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Supporting energy transitions and miscanthus program development at the University of Iowa

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SUPPORTING ENERGY TRANSITIONS AND MISCANTHUS PROGRAM DEVELOPMENT AT THE UNIVERSITY OF IOWA

by

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

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ABSTRACT

Miscanthus is a highly productive, low-input biofuel crop that supports agricultural diversification with improved performance for climate commitment, energy security, and water quality over first generation biofuels. Despite its high performance, no local or regional markets for the feedstock have formed in North America, and current climate-based productivity assessment methods lack the information farmers and decision-makers need to establish commercial scale bioenergy markets, programs, and thermal co-firing plans. This study develops a Miscanthus Suitability Rating and a transferable field-scale siting method, applied at 10 m resolution across the State of Iowa to assess miscanthus production potential and identify individual farms that are highly suitable for large-scale miscanthus cultivation while maintaining a majority of existing row cropping acreage. Results show that highly suitable fields within 50 miles (84 km) of each of Iowa's coal-fired electrical generating units (EGUs) can displace up to 43% of current coal consumption. Every EGU in Iowa has land resource to produce local miscanthus to co-fire with other solid fuels at industry-leading levels without significantly impacting local row crop production. Seven of the state's smaller facilities could even operate exclusively on local miscanthus with advancements in densification technology. The energy evaluation tool developed in this work estimates the energy return on investment (EROI) of Iowa miscanthus for existing thermal generation facilities between 37 and 59, depending on transportation requirements and chemical field applications. This transition would diversify local agribusiness and energy feedstocks, reduce greenhouse gas emissions and provide a sustainable, dispatchable, in-state fuel source to complement wind and solar energy.

PUBLIC ABSTRACT

Miscanthus is a highly productive, low-input grass that can be burned in power plants in the place of coal. Miscanthus diversifies crop species, reduces carbon emissions in both agriculture and energy systems, increases energy security, and improves water quality over current popular biofuels. Despite its high performance, no local or regional markets for the feedstock have formed in North America, and current climate-based productivity assessment methods lack the information farmers and decision-makers need to establish commercial scale bioenergy markets to supply power plants with the fuel. This study develops a Miscanthus Suitability Rating to evaluate the suitability of individual fields for miscanthus cultivation. This rating is applied across the state of Iowa to estimate the potential volume of the crop that could be reasonably produced and identify individual farms that are highly suitable for large-scale miscanthus cultivation. Results show that highly suitable fields within 50 miles (84 km) of each of Iowa's coal-fired electrical generating units (EGUs) can displace up to 43% of current coal consumption. Every EGU in Iowa has land resource to produce local miscanthus to co-fire with other solid fuels at industry-leading levels without significantly impacting local row crop production. Seven of the state's smaller facilities could even operate exclusively on local miscanthus with advancements in densification technology. The energy evaluation tool developed in this work estimates the energy return on investment (EROI) of Iowa miscanthus between 37 and 59, depending on transportation requirements and chemical field applications. This means that the crop would provide 37-59 times more energy than it requires. This transition would diversify local agricultural and energy

systems, reduce greenhouse gas emissions, and provide a sustainable, in-state fuel source to complement wind and solar energy.

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CHAPTER 1 INTRODUCTION

Energy systems power transportation, manufacturing, residential, and agricultural processes around the world. Those in turn serve and power human bodies, global trade, and the world's economy. Energy systems, particularly those powered by fossil fuels, have also caused severe climate changes, environmental damage, international conflict, and energy scarcity. The world's dependence on energy systems, coupled with the enormous impacts and risks they present, has created one of the most pressing problems faced by the current generation: transitioning to sustainable energy systems.

This work uses established and novel energy transition frameworks to analyze previous transition projects at the University of Iowa (UI) and identifies elements of success at the UI that can be applied to similar institutions. Next, this research supports the biomass initiative at the UI by estimating land resource availability for their latest bioenergy crop and proposing a siting method for new fields that considers the interaction of bioenergy programs with field characteristics. The methodology and predictive tools developed in this work will enable local and statewide decision makers to site biomass fields that can achieve higher productivity, more coal displacement, and greater reduction in greenhouse gas (GHG) emissions.

