio-based energy. The quantity of logging residues was based on the FIA TPO forest inventory data as reported by the Southern Research Station. The report is available for various years including 1995, 1999, 2002, and 2005 classified by softwoods or hardwoods [available at http://srsfia2.fs.fed.us/php/tpo2/tpo.php]. Periz-Verdin et al. (2009) converted the average volume of logging residues into dry tons using density values for pine and hardwoods were 0.507 and 0.61 dry tons m^{-3}, respectively of each county. The density values were obtained from a previous study by (Gan and Smith, 2006). The collection of logging residue which consists of bark and scatter pieces, is a difficult operation, and it requires special equipment and labor.

According to Perlack et al. (2005), not all logging residues are available for bioenergy conversion. Based on this study, it was assumed 65% logging residues are removed during the harvest of conventional products. The recovered logging residue material can be chipped, loaded into trucks, and transported to a processing facility. The removal or collection of the logging residue impacts the soil nutrients and rate of soil erosion (Sanchez et al., 2003). But this problem can be solved using fertilization which can restore and even improve productivity of the logging sites in an energy-efficient way (Scott et al., 2006). The optimal amount of biomass that should be left on the soil to compensate for the extraction of essential nutrients (e.g., calcium, magnesium, potassium, and phosphorus) varies between 0.8 and 2.2 tons per ha per rotation period, depending on the region and local conditions (Borjesson, 2000). Periz-Verdin et al. (2009) found that the resulting biomass left on site was greater than the amount recommended by Borjesson (2000). After 65% of logging residues were recovered from timber harvesting, the percentage of biomass (35%) left in the field serves as soil nutrient.

2.3.3 Biomass Conversion

Different percentages of available corn stover and forest logging residue for CHP use were evaluated. Several CS and FLR utilization rates ranging from 2 to 33 percent were considered in this study (Figures 2.1 and 2.2). The maximum rates for available corn stover and forest logging residue were 33% and 30%, respectively. Data on 22 existing CHP facilities in Mississippi and their capacities were obtained from the U.S. Department of Energy (DOE) database (EEA, 2012b). Spatial location data for CHP locations and county seats were determined and used for geographic representation (Petrolia et al. 2008). High Energy Heating Values (HHV) for corn stover and logging residue were set at 7,560 BTU/lb (dry) and 8,570 BTU/lb (dry), respectively (EPA-CHP, 2007; ANTARES Group Inc., 2008). The energy produced using corn stover and forest logging residue was calculated for each county. Viana et al. (2010) found that a typical CHP plant operated for a total of 8000 hours a year or 333 days a year. For this study, the CHP plants in Scott and Washington counties were assumed to be in operation 24 hours a day, 340 days a year and 8160 hours per year. These values were slightly higher than the operational hours reported by Viana et al. (2010). The total CHP energy efficiency was assumed at 70% (EPA-CHP, 2007).

Equations 2.2 and 2.3 were used to calculate the CHP power rating based on the energy content of feedstock (corn stover or forest logging residue):

$$\text{Power Rating} = \text{Feedstock Quantity} * \text{Energy Content of feedstock} * \text{CHP efficiency} \qquad [2.2]$$

$$\text{Power Rating} = \left(\text{dry}\,\frac{\text{ton}}{\text{day}}\right) * \frac{2000\,\text{lb}}{\text{ton}} * \frac{\text{BTU}}{\text{dry lb}} * (0.70) * \frac{1055\text{J}}{\text{BTU}} * \frac{1\text{day}}{24\text{hr}} * \frac{1\text{hr}}{3600\text{s}} * \frac{1\text{kW}}{1000\text{W}} \qquad [2.3]$$

The CHP energy output of dry logging residue was calculated using Equation 2.4. The energy content of dry ton logging residue is 8570 BTU/lb with 70% of CHP efficiency conversion of forest logging residue tons into kilowatt energy (EPA-CHP, 2007). Therefore, a dry ton per day of logging residue can produce CHP energy of 146.51 kW.

$$
\begin{aligned}
8570\left(\frac{\text{BTU}}{\text{lb}}\right)*.70 &= 5999\left(\frac{\text{BTU}}{\text{lb}}\right)*\ 1\text{ton}\ *\ \frac{2000\ \text{lb}}{\text{ton}} \\
&= 11998000\ \text{BTU} * 1055.05\left(\frac{\text{J}}{\text{BTU}}\right) \\
&= \frac{12658489900\ \text{J}}{\text{d}} * \frac{\text{d}}{24\ \text{hr}} * \frac{1\text{hr}}{3600\ \text{s}} \\
&= 146510.3\left(\frac{\text{J}}{\text{s}}\right) \\
&= \frac{\text{W}}{1000} \\
&= 146.51\ \text{kW}
\end{aligned} \qquad [2.4]
$$

The energy content of a dry ton of corn stover was set at 7560 BTU/lb (EPA-CHP, 2007). The CHP efficiency was also set at 70%. Using equation 2.5, one dry ton per day of corn stover can produce 129.24 kW.

$$
\begin{aligned}
7560\left(\frac{\text{BTU}}{\text{lb}}\right)*.70 &= 5292\left(\frac{\text{BTU}}{\text{lb}}\right)*1\text{ton} * 2000\ \frac{\text{lb}}{\text{ton}} \\
&= 10584000\text{BTU} * 1055.05\left(\frac{\text{J}}{\text{BTU}}\right) \\
&= \frac{11166649200\text{J}}{\text{d}} * \frac{\text{d}}{24\text{hr}} * \frac{1\text{hr}}{3600\text{s}} \\
&= 1292436\left(\frac{\text{J}}{\text{s}}\right) \\
&= \frac{\text{W}}{1000} \\
&= 129.24\ \text{kW}
\end{aligned} \qquad [2.5]
$$

2.3.4 Analysis of Available Biomass using GIS

For this study, biomass supply data were provided at the county level, and it was assumed that the biomass in each county was evenly distributed. The existing woody biomass CHP plant is located in Scott county (Figure 2.3) and approximately 76% of the total acreage is forested area (MIFI, 2005). The second CHP plant selected for this study is located in Washington county (Figure 2.3). The county is in the Mississippi Delta region, and the region is a highly agricultural area, hence, it has large supplies of corn stover.

Spatial analysis using ArcMap (ESRI, 2011) was used to estimate the supply data for particular CHP location. The location of the CHP plants in Scott and Washington was overlaid onto the Mississippi counties map. The Proximity Analysis Tool, which is a feature of ArcMap, was used to create multiple buffers around the CHP plant, from 10 to 40 miles, with 10-mile increments. The intersect tool was used to find the area between each buffer that intersects with each particular county. A fraction was calculated at each distance increment to determine what portion of the area of the circle was in the targeted area counties. Scott and Washington counties were designated as the target counties. Scott county shares the boundary with seven neighboring counties namely Jasper, Neshoba, Smith, Leake, Rankin, Madison, and Newton, while Washington county shares the boundary with five neighboring counties namely Sharkey, Bolivar, Sunflower, Issaquena, and Humphreys (Figure 2.3). The area of each county that fell within a particular buffer scenario for each CHP plant was calculated and summed to get the total area. A fractional area percentage was assigned only if a fraction of the county was covered or ‘clipped’ by the buffer operation. This fraction is used to determine the amount of available biomass from each county that is located within a given circle. The 10-mile buffer area represented the required amount of biomass needed to satisfy the existing demand of the CHP plant. The 30-mile buffer area represented the amount of biomass available for the CHP plant that can potentially produce energy above the existing capacity.

2.4 Results and Discussion

2.4.1 CHP Capacity Based on Available Forest Logging Residue

The top five Mississippi counties in terms of available forest logging residue are listed in Table 2.1. The Amite, Copiah and Wilkinson counties are in the southwest region of Mississippi (Figure 2.4). Clarke county is located in central region at Mississippi, and Wayne county is located in the southeast region of Mississippi. Each of the 5 counties is covered by forest area that is 80 to 86% of the county area (MIFI, 2005). Thus, these 5 counties are predominately covered by forest and the high percentage of forest land is reflected in the logging residue available in these counties. The top 5 counties can each produce at least 8,257 kW of CHP power from utilizing 30% of available forest logging residue (Table 2.1). The available logging residue tons ranged from 188 tons per day to 222 tons per day.

Table 2.1 Top 5 Mississippi counties in terms of available forest logging residue and their potential CHP capacities

County	FLR (ton/day)	FLR UR at 30% (ton/day)	CHP UR at 30% (kW)
Amite	222	67	9,766
Copiah	219	66	9,617
Clarke	218	66	9,598
Wayne	212	64	9,316
Wilkinson	188	56	8,257

* Forest Logging Residue (FLR), utilization rate (UR)

2.4.2 CHP Capacity Based on Available Corn Stover

Table 2.2 lists the top five Mississippi counties in terms of corn stover availability. These counties are located in the Delta region, which has predominantly agriculture land cover (Figure 2.5). Washington county had the highest corn stover production among the counties, and it produced 10.4 million bushels of corn in 2010, which was nearly four times the production in 2001 (2.8 million bushels) (NASS-USDA, 2011). In the last decade, corn production has surged in the Delta region because of the higher value for corn arising from its demand for fuel ethanol production. The potential CHP capacities in the top five Mississippi counties range from 8,021kW to 13,497kW (Table 2.2).

Table 2.2 Top 5 Mississippi counties in terms of corn stover availability and their potential CHP capacities

County	CS (ton/day)	CS UR at 33% (ton/day)	CHP UR at 33% (kW)
Washington	597	197	13,497
Yazoo	594	196	13,430
Sunflower	396	131	8,954
Leflore	393	130	8,878
Sharkey	355	117	8,021

* Available Corn Stover (CS), Utilization Rate (UR)

There are 20 counties in Mississippi that can each produce 8,000 kW or higher CHP power based on combined utilization of corn stover and forest logging residue (Table 2.3). Five counties namely Washington, Issaquena, Sharkey, Bolivar, and Sunflower that can produce 8,000 kW or higher CHP power are located in the Mississippi Delta region. Yazoo county had the highest amount of available feedstock for CHP production, and its potential CHP capacity was estimated at 19,564 kW. For the counties with potential CHP capacities higher than 10,000 kW, except for Noxubee and Holmes, corn stover was the main feedstock for CHP energy production (Table 2.3). There are five counties namely Wilkinson, Wayne, Clarke, Copiah, and Amite that can each produce CHP power more than 8,000 kW, utilizing only forest logging residue. The potential county- level CHP capacities, based on combined utilization of corn stover and forest logging residue, range from 1,797kW to 19,564kW (Figure 2.6).