Since adopting their first biomass fuel in 2003, the UI has invested heavily in sustainable energy systems. Their latest biomass fuel, which receives the most attention in this work, is *Miscanthus x giganteus* (miscanthus), a highly productive and efficient bioenergy grass. The UI began planting miscanthus in 2013 because it has the potential to address climate change, agricultural pollution, energy insecurity, and other environmental concerns better than other locally-available alternative energy sources. Second generation biofuels like miscanthus are more productive than first generation biofuels like corn and soy beans, they require minimal field inputs, and the direct combustion of these crops makes for a strikingly lean supply chain. The state of Iowa is a favorable location to explore the development of miscanthus because, among the states and regions with high predicted miscanthus productivity (Jain et al., 2010), Iowa has the most acres of agricultural land.

Miscanthus presents advantages in fields compared to traditional, annual row crops. Miscanthus is a perennial grass, growing for 10-20 in commercial applications, which reduces inputs from planting by more than 90%, eliminates the need for cover crops, and reduces the risk of soil erosion in winter months. Miscanthus cultivation can improve wildlife habitats, biodiversity (Anderson and Furgusson, 2006), soil fertility, and carbon sequestration (Mishra et al., 2013). Miscanthus can also reduce soil erosion and nutrient pollution when replacing corn or when planted as buffer strips between corn stands and water bodies (Gopalakrishnan et al., 2012). Even on tiled soils[1], a mature miscanthus stand can reduce nitrogen losses in tile drainage to less than 3% of that measured on corn fields (Smith et al., 2013).

Miscanthus has also exhibited advantages over other bioenergy grasses, producing as much as 3 times the biomass as switchgrass (Heaton et al., 2008). Miscanthus is efficient in use of sunlight, water and nutrients (Heaton et al., 2004). In addition, *Miscanthus x giganteus* is a sterile hybrid, which nearly eliminates the risk of invasion in natural ecosystems (Milster, 2017).

Miscanthus also has advantages over fossil fuels, when the supply chains for each are compared. GHG emissions for miscanthus supply chains are just 13% of that for coal by one calculation (Styles and Jones, 2007).[2] In agricultural regions with no fossil fuel resources, miscanthus can be sourced in closer proximity to power plants, supporting local jobs and agribusiness. There is also work being done to develop more storage and densification methods miscanthus to complement renewable fuel sources that have more limited storage capabilities (Miao et al., 2015; Kambo and Dutta, 2014; Chaoui and Eckhoff, 2014; Tumuluru et al., 2011 and 2012).

Despite these promises of miscanthus bioenergy, analytical tools to inform policymakers and planners in the development of new programs are insufficient. Existing biophysical and geospatial models use precipitation, solar irradiation, temperature, and other climate data to predict miscanthus productivity in Europe (Hastings et al., 2009) and the Midwestern United States (Miguez et al., 2011; Jain et al., 2010; Mishra et al., 2013). They provide extensive data to inform decisions about the best climate zones in which to site miscanthus production, but not about the most suitable fields within a climate zone. Once an EGU or third party supplier decides to pursue miscanthus production, they need to identify fields within the surrounding counties best suited to miscanthus production. Slope, soil quality, and flooding tendencies dramatically affect crop productivity, social impacts and environmental outcomes of cultivating miscanthus on that field. These characteristics can change from one field to the next. Given the lack of this local information, critical field selection decisions by local energy planners or power plant operators are made with no more information than land rent values or expressed interest by landowners.

In Iowa, most potential miscanthus fields are currently planted in corn or a corn-soybean rotation. Compared to corn and soybeans, miscanthus interacts very differently with the surrounding environment. Traditional rows of corn provide minimal protection from soil erosion and require large amounts of fertilizer and other chemical applications.[3] These factors lead to problematic soil erosion and nitrogen pollution (Renard et al., 1997; Williams et al., 2014). An average of 5.7 tons of soil were lost per acre per year from 2007 to 2014 from Iowa fields (Cruse, 2016). Nitrogen pollution has pushed the nitrate level in Iowa rivers as high as three times the safe drinking water limit in 2013, according to the United States Geological Survey nitrate monitoring data. Field tiling has magnified this problem because it carries nitrogen to ditches and rivers faster than it could be transported over land (David et al., 1997). Land that requires tiling in order to maximize profitability for corn has a lower opportunity cost when considering the transition to miscanthus cultivation. In comparison to a tiled corn field, an un-tiled miscanthus field will significantly reduce soil and nitrogen runoff as a result of smaller chemical applications, better soil protection, and the avoidance of tiling (Potter et al., 2006; Gopalakrishnan et al., 2012; Ng et al., 2010; Smith et al., 2013). For these reasons, it is advantageous to consider field characteristics in the siting of miscanthus fields in addition to climate factors that have been considered in previous productivity models.

After siting a miscanthus field, there are several ways to evaluate the resulting miscanthus bioenergy program. Many studies have evaluated the effectiveness of miscanthus as a fuel source on the basis of economics and GHG emissions (Jain et al., 2010; Styles, 2007; Schneider and McCarl, 2003). Jain et al. (2010) found the value of miscanthus fuel must reach $88/ton to balance expenses to produce and transport the crop. Current (2016) coal prices in the Midwest are roughly the equivalent of $35/ton of miscanthus, based on energy content, according to the US Energy Information Administration (EIA). Styles (2007) calculated that the miscanthus supply chain has roughly 13% the global warming potential of the coal supply chain.[1] Schneider and McCarl (2003) studied the economic potential of biomass in a GHG market and found biomass to be the most effective climate mitigation strategy when the cost of carbon is at or above $70 per ton of CO_2. These data help decision-makers determine the value of both miscanthus fuel and avoided carbon emissions.

However, other metrics can also improve our understanding and management of miscanthus programs. Energy Returned on investment (EROI) [4] is a critical evaluation for products whose primary role is generating energy. For example, corn ethanol has an estimated average EROI of only 1.07 ± 0.2 (Murphy, 2011). This means corn ethanol, although it is a valuable fuel additive, is not effective as a primary source of energy because it requires about as much energy to produce as it contains. Investing in fuels such as these is often not effective. Therefore, EROI calculations performed in this research are important in the development of miscanthus for bioenergy.

In support of the UI miscanthus program, this study produces a suitability rating for miscanthus siting that uses field characteristics and targets social and environmental outcomes in addition to yield. This suitability rating is applied to the state of Iowa at sub-field resolution, informing the potential land resource available to support miscanthus programs across the state.

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[1] 'Tiling' involves burying perforated pipes throughout a field to lower the water table and prevent flooding or ponding in fields, allowing ready access to fields and preventing crop damage from flooding (Urban et al., 2015).

[2] Estimated greenhouse gas emissions are 0.131 kg CO_2 eq. kWh^{-1} for the miscanthus supply chain compared to 0.990 kg CO_2 eq. kWh^{-1} for that of coal (Styles, 2007).

[3] 110-140 lbs N/acre for corn, compared to 0 for soybeans, 0-60 for oats and rye, and 50-120 for switchgrass, according to the University of Wisconsin Extension Service (Laboski and Peters, 2012), and 63lb/acre recommended by Repreve Renewables (UI Facilities Management et al., 2014).

[4] This metric is a ratio of energy outputs over inputs, so EROI = 1 represents a fuel that requires the same amount of energy to prepare as the energy it provides.

CHAPTER 2 FRAMEWORKS IN ENERGY TRANSITION

The development of biomass siting tools for the University of Iowa's Miscanthus Bioenergy Program was highly dependent on the larger context of the University Power Plant. Miscanthus fuel, and all new fuels, will interact with storage facilities, handling and combustion equipment, employees, contractors, and other entities in different ways than previous fuels, and it is still unclear how these interactions will develop. Consulting energy transition theory and previous fuel integrations are two ways to manage the complexity and uncertainty surrounding the cultivation, processing, handling, storage, and combustion of this new fuel.