Table 2.3 Counties with potential CHP capacity more than 8,000 kW with combined use of Corn Stover (CS) and Forest Logging Residue (FLR)

Serial No.	County	CS (ton/day)	CHP CS (kW)	FLR (ton/day)	CHP FLR (kW)	CHP CS & FLR (kW)
1	Yazoo	594	13,430	140	6,134	19,564
2	+Washington	597	13,497	32	1,425	14,922
3	Noxubee	279	6,317	124	5,466	11,783
4	+Issaquena	285	6,453	98	4,315	10,769
5	Holmes	198	4,487	139	6,112	10,599
6	+Sharkey	355	8,021	54	2,391	10,412
7	Leflore	393	8,878	34	1,486	10,364
8	#Amite	0	0	222	9,766	9,766
9	Madison	157	3,539	141	6,195	9,734
10	Tallahatchie	316	7,151	57	2,492	9,643
11	#Copiah	0	0	219	9,617	9,617
12	#Clarke	0	0	218	9,598	9,598
13	Warren	108	2,430	162	7,103	9,534
14	#Wayne	0	0	212	9,316	9,316
15	Panola	88	1,999	166	7,306	9,305
16	+Bolivar	315	7,131	49	2,145	9,276
17	+Sunflower	396	8,954	4	166	9,120
18	Hinds	96	2,161	156	6,871	9,032
19	Rankin	30	689	183	8,044	8,732
20	#Wilkinson	0	0	188	8,257	8,257

* Corn stover (CS) utilization rate was assumed to be 33% and forest logging residue (FLR) utilization level was assumed to be 30%. + counties which are located in the delta region. # counties which are produce CHP power more than 8,000 kW, utilizing only forest logging residue

Table 2.4 Counties with existing CHP facilities, available biomass and required utilization levels to support current CHP capacity

CHP plant (kW)	CS (ton/day)	FLR (ton/day)	RUR CS CHP capacity (%)	RUR FLR CHP capacity (%)
Washington (5,000)	597	32	13	15*
Scott (1,000)	21	107	7**	7

* Required Utilization Rate (RUR), Forest Logging Residue (FLR), Corn Stover (CS)

Forest Logging Residue supply was calculated as an average supply of 1995, 1999, and 2002.

* There is not sufficient logging residue in Washington county to operate a 5,000 kW plant. However, combining the FLR in 4 adjacent counties at 15% utilization rate will be sufficient to support a 5,000 kW plant.

Corn stover supply was calculated as an average supply of 2001 to 2010.

**There is not sufficient corn stover in Scott county to operate a 1,000 kW plant. However, combining the FLR in 4 adjacent counties at 7% utilization rate will be sufficient to support a 1,000 kW plant.

The CHP facility in Washington county has an existing capacity of 5,000 kW. In this study, we found that the CHP plant in Washington county can be operated with just 13% utilization level of corn stover (Table 2.4). The CHP plant could also run at the existing capacity at a 15% utilization rate of forest logging residue drawn from Washington county and 4 adjacent counties. The 1,000 kW capacity CHP plant in Scott county can be operated with 7% utilization level of forest logging residue within the count, but would require using corn stover at 7% utilization level from adjacent 4 counties (Table 2.4).

Table 2.5 Potential capacities of CHP plants in Washington and Scott based on higher utilization rates of corn stover and forest logging residue feedstock

CHP plant capacity (kW)	CS CHP capacity (kW)	FLR CHP capacity (kW)	CS & FLR CHP capacity (kW)
Washington(5,000)	13,497	1,425	14,922
Scott (1,000)	477	4,717	5,193

*Based on 30% utilization of FLR and 33% utilization of CS

In Washington county, it was possible to increase the capacity of the CHP plant from 5,000 kW to 13,497 kW by using a sustainable CS utilization level of 33% (Table 2.5). Similarly in Scott county, a 30% FLR utilization level could potentially increase the capacity of the CHP plant from 1,000 kW to 4,717 kW (Table 2.5). The capacities of CHP plants in Scott and Washington counties could increase to 5,193 kW and 14,922 kW, respectively, by combining both types of feedstock.

Table 2.6 Biomass availability and equivalent CHP capacities in Scott and Washington counties within a 10-mile radius from existing CHP plant location

CHP plant (kW)	Counties covered	Area 10-mile Radius (%)	FLR (kW)	CS (kW)	CS & FLR (kW)	Total (kW)
Scott (1,000)	Scott	40.1	1,893	191	2,084	2,763
	Smith	1.9	64	0	64	
	Rankin	7.0	567	49	616	
Washington (5,000)	Washington	33.1	472	4,472	4,944	5,236
	Bolivar	3.1	68	225	292	

*Based on 30% utilization of FLR and 33% utilization of CS, CHP capacity (kW)

The equivalent CHP power produced based amount of available biomass within a 10-mile buffer from the CHP plants in Scott and Washington counties are summarized in Table 2.6. In Scott county, the amount of logging residue within the 10-mile radius of the plant CHP plant was sufficient to produce 1,893kW, which is higher than the existing capacity (1,000 kW). On the other hand, the low amount of available corn stover within the 10-mile buffer can only produce 191 kW of CHP power. The predominant land use (forest) in Scott County clearly supports a CHP plant that uses mostly forest logging residue. The total potential CHP capacity using both feed stocks within the Scott county itself is 2,084 kW. The available feedstock within a 10-mile radius, including the areas that fall in immediate neighboring counties (Figure 2.7) can support a CHP capacity of 2,763 kW. In Washington county, the potential CHP capacity using forest logging residue is 472 kW, while using corn stover can support a higher CHP capacity of 4,472 kW. The total for these both feedstock in the Washington county is 4,944 kW. If the neighboring counties inside the 10-mile radial distance were considered, the potential CHP capacity is 5,236 kW. These results show the available feedstock supply within a 10-mile radius can support the existing capacity of CHP plants in the Scott and Washington counties.

Increasing the distance from the plant can produce more biomass for CHP production. In Scott county, the available logging residue within the 30-mile buffer of the CHP plant is sufficient to produce 4,717 kW, which is almost five times than the existing capacity (1,000 kW) (Table 2.7). The corn stover collected within the 30-mile is able to produce 477 kW. The total potential CHP capacity using both feedstocks within the Scott county itself is 5,194 kW. The available feedstock within a 30-mile radial area, including the areas that fall in immediate neighboring counties (Figure 2.7), can potentially produce

24,545 kW. In Washington county, the potential CHP capacity using forest logging residue was calculated at 1,425 kW, while the potential CHP capacity using corn stover was 13,496 kW (Table 2.8). The total potential energy production using both types of feedstock in the Washington county was 14,921kW. With third source buffer scenario, the existing plants can draw all 100% of available biomass because all the areas were covered within 30 miles. Utilizing both types of feedstocks, the potential capacity of the CHP plants in Scott and Washington is 24,545 kW and 27,558 kW, respectively (Figure 2.7). The results suggest that biomass is readily available and can be utilized at a conservative and sustainable rate, drawing feedstock from a relatively small area. Furthermore, the estimated potential increases in energy production provide a significant portion that can satisfy the growing energy demand in Mississippi.

Table 2.7 Biomass availability and equivalent CHP capacities in Scott and Washington counties within a 30-mile radial distance from existing CHP plant location

County	Counties covered	Area 30 mile Radius (%)	FLR (kW)	CS (kW)	CS & FLR (kW)	Total (kW)
Scott	Scott	100.0	4,717	477	5,194	24,545
	Jasper	13.3	665	0	665	
	Neshoba	4.3	287	0	287	
	Smith	68.4	2,255	0	2,255	
	Leake	50.2	2,969	0	2,969	
	Rankin	86.4	6,952	595	7,548	
	Newton	41.9	1,906	114	2,021	
	Madison	37.0	2,295	1,311	3,606	
Washington	Washington	100.0	1,425	13,496	14,921	27,558
	Sharkey	11.5	276	926	1,203	
	Bolivar	57.5	1,234	4,102	5,336	
	Sunflower	50.1	83	4,488	4,571	
	Humphreys	17.0	158	1,056	1,214	
	Issaquena	2.9	126	189	315	

*Based on 30% utilization of FLR and 33% utilization of CS, CHP capacity (kW)

Table 2.8 shows the estimated power capacities of the CHP plants based on available biomass drawn from adjacent counties. All CS and FLR data collected from various sources were reported at the county-level, hence, in calculating the available biomass for CHP power production, it was assumed that CS and FLR were distributed throughout each county. At 30% utilization level of FLR in Scott and their adjacent counties the amount of available biomass ranged from 23 to 55 tons/day. These available tons can produce CHP power range from 3.3MW to 8MW (Smith, Rankin). The Scott county adjacent counties are Jasper, Neshoba, Smith, Leake, Rankin, Newton and

Madison. These counties are located in the central region of Mississippi. These regions predominately covered forest. Hence the forest logging residue availability was high. The CHP plant is in Washington and their adjacent counties are Sharkey, Bolivar, Sunflower, Humphreys and Issaguena. The available FLR in Washington and adjacent counties ranged from 1 to 29 tons per day, and the corresponding CHP capacities were 166 kW in Sunflower county to 4.3 MW in Issaquena county. Washington county and its adjacent counties are located in Delta region in Mississippi which is predominantly agriculture crop land area, and forestry areas are minimal.

Table 2.8 Biomass availability and equivalent CHP capacities in Scott and Washington counties and adjacent counties (AC) from existing CHP plant location

CHP County	AC	FLR Tons/day	FLR (kW)	CS Tons/day	CS (kW)	FLR&CS (kW)	Total (kW)
Scott	Scott	32	4,717	4	477	5,194	49,399
	Jasper	34	4,987	0	0	4,987	
	Neshoba	46	6,722	0	0	6,722	
	Smith	23	3,298	0	0	3,298	
	Leake	40	5,908	0	0	5,908	
	Rankin	55	8,044	5	689	8,733	
	Newton	31	4,550	2	273	4,823	
	Madison	42	6,195	27	3,539	9,734	
Washington	Washington	10	1,425	104	13,497	14,922	61,625
	Sharkey	16	2,391	62	8,021	10,412	
	Bolivar	15	2,145	55	7,131	9,276	
	Sunflower	1	166	69	8,954	9,120	
	Humphreys	6	927	48	6,200	7,127	
	Issaquena	29	4,315	50	6,453	10,768	

*Based on 30% utilization of FLR and 33% utilization of CS, CHP capacity (kW)

Using 33% utilization rate in Scott and adjacent counties, the available CS ranged from 2 to 27 tons/day, and CHP power production ranged from 273 kW in Newton county to 3.5 MW in Madison. On the other hand, the available CS in Washington and adjacent counties were significantly higher, ranging from 48 to 104 tons/day. The corresponding CHP power production amounted to 6.5 MW in Humphreys county to 13.5 MW in Washington county. Combining both CS and FLR can produce 3.3 MW to 9.7 MW in Smith county and Madison county, respectively. In Washington county and its adjacent counties, the combined available CS and FLR feedstock can potentially produce

CHP power from 7.1 MW in Humphreys county to 14.9 MW in Washington. If all available biomass were considered in Scott and its adjacent counties, the total CHP production would be 49.4 MW. On the other hand, the potential CHP production would be 61.6 MW if CS and FLR were drawn from Washington and its adjacent counties.

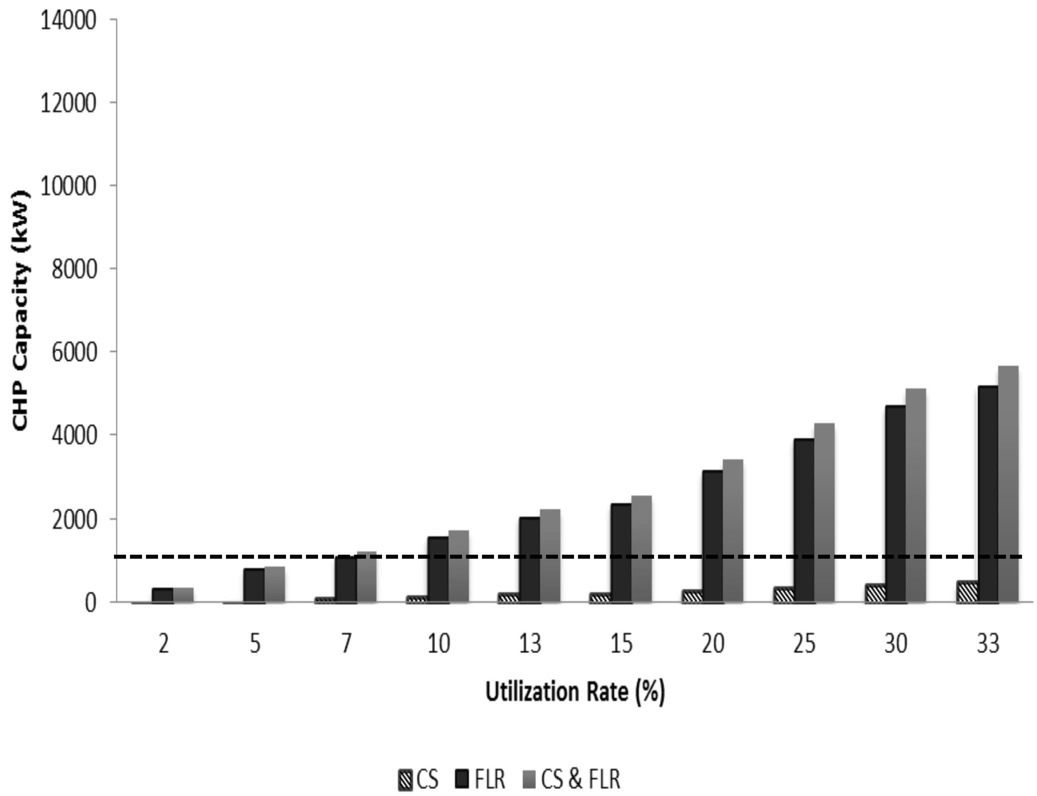

Figure 2.1 The capacities of the CHP plant in Scott county based on different utilization rates (%) of biomass feedstock

---Represents the existing capacity of the CHP plant in Scott county (1,000kW).

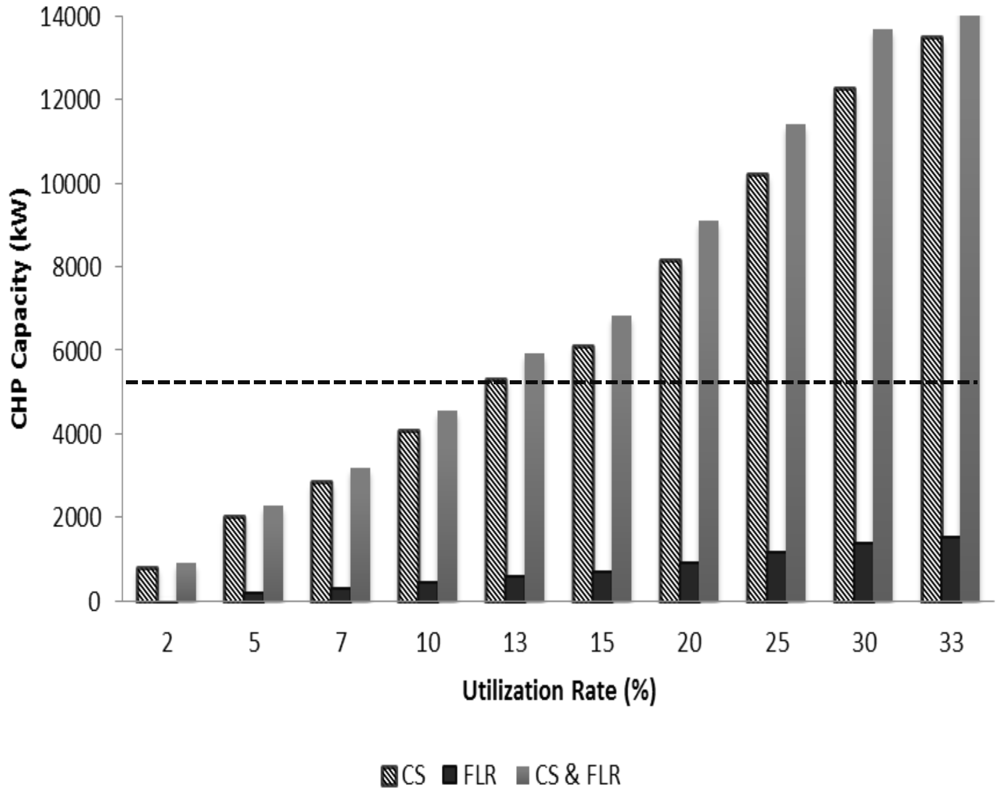

Figure 2.2 The capacities of the CHP plant Washington county calculated based on different utilization rates (%) of biomass feedstock

---- Represents the existing capacity of the CHP plant in Washington county (5,000 kW).

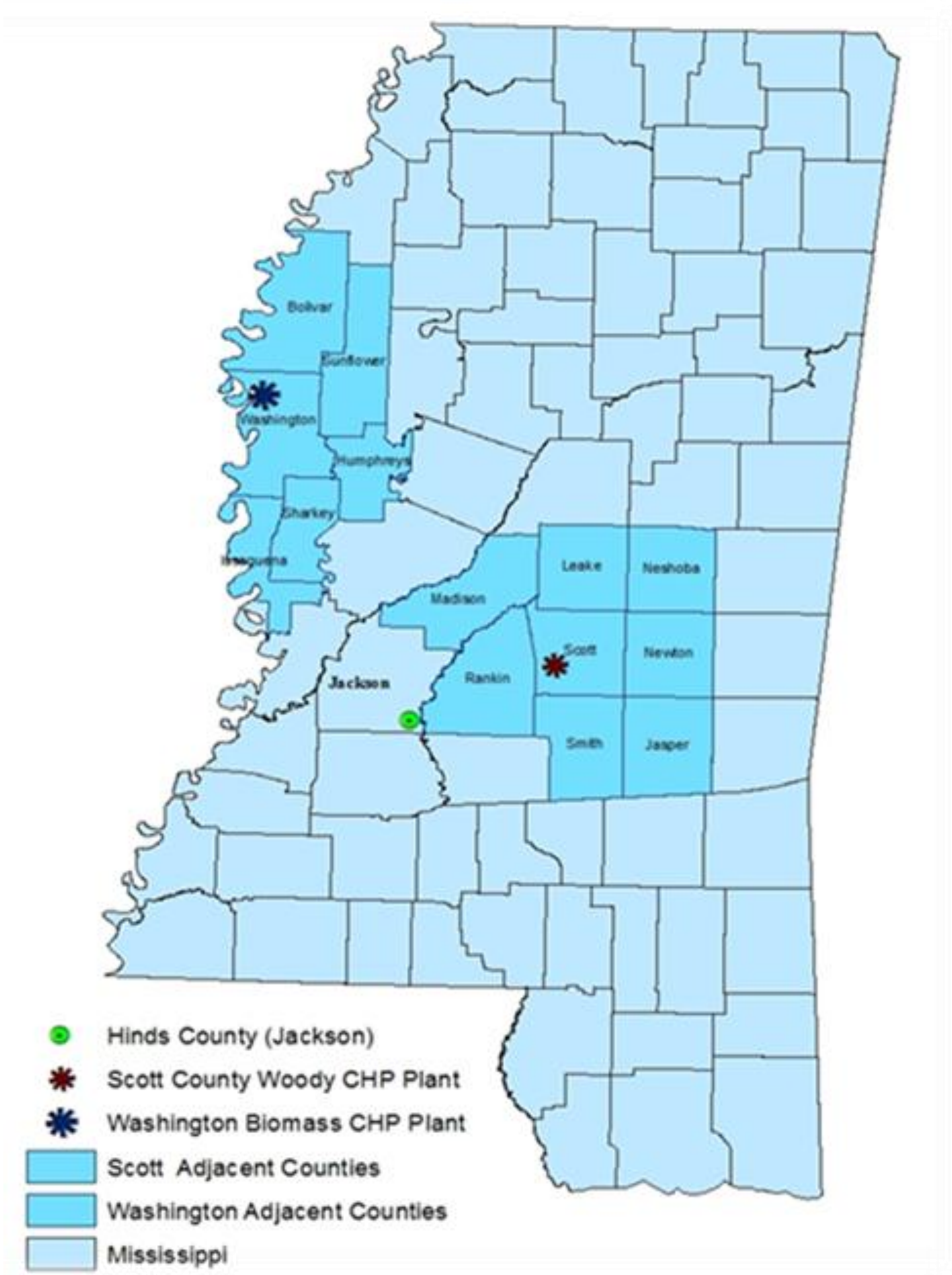

Figure 2.3 Map showing the location of the CHP plants considered in this study

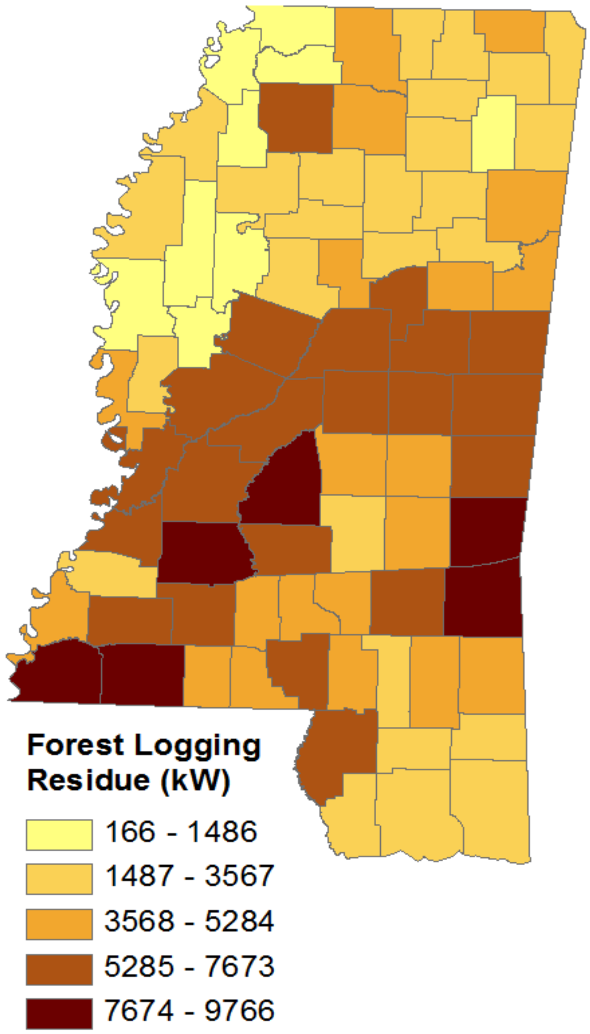

Figure 2.4 County - level potential CHP capacities (kW) for Mississippi based on 30% utilization of forest logging residue

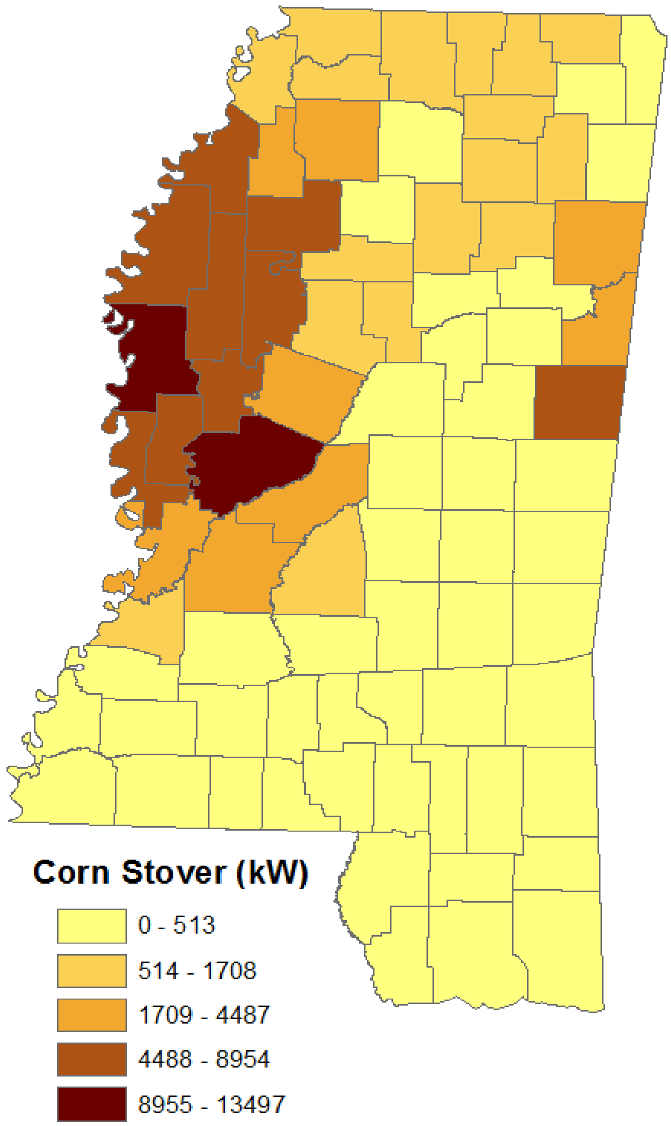

Figure 2.5 County - level potential CHP capacities (kW) for Mississippi based on 33% utilization of corn stover