2.1 Socio-technical Configurations

The study of energy (or 'sustainability') transitions as it exists today emerged in the late 1970's with the Technological Regime framework, described as an "evolutionary model of the processes of technological advance and economic growth" (Nelson et al. 1977). Since then, it has grown quickly in the number of publications (roughly tripling every decade) and in the breadth of contributing expertise, attracting economists, anthropologists, sociologists, policy analysts, historians, engineers and more. This breadth has led to a view of energy systems that considers not only the technological systems, but also the structures that support and utilize a given technology.

Geels (2002) calls this inclusive view of energy systems a sociotechnical configuration. Figure 1 shows, for example, selection pressures and limitations that might be included in a "Sociotechnical Configuration for Personal Transportation." These are forces that have shaped the development of effective technology for personal transportation. Understanding the role of each of these components can guide regime actors in changing them. The diagram does not, however, reveal the relationships between these components. Therefore, as components change, the diagram does not indicate which other components they are most likely to impact. This work proposes a variation of this diagram that indicates the relationships in a Sociotechnical Configuration for Energy Generation at the University of Iowa, shown in Figure 2.

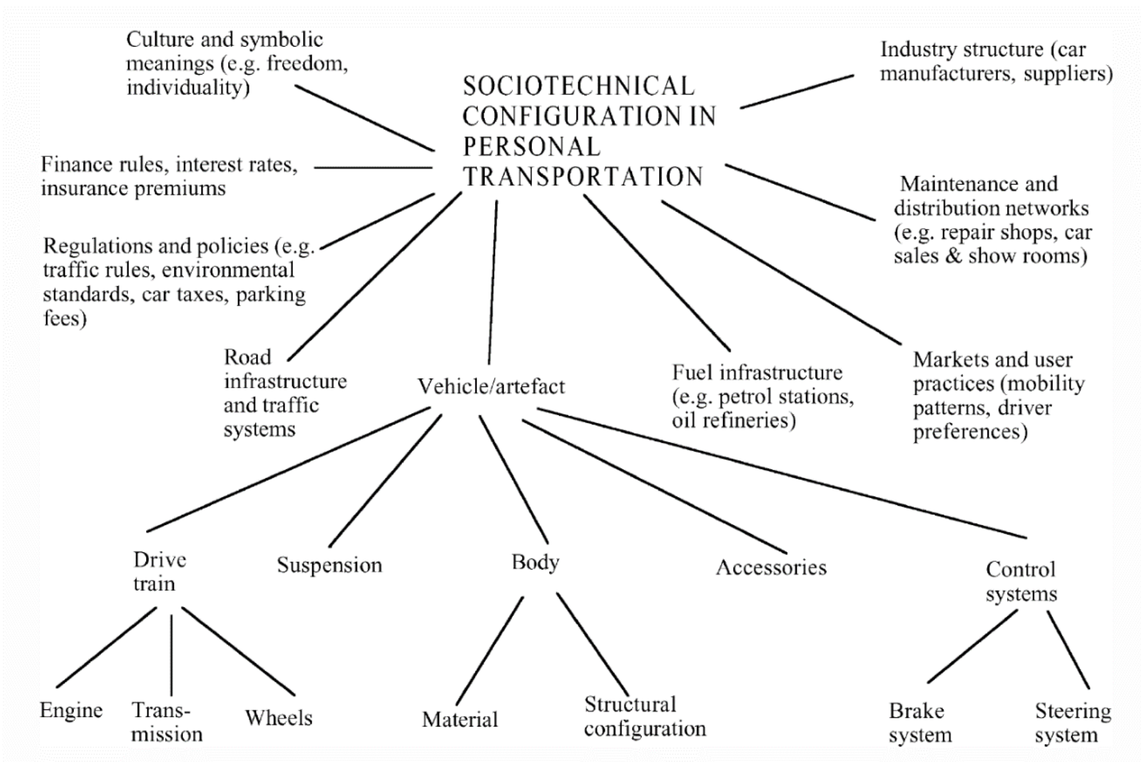

Figure 1: This diagram shows the technological systems and social structures that contribute to personal transportation (Geels, 2002)