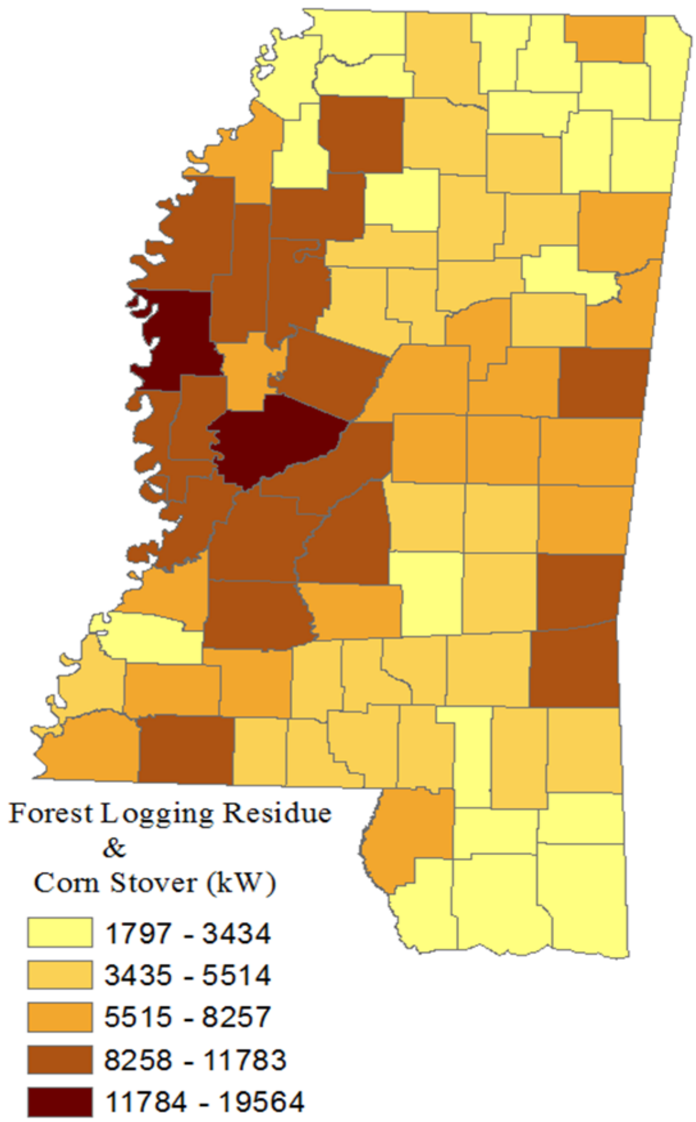

Figure 2.6 County- level potential CHP capacities (kW) for Mississippi based on combined use of corn stover (33%) and forest logging residue (30%)

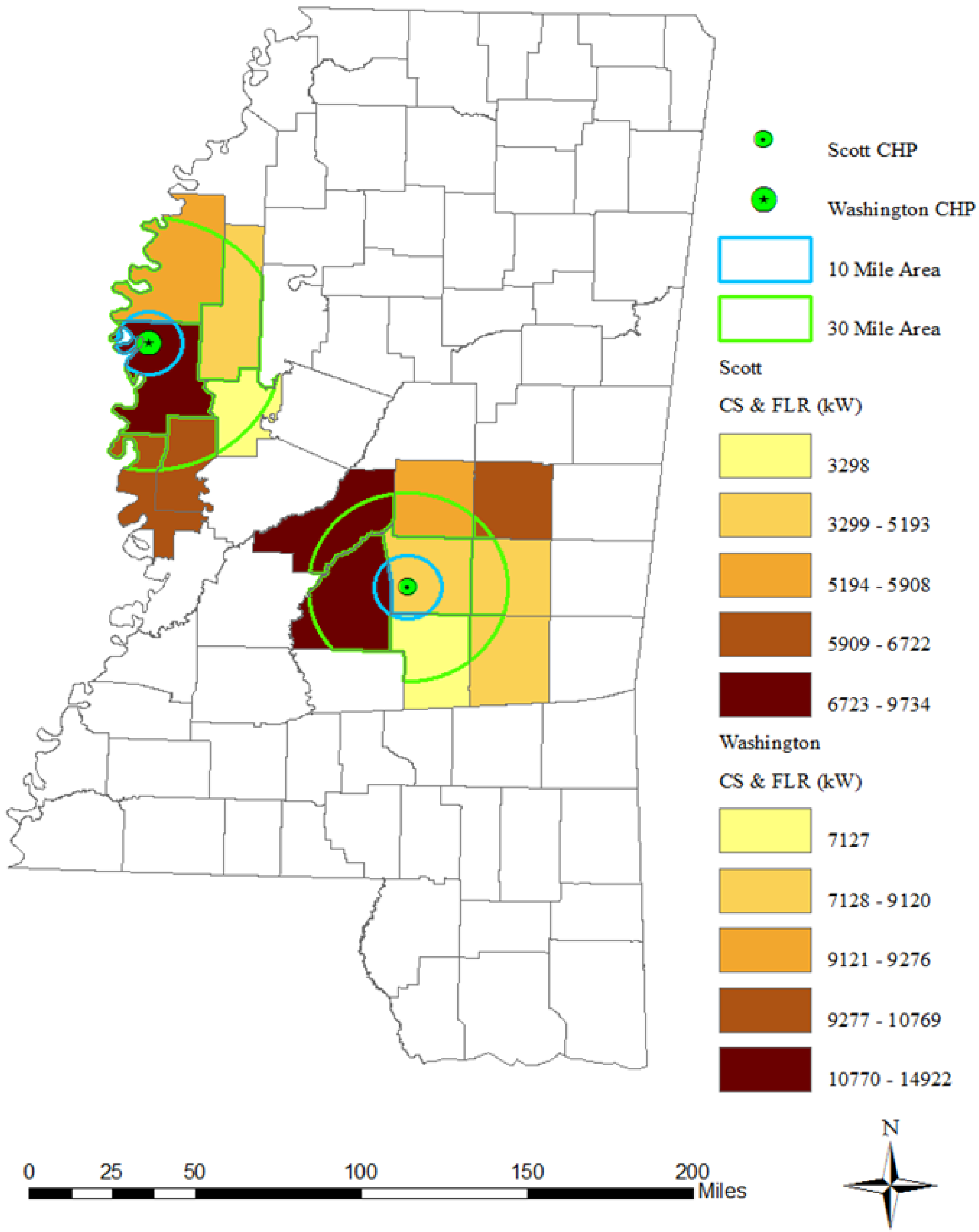

Figure 2.7 Map of existing CHP plants (kW) in Scott and Washington counties and the 10- and 30- mile buffer supply zone

2.5 Conclusions

The potential increase in CHP capacity was assessed based on a sustainable utilization rate of available corn stover and forest logging residue in Mississippi. The results show that the available corn stover is 2,048,985 tons/year, and forest logging residues is 2,763,231 tons/year. The total amount of available biomass feedstock is 4,812,216 tons/year, which represents a significant amount of renewable resource that can be utilized for CHP production in Mississippi. The amount of available corn stover can produce up to 264.8 MW of power generated through the use of CHP technology, if the feedstock utilization rate is set at 100%. In this study, a sustainable corn stover utilization rate of 33% can produce up to 126.9 MW. Full utilization (100%) of forest logging residue can produce energy up to 404.8 GW, while a sustainable utilization rate of 30% of forest logging residue can produce 332.7 MW of power using CHP. Mississippi Delta region is the main source for corn stover, while the southwest region of Mississippi has more forested areas, which can be tapped for energy production.

Using GIS to delineate the supply zones, we found that the available biomass within a 10-mile radius from the CHP plants can satisfy the existing requirement of CHP plants in Scott and Washington with a capacity of 1MW and 5MW, respectively. Increasing the radial distance of biomass utilization to 30 miles can potentially produce 24.5MW and 27.6MW in Scott and Washington counties, respectively. Furthermore, if adjacent counties were considered as biomass supply areas, the available feedstock can produce 49.4MW and 61.6MW in Scott and Washington counties, respectively. These results show that the maximum CHP plant capacity can be increased from 1 MW to 49.4 MW and from 5 MW to 61.6 MW, based solely on a sustainable utilization of available biomass. The main factor that can affect the expansion of CHP plants is establishing the zone of biomass source areas, which in turn would affect capital costs and transportation costs. A realistic approach might be to double the capacity of the CHP plant in Scott county from 1 MW to 2 MW, and in Washington county from 5 MW to 10 MW.

CHAPTER III

ANALYSIS OF TRANSPORTATION COSTS ASSOCIATED WITH INCREASED CAPACITIES OF BIOMASS-BASED CHP PLANTS IN MISSISSIPPI

3.1 Abstract

Mississippi has vast amounts of corn stover and forest logging residue that can be used for CHP energy production. This study focused on the analysis of cost parameters associated with increasing the energy capacity of two existing CHP plants in Mississippi. The proximity analysis tool was used to spatially analyze the feedstock residue available within the haul zones, and the network analyst tool was used to find the shortest distance in each haul zone or radial zone from the biomass source to the CHP plant. The effect of plant capacity on the cost of energy production was examined by determining the costs involved, namely, capital cost, biomass cost and operating cost. Different cost components including feedstock farm gate cost, transportation cost, CHP plant capital cost, and operating cost were used to calculate the total unit cost (TUC) for each CHP plant. Higher plant capacity has the advantage of economy of scale because capital cost on a per capacity basis decreases as plant capacity increases. However, the disadvantage with higher capacity is that the increased cost of biomass makes the transportation costs higher. Transporting feedstock within a smaller source area (10-mile radius) had lower transportation costs but higher total unit cost than the two other source buffer scenarios. However, capital costs associated with higher plant capacities were significantly higher and plant expansion may not be economically advantageous. TUC decreased as the CHP

capacity increased regardless of the type of feedstock used for energy production. The results show that for low capacity plants, renting a truck to transport feedstock would be a better option than owning a truck. Truck owning option was cheaper than rental truck only for high capacity plants. In Washington county, the lowest TUC was $0.018/kWh. In Scott county, the lowest TUC was $0.015/kWh. A modest increase in CHP capacity, that is from 1 MW to 2 MW in Scott county and 5 MW to 10 MW in Washington county, might be a feasible approach by drawing feedstock from a smaller area and at lower utilization rates (33% for CS and 30% for FLR), while keeping transportation costs low.

3.2 Introduction

Biomass transportation plays a significant part in determining the economic feasibility of CHP plants. The determination of transportation paths and distances is an important part of the economic feasibility of CHP production. Network analysis in Geographic Information Systems (GIS) has a strong theoretical basis in the mathematical disciplines of graph theory and topology (Curtin, 2007). GIS and network analysis have been used to evaluate road network flow (Wu et al., 2001; Jones and Schultz et al., 2009; Langholtz et al., 2007; Fromboa et al., 2009) and to optimize collection route and transportation for solid waste management system (Ghose et al., 2006). Khachatryan et al. (2009) used GIS to analyze the available agricultural crop residue that can be harvested, and the cost associated with transporting the feedstoc for cellulose ethanol processing in ashington. erpi a et al. and Ranta (2005) outlined a procedure to integrate biomass source location to destination with real road network. The procedure involved calculating the available biomass for energy and establishing the transportation network. Network analysis was used to identify available sites for collecting biomass and optimal location for bioenergy plants. Several factors were considered in the network analysis to establish the optimal locations. These factors include time, distance and transportation costs.

Mississippi currently operates two medium sized biomass based CHP plants, which are located in Scott county (1,000 kW) and Washington county (5,000 kW). As previously presented in Chapter 2, there were sufficient quantities of corn stover and forest logging residue available to increase the capacity of these existing CHP plants. Three different buffer distance scenarios for biomass collection were evaluated namely, 10-mile radial distance, 30-mile radial distance or all the biomass from adjacent counties, and the biomass type used (forest logging residue, corn stover or the combination of the two). The capacity of the CHP plant in the Scott county can be increased between 2,497 kW and 49,398 kW depending on the area covered for biomass collection, while the capacity of the plant in Washington county can be increased between 5,237 kW and 61,625 kW. The predominant biomass feedstocks in Scott and Washington were forest logging residue and corn stover, respectively.

Puttock (1987) noted that the economics of whole-tree chips for energy use was competitive with natural gas if transportation distance was within 80 km, and if the transportation distance for logging residue within 200 km then it is a feasible substitute for coal. Compared hauling costs of the two transportation models, roll on/off container system was not competitive with a regular highway chip van unless part of the road is not having access for highway chip van (Rawlings et al., 2004). Bryce (1993) suggested that decreasing moisture contents and improving trucking efficiency would increase the utilization of logging residue for energy production by increasing the haul capacities. The biomass supply analysis and logistics model (IBSAL) was developed to simulate the dynamic processes involved in collecting, storing and transporting the agricultural biomass to a bio refinery (Sokhansanj et al., 2006). Staskoa et al. (2011) compared the woody biomass cost supply for energy production and competing industry (paper mills) in the southeastern U.S. The weighted average logging cost for energy production was about $43 per dry ton and was $39 per dry ton for paper mills.

Models have been used for estimating potential biomass supplies and for identifying the location of the energy crops grown and spatial variability in their yields and transportation cost for an energy facility (Ranta, 2005; Vainio et al., 2009; Voivontas et al., 2000). Graham et al. (2000) found that transportation cost increased when demand increased. Comer et al. (2007) analyzed potential biomass supplies around the location of the proposed Warrenton power plant to determine whether there was enough supply of biomass available to support a 250-500 ton/day biomass-to-energy facility. The study set the supply-shed boundary at 50 miles, and concluded that the transportation of biomass fuel beyond 50 miles is likely to be economically prohibitive. Krukanont et al. (2003) used a mathematical model to calculate the costs of biomass fuel and identify the optimum size of power plant considering characteristics of regions, moisture content, and fuel availability density. Several studies evaluated GIS to identify the optimum bio refinery location (Xie and Zhao, 2009; Freppaz et al., 2003; Moller and Nielsen, 2007). Mixed Integer Linear Programming (MILP) model was integrated into a GIS tool to determine the biomass quantities and optimize the locations of bio refineries (Fernandes et al., 2010). Three types of availability have typically been reported in woody biomass studies completed to date. The first type is “potentially available”, which is all of the quantity of woody biomass (Milbrandt, 2005; Walsh et al., 2000; Gan, 2007). The second type is “technically available”, which is the percentage of recoverable amount of biomass that could be utilized er lac e t al., 5 . The third type is “economically available”, which is the amount of woody biomass available at a given market price (Walsh et al., 2003; BRDB, 2008). Several studies have developed GIS based models for finding delivered cost for the study area for collection and transportation of biomass to energy production plants (Graham et al., 1996; Graham et al., 1996; Zhan et al., 2005). The studies incorporated spatial differences which affect the collection and transportations cost and also found the least cost location. Brechbill and Tyner (2008) compiled costs involved in corn stover and switchgrass utilization from different research studies. The costs incorporated were farm gate cost, nutrient replacement cost, transportation cost, and loading cost. The total per ton costs for corn stover biomass, transported within 30 miles, ranged between $39 and $46. This supply curve can be applied to any plant size and could also be used to evaluate the greenhouse gas emission reduction cost.

Mani et al. (2009) calculated the corn stover based plant’s capital and operating costs and compared with existing natural gas fired heating system. The corn stover plant operating cost was higher than coal, but coal had the highest environmental impacts. Corn stover fired heat and power generation system improved net energy balance relative to fossil fuel based systems. Wahlund et al. (2004) determined that the best option for Sweden to achieve the largest CO2 reduction at the lowest cost and found the best method was to substitute coal with woody biomass fuel pellets. Graf and Koehler (2000) evaluated forest residue farm gate cost and transport cost for ethanol production in Oregon. The cost of removing and delivering forest residue was about $40 per dry ton with loading and hauling costs. Chipper-forwarder can chip biomass into a pile and transport the chips to roadside. Harvesting cost using chipper-forwarder was estimated to be between $15 and $25 per dry ton (Bryce et al., 1986). Calculated the profit of the biomass energy plant 5 to 50MW analyzed various costs involved, such as capital investment cost, total operating costs, vehicle transport costs, vehicles capacity, and biomass cost (Caputo et al., 2005).

There are sufficient quantities of corn stover and forest logging residue available to increase the capacity of these existing CHP plants. Higher plant capacity has the advantage of economy of scale because capital cost on a per capacity basis decreases as plant capacity increases. But the disadvantage with higher capacity is the increased cost of biomass as a result of higher cost of transporting biomass. In this work, we examined the effect of plant capacity on cost of energy production by determining several cost components including capital cost, biomass cost and operating cost. The main objectives of this study were: a) to identify the optimal path for biomass supply areas to CHP facilities, and b) to evaluate the transportation costs associated with an increase in CHP energy capacity using corn stover and forest logging residues.

3.3 Materials and Methods

3.3.1 Study Area

The analysis of transportation costs associated with the utilization of biomass feedstock for CHP application focused on existing CHP facilities or plants in Mississippi. There are 22 CHP facilities in the state of Mississippi that generate a total of 570,382 kW (EEA-Inc., 2010). The applications of these units range from dairy facilities (capacity: 50 kW) to oil refineries (capacity: 146,900 kW). There are 8 CHP facilities with lower capacities (< 5,000 kW) that are fueled by either wood, wood waste or other biomass sources. The biomass based CHP facilities are using the boiler/steam turbine and wood based CHP facilities are using the reciprocating engine CHP technology. Two biomass based CHP plants in Mississippi were selected for this study. The capacities of CHP plants in Scott county and Washington county are 1000 kW and 5000 kW, respectively. Fourteen counties were selected as biomass source areas for two existing bio-based CHP plants. The counties are Scott, Jasper, Neshoba, Smith, Leake, Rankin, Newton, Madison, Washington, Sharkey, Bolivar, Sunflower, Humphreys, and Issaquena.

3.3.2 GIS Road Network Analysis

Maintenance of topological properties is an important element in order to perform analysis on the data using the Arc Map Network Analyst extension (ESRI, 2011). A network dataset must be created with the appropriate network connectivity settings and attributes defined. The United States Census Bureau produces the Topologically Integrated Geographic Encoding and Referencing (TIGER) shapefile datasets detailing all public and political spatial information (Ryals, 2010). TIGER line shape files contain roads (primary, secondary, and county, street), railroads, rivers and other geographic areas. Many global positioning system (GPS) navigation devices use TIGER files as a road network. The TIGER road network includes data relating to the type, name, county, along with many other attributes. The metadata gives the detailed information about the attributes of the road network.

The base map for county boundaries and line shape file for Mississippi were downloaded from U.S. Census Bureau's TIGER database (U.S. Census Bureau, 2011). The original datum of the TIGER files was the North American Datum of 1983 (NAD 83). TIGER shape files were projected into UTM 16 North which is the UTM zone for Mississippi. The 2010 TIGER line shape files were downloaded for each of the fourteen counties included in the study area. This dataset was used as the basis for the transportation cost analysis. The distance unit for the projection was meters.

Before the network dataset was built, a geo- database and feature dataset with the necessary projections was created. The network dataset was created using ArcMap Network Analyst (ESRI, 2012) with global turns (Global turns are basically present at every transition between two adjacent edges within a network dataset and main purpose of global turns is to improve travel time estimate), and feature class type (e.g. one-way, two-way). The speed limit assigned to each road type was based on road hierarchy. Network analysis is often involves the minimization of a cost finding the best route. Common examples include finding the fastest route (minimizing travel time) or the shortest route (minimizing distance). The distance (meters) was in cost attributes of the network dataset and converted into miles (ESRI, 2012).

The downloaded TIGER Line shapefiles were originally county-level datasets. The Mississippi TIGER county boundary files were clipped into 8 neighboring counties of Scott and 6 neighboring counties of Washington, and merged into a single polygon feature class representing the study area. The TIGER road network was merged with the county boundary map of the study area in order to determine the transportation network for the feedstock collection.

The network extension tool in ArcMap is a powerful that provides a network-based spatial analysis that includes the optimal route, travel directions, closest facility, service area analysis, shortest path, drive-time analysis and origin-destination analysis (Khachatryan, 2009). ArcMap Network Analyst enables users to dynamically model realistic network conditions, including turn restrictions, speed limits, connectivity, and traffic conditions, as well as user defined parameters. The network analysis type called shortest path and origin-destination (SP-OD) cost was selected to determine the optimal distance from biomass supplies to CHP plant locations. The OD cost matrix identifies and calculates the least-cost paths along the network from multiple origins to multiple destinations. (ESRI, 2011). Three unique distance scenarios, namely, 10-mile buffer zone, 30-mile buffer zone, and neighboring counties were evaluated using the SP-OD cost matrix algorithm of the network analysis tool in Arc Map.

3.3.3 Analysis of Transportation Cost

The optimal route from the biomass source to CHP plants determined from the GIS network analysis was used in estimating the transportation costs. The primary means of transporting corn stover and forest logging residue is by truck. As corn stover is typically available only for half of a year, the allowable trucking time for corn stover was assumed to be 170 days per year. On the other hand, forest logging residue is available year round, and the allowable trucking time was 340 days per year. The truck biomass capacity for corn stover and forest logging residue is 20 tons and 40 tons, respectively, based on Searcy et al. (2007). It was assumed that biomass would be stored inside the CHP plant premises. The number of biomass trucks required for a CHP plant was dependent upon the plant capacity, actual road distance and type of biomass used in the plant (CS, FLR or combination of the two).

The basis for capital cost was \$12 million for a CHP plant capacity of 5,000 kW (McNeil Technologies, Inc., 2003). The capital cost of a plant was calculated based on the six-tenths power factor rule (Peters and Timmerhaus, 1980) as follows:

$$\text{Capital cost} = \$12 \text{ million} * [(\text{plant capacity in kW}/5{,}000 \text{ kW})^{0.6}] \qquad [3.1]$$

The operating cost for CHP plant was assumed to be \$0.003/kWh (McNeil Technologies, Inc., 2003). Farm gate cost for corn stover was \$35/ton (Brechbill and Tyner, 2008) and the farm gate cost for forest logging residue was \$19.7/ton (Perez-Verdin et al., 2009).