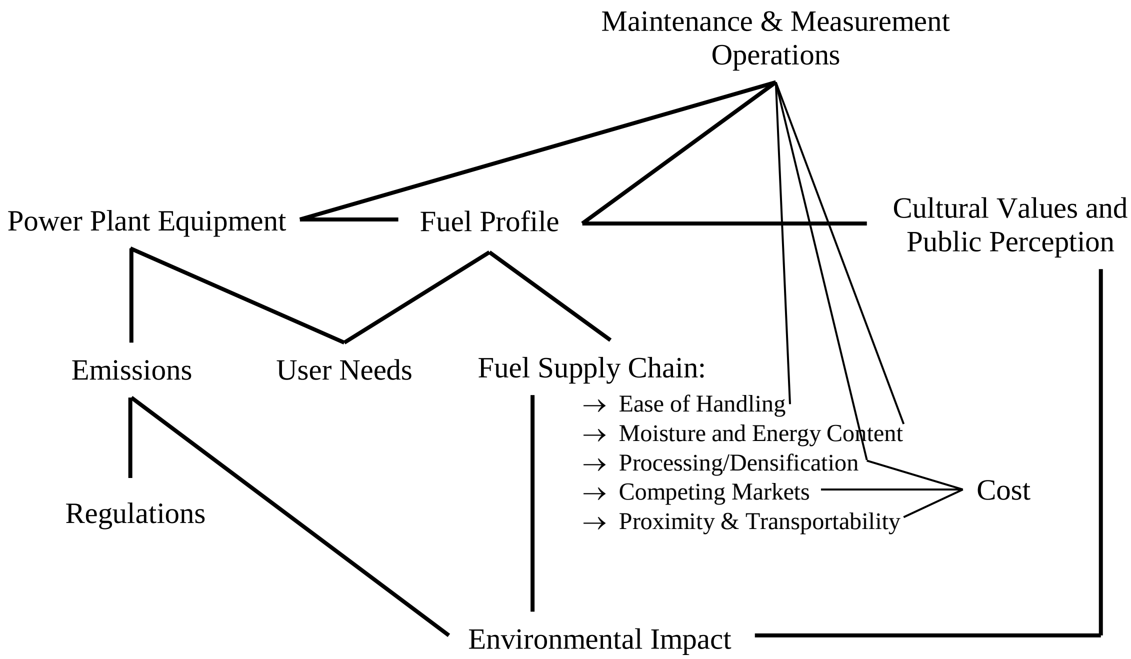

Figure 2: This diagram shows the technological systems and social structures that contribute to energy generation at the UI as well some of the relationships between them.

Examining the connections between elements in Figure 2 illustrates the value of denoting these relationships instead of simply listing factors that influence the system. The Fuel Profile (which fuels are used and in what proportions) is affected by Cultural Values and Public Perception, Maintenance and Measurement Operations in the power plant, User Needs, and Power Plant Equipment. Cultural Values influence decisions about the Fuel Profile because ambitious sustainable fuel projects and goals like the 2020 Vision (University of Iowa, 2010) depend on the support of university administration, staff and students that value sustainability. Public Perception, however, has also inhibited adoption of sustainable fuels in the past because of misconceptions about their safety or sustainability. Maintenance and Measurement Operations as well as Power Plant Equipment influence fuel decisions because of the ways fuels interact with them. Some fuels reduce emissions and actually clean conveyors, while others plug up and damage conveyor equipment or require consistent cleaning and maintenance in hard to reach places. Finally, User

Needs on campus, especially those of certain research buildings and the University of Iowa Hospitals and Clinics (UIHC), include highly reliable energy. This need led to the purchase of four natural gas engines in 2013 for $17 M to ensure reliable back up power. The dispatchable fuels that feed the boilers must also come from a reliable, dispatchable source. Moving back to the left side of Figure 2, Power Plant Equipment, from boilers to scrubbers, affect stack Emissions that are subject to environmental Regulations. These regulated stack emissions and emissions embodied in fuel make up most of the system's Environmental Impact, which has increasing influence in a Culture that Values sustainability.

This diagram also shows some of the fuel characteristics listed under Fuel Supply Chain that professionals from Utilities & Energy Management and the Office of Sustainability have identified as most important to successful integration of new fuels, i.e. transition of the configuration (Christiansen and Paterson and Hazen, 2016; Milster and Anderson, 2017). These are summarized more thoroughly in Table 1 and discussed in reference to each sustainable fuel project in Section 2.2.