The time for loading and unloading of biomass was based on 2 hours and the total time that the truck could operate, including waiting time, was set at 10 hours per day (Berwick, 1997). The average speed of the truck was assumed to be 45 miles per hour (Berwick, 1997). The number of trips made by the truck per day was dependent upon the transportation distance.

Fuel cost was assumed as \$4.00/gal. Fuel efficiency was assumed as 5.72 miles/gal for loaded truck and 7.7 miles/gal for empty truck (Berwick, 1997). Thus, the transportation cost was \$1.12/mile for loaded truck and \$0.83/mile for empty truck. The labor cost for trucking was assumed as 60% of fuel cost based on values from Berwick (1997). Loading and unloading cost was \$3.74/ton and \$3.52/ton for corn stover and forest logging residue, respectively (Kumar, 2007; ANTARES Group Inc., 2008). Thus, the loading and unloading cost per truck load was \$74.80 and \$140.80 for corn stover and forest logging residue, respectively.

Truck cost was assumed to be \$110,000 and the salvage value after 10 years of usage was assumed as \$ 28,600. Based on straight line depreciation method, the annual truck cost was \$9,400/yr (Khachatryan et al., 2009a). The truck maintenance cost was assumed to be 50% of truck cost based on values from Berwick (1997). Several rental truck options were considered in the analysis namely, a) value of \$0.245/ton/mile (Perrin, 2010), inclusive of loading and unloading cost, and a) value of \$0.15/ton/mile for corn stover and \$0.14/ton/mile for forest logging residue (USDA Agricultural Marketing Service, 2005). In calculating the total unit cost (TUC), the following designations were used in this study, a) Option 1 – plant owned truck, b) Option 2 – custom rental rate based on Perrin (2010) and c) Option 3 – custom rental rate based on USDA Agricultural Marketing Service (2005).

3.4 Results and Discussion

3.4.1 Buffer Analysis

The optimal route for each buffer distance scenario was determined using the shortest path. Figure 3.1 presents a pictorial road analysis for Washington county for three scenarios, 10-mile buffer and 30-mile buffer area and their shortest road distance based on ArcMap Network analysis. The inner circle represents the 10-mile area and the outer circle represents 30-mile area of the CHP plant neighboring counties. The shortest path distance was taken for calculating transportation cost to transport corresponding biomass availability in these buffered areas. Figure 3.2 represents boundary sharing counties for Washington CHP plant and available biomass supply points (county seats). In this case, county seats were considered as biomass supply points. Arc Map origin-destination cost matrix algorithm was used to determine shortest route from supply points to CHP locations. A map showing the buffer scenarios and corresponding routes in Scott county is shown in Figure 3.3. The shortest paths from the county seats to the CHP plant in Scott county is presented in Figure 3.4.

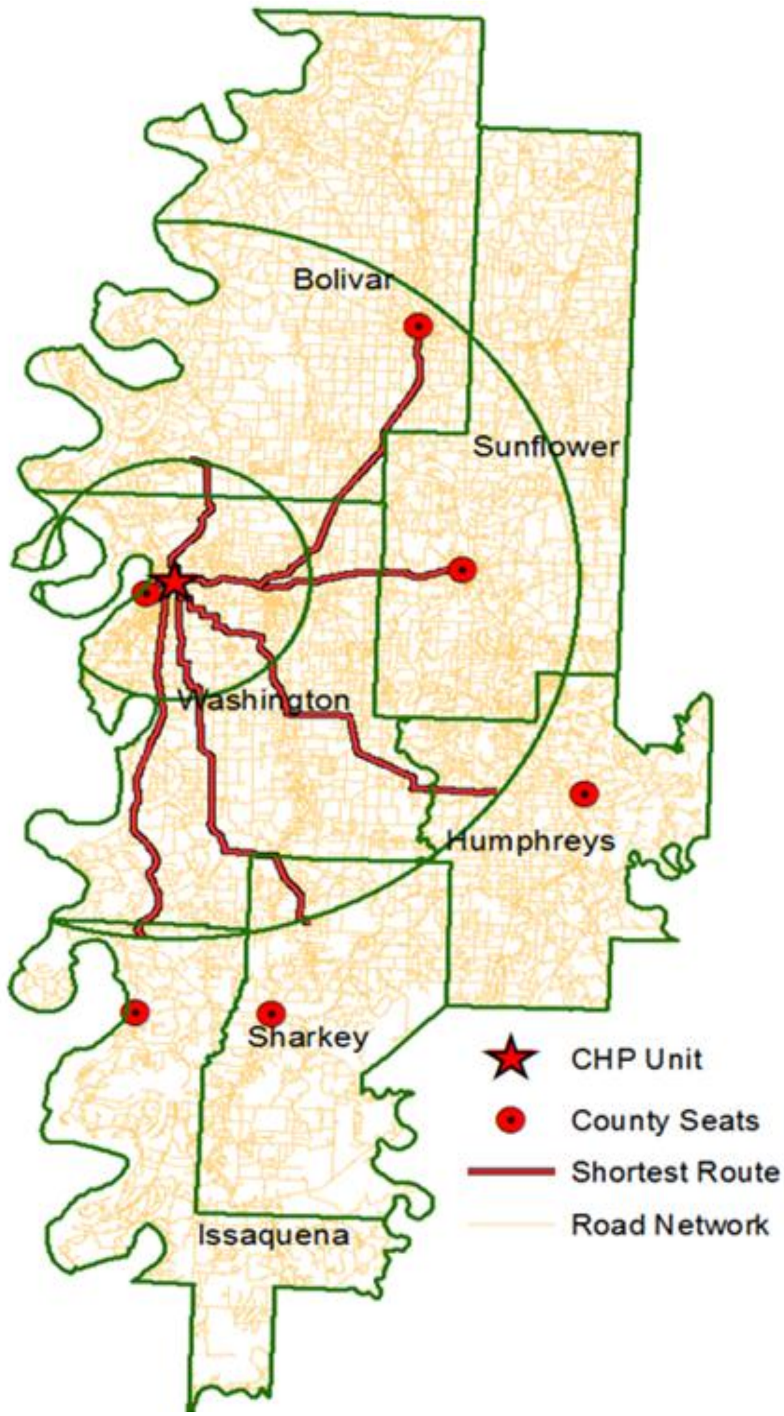

Figure 3.1 Shortest Path For Washington County CHP Plant and Biomass locations(10 mile & 30 Mile Buffer Zone)

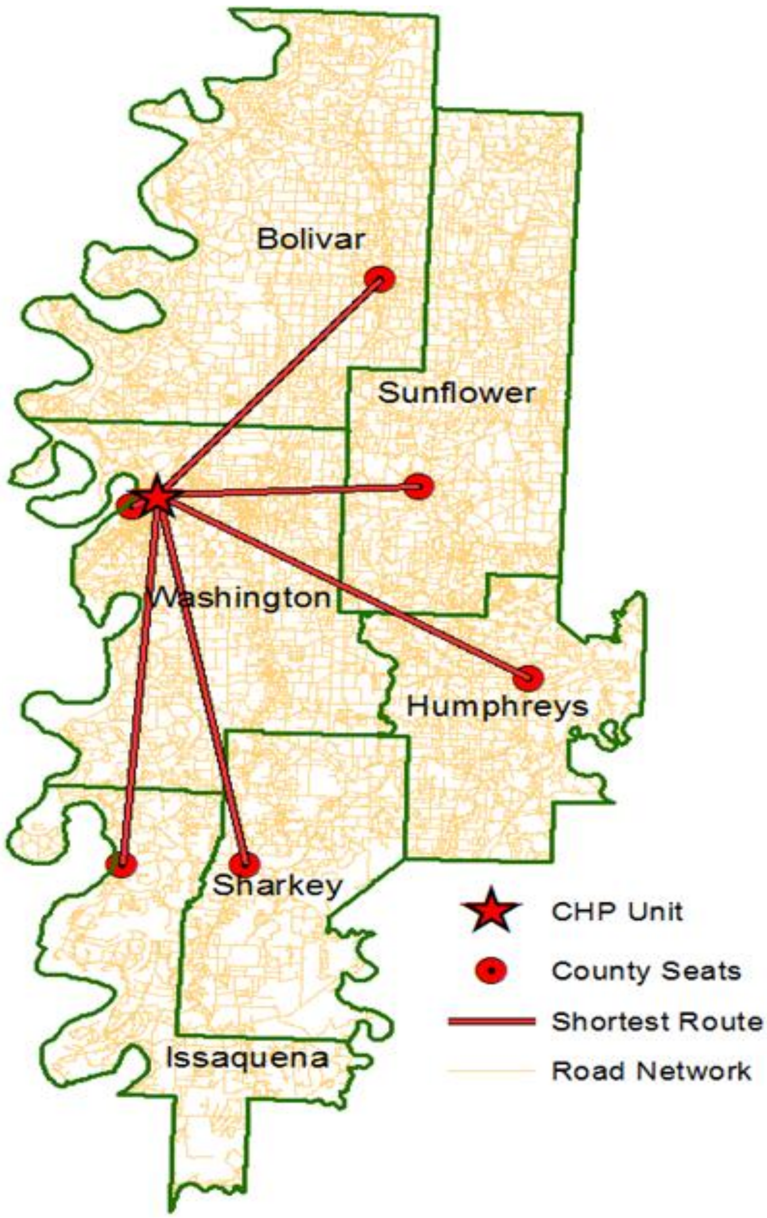

Figure 3.2 A map showing the shortest routes from the county seats to the CHP plant in Washington county

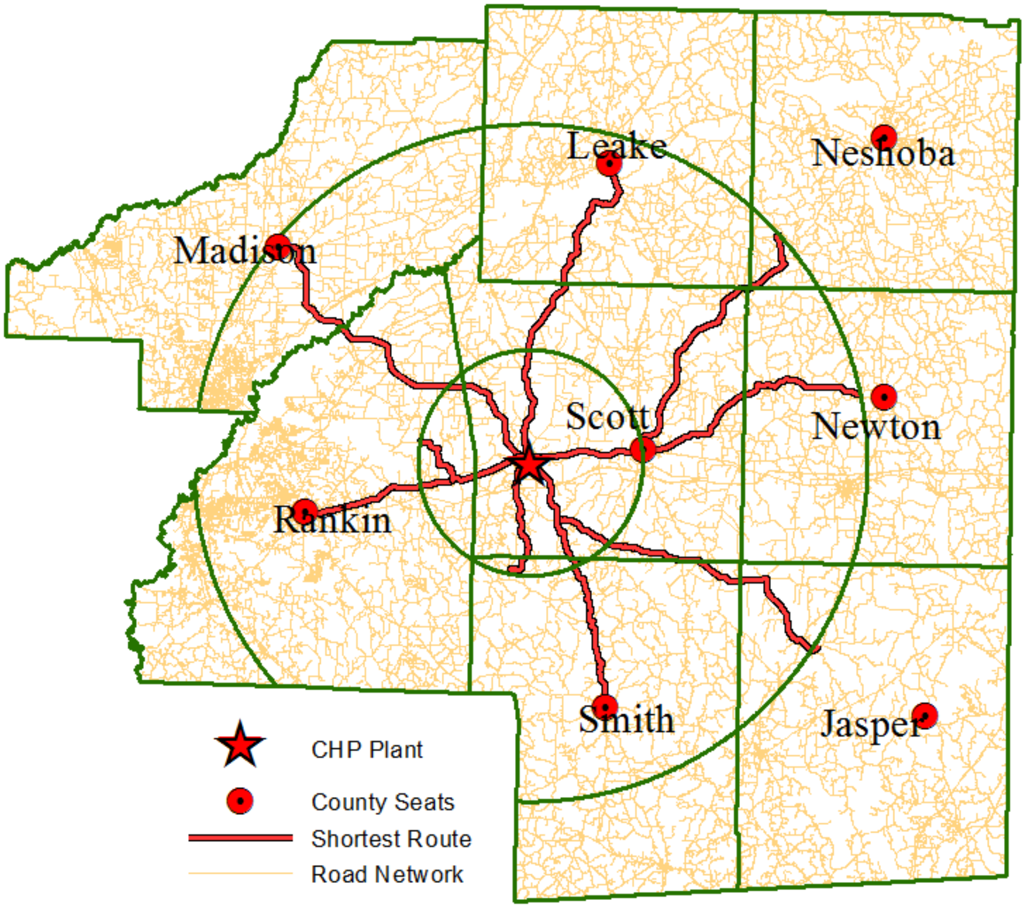

Figure 3.3 Shortest Path For Scott County CHP Plant to Adjacent Counties 10 and 30 mile Zone (Biomass locations)

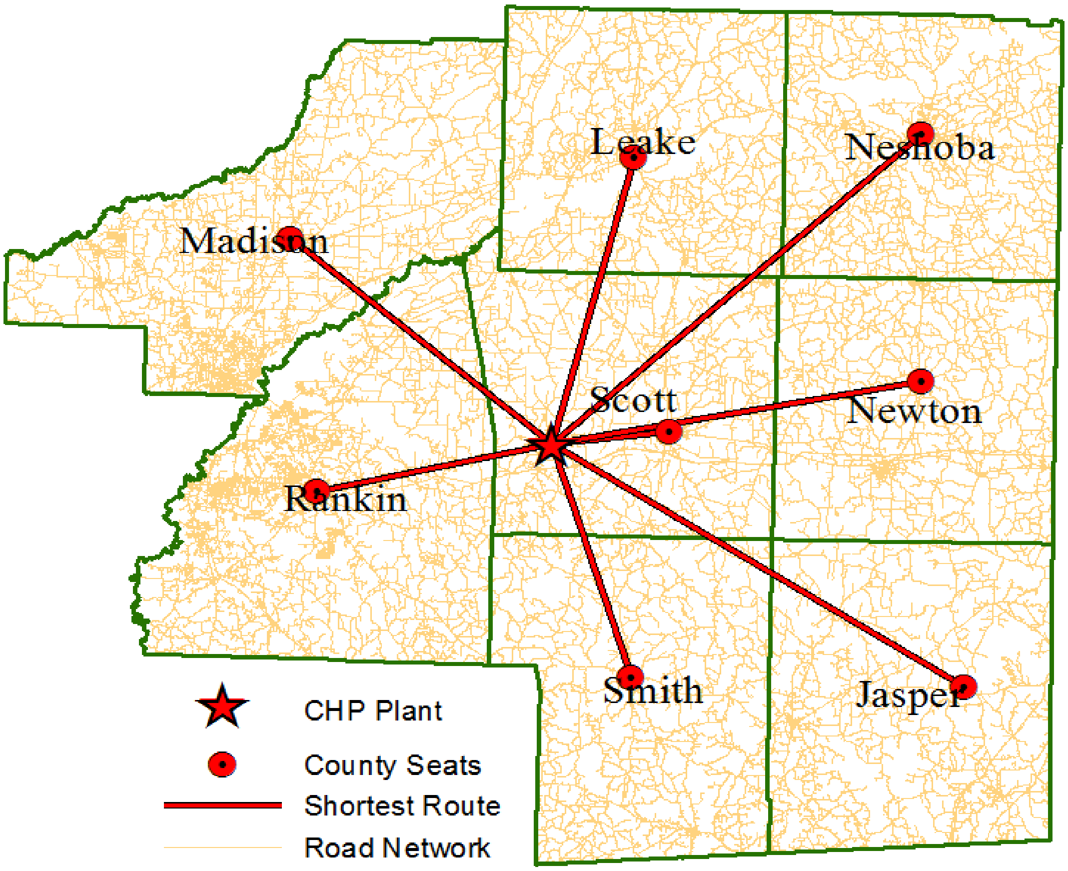

Figure 3.4 A map showing the shortest routes from the county seats to the CHP plant in Scott county

3.4.2 Transportation Cost

The estimated cost parameters associated with different capacities of biomass-based CHP plants in Washington and Scott counties are presented in Table 3.1 and 3.2, respectively. In general, the total capital costs and farm gate biomass (FGB) costs increase with increasing CHP capacity regardless of the type of feedstock. However, in Washington county, corn stover is the predominant feedstock, and the FGB cost of corn stover was significantly higher than FLR. The payload capacity of trucks used to haul CS (20 tons) is half of what is used to haul FLR (40 tons). Therefore, trucks hauling FLR require fewer trips than CS.

Three truck ownership and rental options were evaluated in this study. In general, the TUC decreased as the CHP capacity increased, regardless of the type of feedstock. In Washington county, the lowest TUC was $0.018/kWh for forest logging residue for Option 3. In Scott county, the lowest TUC was $0.015/kWh for FLR for option 1 as well as option 3.

Corn stover based plants in Washington county had lower TUC than CS based plants in Scott county with similar supply area (Tables 3.1 and 3.2). The reason for the lower TUC for Washington county was the higher capacity of the plant that resulted in economy of scale in terms of capital cost. Higher capacity of CS based plants in Washington county was due to higher availability of CS within the same supply area compared to Scott county. Washington county is located in the delta region that cultivates corn significantly. Scott county is not located in the delta region.

In Washington county, the CS based plants had lower TUC compared to FLR based plant with similar supply area, despite the higher cost incurred for CS if the feedstock utilization rate is 100% transportation resulting from lower payload capacity for CS (Table 3.1 and Figure 3.5). The reason for lower TUC, for CS based plants compared to FLR plants in Washington county, was the economy of scale in terms of capital cost due to higher availability of CS than FLR in the same supply area. In Scott county, TUC for CS based plants were higher than FLR in similar supply area because of lower capacity of CS based plants as well as higher transportation cost for CS due to lower payload capacity (Table 3.2 and Figure 3.6)

The custom rental truck Option 3 transportation was cheaper than the other two options because of the charge out rate of $0.14 to $0.15/ton/mile suggested by the study (USDA Agricultural Marketing Service, 2005) is perhaps an underestimation (Tables 3.1

and 3.2). Truck owning option 1 was cheaper than option 2 custom rental truck transportation, only for high capacity plants because the owned truck is utilized fully in higher capacity plants (Tables 3.1 and 3.2). For low capacity plants, rental option would be better than owning a truck because the truck would be underutilized.

Even though TUC is lower at higher capacity, it might not be feasible for a CHP plant to obtain capital investment for very high capacities. For example, an existing 1,000 kW plant (in Scott county) that already incurred a capital cost of $4.6 million would require a further investment of $42.8 million to expand to the highest possible capacity of 49,398 kW (Table 3.2). This scenario does not seem feasible from the standpoint of obtaining capital investment. Hence, it is reasonable to say that the plant capacity of 2,524 kW or 2,764 kW (10 mile buffer) would be a feasible option because the additional capital investment required would only be $3.4 to 3.8 million. Similarly, for Washington county, we expect that expanding from a capacity of 5,000 kW to 10,000 kW would be a feasible option. A 10,000 kW capacity was not specifically studied in this work for Washington county, but the area where the biomass can be collected would lie between the 10-mile buffer and 30-mile buffer zone.

Table 3.1 Summary table of associated costs of different CHP capacities in Washington County*

Biomass Type	Supply area	CHP Capacity (kW)	Capital cost ($ million/yr)	FGB cost, $/yr	Option 1 TR Cost ($/yr)	Option 1 TUC $/kWh	Option 2 TR Cost ($/yr)	Option 2 TUC $/kWh	Option 3 TR Cost ($/yr)	Option 3 TUC $/kWh
FLR	10 miles	540**	3,156,716	24,600	12,785	0.040	1,253	0.038	716	0.037
	30 miles	3,302**	9,355,467	150,811	42,561	0.024	37,561	0.024	21,463	0.023
	AC	11,369	19,643,894	519,747	144,301	0.019	217,571	0.019	124,326	0.018
CS	10 miles	4,697**	11,558,237	431,725	58,325	0.028	10,182	0.027	6,234	0.026
	30 miles	24,257	30,952,911	2,232,580	353,285	0.022	226,902	0.022	138,919	0.021
	AC	50,257	47,919,867	4,627,469	894,949	0.021	842,675	0.021	515,924	0.020
FLR+CS	10 miles	5,237	12,338,114	456,325	71,110	0.027	11,435	0.025	6,950	0.025
	30 miles	27,559	33,416,220	2,383,391	395,845	0.021	264,462	0.021	160,383	0.020
	AC	61,625	54,157,102	5,147,216	1,039,249	0.020	1,060,247	0.020	640,250	0.019

* FGB: farm gate biomass cost; Option 1: own truck; Option 2- rental option based on Perrin (2010); Option 3-rental option based on USDA Agricultural Marketing Service (2005), Option 1 TUC: Total Unit Cost; Option 2 TUC: Total Unit Cost; Option 3 TUC: Total Unit Cost; TR: Transportation Cost, AC: Adjacent Counties

** Calculated capacity is less than existing capacity (5000kW)

Table 3.2 Summary table of associated costs of different CHP capacities in Scott County*

Biomass Type	Supply area	CHP Capacity (kW)	Capital cost ($ million/yr)	FGB (cost, $/yr)	Option 1 TR Cost ($/yr)	Option 1 TUC ($/kWh)	Option 2 TR Cost ($/yr)	Option 2 TUC ($/kWh)	Option 3 TR Cost ($/yr)	Option 3 TUC ($/kWh)
FLR	10 miles	2,524	7,962,562	115,068	31,972	0.026	16,440	0.025	9,395	0.025
	30 miles	22,046	29,227,867	1,007,576	256,973	0.017	304,852	0.017	174,201	0.016
	AC	44,422	44,499,600	2,030,826	563,746	0.015	845,904	0.016	483,374	0.015
CS	10 miles	240**	1,940,555	22,050	11,195	0.060	1,755	0.055	1,075	0.054
	30 miles	2,497	7,911,346	229,740	50,150	0.032	43,875	0.032	26,863	0.031
	AC	4,977	11,966,347	458,234	104,755	0.029	99,281	0.017	60,784	0.028
FLR+CS	10 miles	2,764	8,408,569	137,118	43,166	0.026	18,196	0.025	10,469	0.024
	30 miles	24,543	31,171,366	1,237,316	307,123	0.017	348,727	0.017	201,064	0.016
	AC	49,398	47,427,093	2,489,060	668,501	0.016	945,185	0.016	544,158	0.015

* FGB: farm gate biomass cost; Option 1: own truck; Option 2- rental option based on Perrin (2010); Option 3-rental option based on USDA Agricultural Marketing Service (2005), Option 1 TUC: Total Unit Cost; Option 2 TUC: Total Unit Cost; Option 3 TUC: Total Unit Cost; TR: Transportation Cost, AC: Adjacent Counties

** Calculated capacity is less than existing capacity (1000kW)

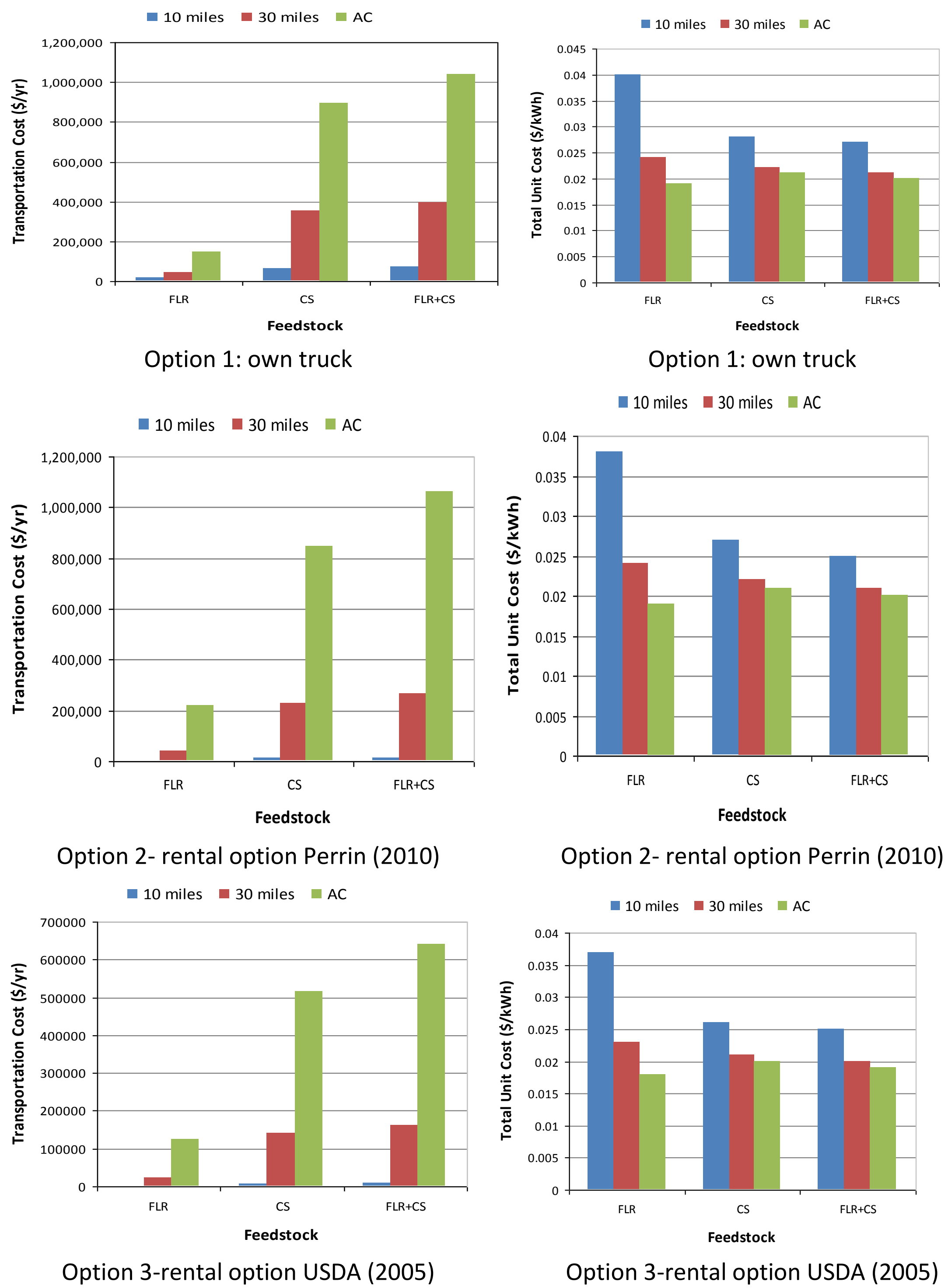

Figure 3.5 Transportation cost (left) and total unit cost (right) for different truck ownership options associated with biomass feedstock supply for a CHP plant in Washington county

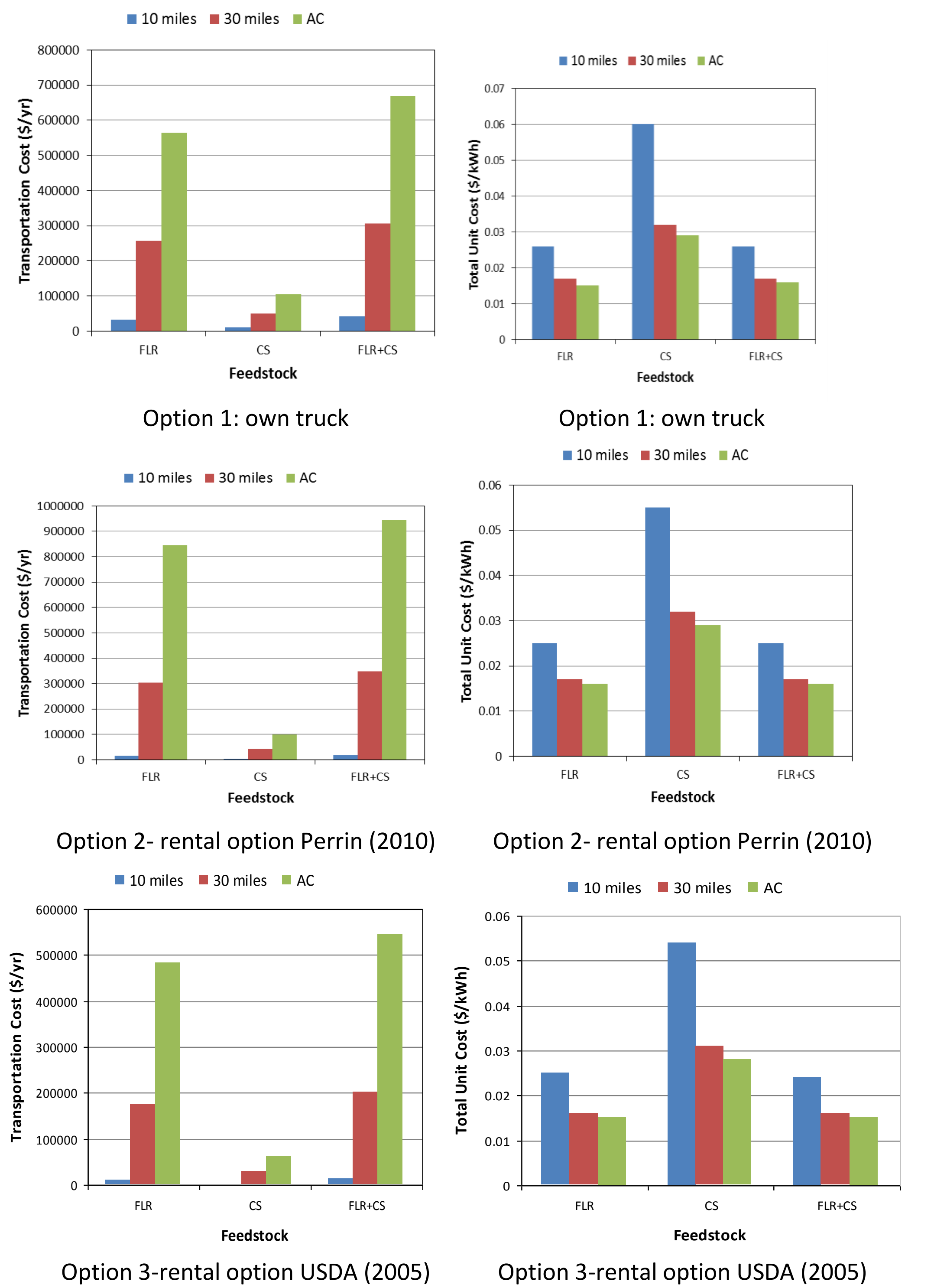

Figure 3.6 Transportation cost (left) and total unit cost (right) for different truck ownership options associated with biomass feedstock supply for a CHP plant in Scott county

3.5 Conclusions

The biomass transportation distances were determined using GIS tools and the distances were used to determine the transportation cost. It was found that rental option would be better than owning a truck for low capacity plants. On the other hand, owning a truck was cheaper than renting a truck to transport biomass feedstock, only for high capacity plants. The TUC decreased as the CHP capacity increased, regardless of the type of feedstock. In Washington county, the lowest TUC was $0.018/kWh. In Scott county, the lowest TUC was $0.015/kWh.

Transporting feedstock within a smaller source area (10-mile radius) had lower transportation costs but higher total unit cost than the two other source buffer scenarios. However, capital costs associated with higher plant capacities were significantly higher and plant expansion may not be economically advantageous. A modest increase in CHP capacity, that is from 1 MW to 2 MW in Scott county and 5 MW to 10 MW in Washington county, might be a feasible approach by drawing feedstock from a smaller area and at lower utilization rates (33% for CS and 30% for FLR), while keeping transportation costs low.

CHAPTER IV

GENERAL CONCLUSIONS

The potential increase in CHP capacity was assessed based on a sustainable utilization rate of available corn stover and forest logging residue in Mississippi. The results show that the available corn stover is 2,048,985 tons/year, and forest logging residues is 2,763,231 tons/year. The total amount of available biomass feedstock is 4,812,216 tons/year, which represents a significant amount of renewable resource that can be utilized for CHP production in Mississippi. The amount of available corn stover can produce up to 264.8 MW of power generated through the use of CHP technology, if the feedstock utilization rate is set at 100%. In this study, a sustainable corn stover utilization rate of 33% can produce up to 126.9 MW. Full utilization (100%) of forest logging residue can produce energy up to 404.8 GW, while a sustainable utilization rate of 30% of forest logging residue can produce 332.7 MW of power using CHP. Mississippi Delta region is the main source for corn stover, while the southwest region of Mississippi has more forested areas, which can be tapped for energy production.

Using GIS to delineate the supply zones, we found that the available biomass within a 10-mile radius from the CHP plants can satisfy the existing requirement of CHP plants in Scott and Washington with a capacity of 1MW and 5MW, respectively. Increasing the radial distance of biomass utilization to 30 miles can potentially produce 24.5MW and 27.6MW in Scott and Washington counties, respectively. Furthermore, if adjacent counties were considered as biomass supply areas, the available feedstock can more than double the energy capacity, producing 49.4MW and 61.6MW in Scott and Washington counties, respectively. These results show that the maximum CHP plant capacity can be increased from 1 MW to 49.4 MW and from 5 MW to 61.6 MW, based solely on a sustainable utilization of available biomass. The main factor that can affect the expansion of CHP plants is establishing the zone of biomass source areas, which in turn would affect capital costs and transportation costs. A realistic approach might be to double the capacity of the CHP plant in Scott county from 1 MW to 2 MW, and in Washington county from 5 MW to 10 MW.

The biomass transportation distances were determined using GIS tools and the distances were used to determine the transportation cost. It was found that rental option would be better than owning a truck for low capacity plants. Owning a truck to transport feedstock was cheaper than renting a truck, only for high capacity plants. The TUC decreased as the CHP capacity increased, regardless of the type of feedstock. In Washington county, the lowest TUC was \$0.018/kWh. In Scott county, the lowest TUC was \$0.015/kWh.

Transporting feedstock within a smaller source area (10-mile radius) had lower transportation costs but higher total unit cost than the two other source buffer scenarios. However, capital costs associated with higher plant capacities were significantly higher and plant expansion may not be economically advantageous. A modest increase in CHP capacity, that is from 1 MW to 2 MW in Scott county and 5 MW to 10 MW in Washington county, might be a feasible approach by drawing feedstock from a smaller area and at lower utilization rates (33% for CS and 30% for FLR), while keeping transportation costs low.

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