In the miscanthus fuel supply chain, densification is critical to integrate higher blends of miscanthus, since the boilers can only accommodate about 8% of the raw chopped grass, by energy. There are a number of potential plans for densification still under consideration, and they have a wide range of resulting environmental implications and cost per unit of fuel energy. These outcomes are largely dependent on the source of energy for the densification plant, which is explored in Section 2.2 with potential landfill methane projects. Without discussing details of densification plans, Figure 2 indicates that the densification plan will affect the fuel profile, environmental impact of the system, the cost of the fuel supply chain, and operations at the power plant.

As the uncertainty surrounding miscanthus densification illustrates, components in sociotechnical configurations change over time, and one change can affect a whole socio-technical configuration. To make sense of potential changes, their implications, and drivers of these changes, the literature uses several categorizations. This work focuses on two of these: the Multi-Level Perspective and Institutional-Discursive-Technological categories of change. These categorizations are used relatively implicitly throughout analysis of previous transition projects, but they are worth introducing since they were used as frameworks to collect comprehensive information about the projects.

The Multi-Level Perspective (Geels, 2002 and 2012; Geels et al., 2014; Wainstein, 2016; Rip, 2002; Van den Ende and Kemp, 1999) separates changes into niche, regime, and landscape levels. The dominant mainstream configuration, or regime, can adopt niche technologies to adjust to changing landscape pressures. Regimes can also be overtaken by mature niche technologies if they ignore landscape pressures. In this work, the UI is the focus, so it is assumed as the 'regime.' Consequently, larger structures like government regulations and social/cultural values are landscape factors that constrict and pressure the regime. Finally, emerging specialists and innovations that exist on a smaller scale of relevance and impact than the regime would be considered niche-level factors. In Figure 2, Regulations and Cultural Values & Public Perception are examples of landscape pressures, while Power Plant Equipment and the Fuel Supply Chain are regularly affected by niche technologies.

As van der Vleuten and Hogselius noted (2012), "incumbent energy systems are difficult to change because they are constituted by historically shaped alignments of many technical, [institutional, and discursive] components." All three of these distinctions are identified in the analysis of UI transition projects. Technological factors include specifications of equipment at the power plant and within the supply chain, niche technology innovations, and renovations to existing equipment. Institutional factors include changes made to employees' roles, communication modes between departments and beyond the university, collaborations with contractors, policies, and regulations. Discursive factors refer to cultural norms, and user tendencies.

2.2 Transition Initiatives at the University of Iowa

In 2010, the University released a new sustainability plan, the "2020 Vision," outlining 7 sustainability goals with specific strategies and quantifiable targets for each (University of Iowa, 2010). Two of these goals articulate selection preferences for fuel acquisition on campus: increase renewable energy supply to 40% of total energy portfolio with attention to long-term supply and fuel price stability, and develop partnerships to advance collaborative sustainability initiatives. Both goals have seen significant progress, as the profiles of sustainability initiatives will reflect. In February of 2017, the UI released a new goal to eliminate coal from their energy profile entirely by 2025.

To contextualize the showcased initiatives, some background on UI energy systems is necessary. The UI's main power plant supplies roughly a quarter of the electricity consumed on campus. The most valuable operation of the plant is not electricity, however, but steam production. The collocation of electricity and steam production (called combined heat and power, CHP) means that waste heat from electricity generation is utilized for other, steam-powered processes, increasing the overall efficiency of the plant from 30-40% to as high as 80% (Rezaie and Rosen, 2016). The UI Iowa Hospitals and Clinics (UIHC) and campus buildings use steam for space heating and cooling (using steam-powered chillers), sterilization, humidification, cooking and water heating. These processes rely on extensive steam distribution infrastructure and other equipment that have been continually expanded since the power plant was constructed in 1927. Because of high temperature processes and existing district heating assets, University employees agree that combustion will have a place in energy systems on campus for all of the foreseeable future.

Due to these strong incentives to continue relying on steam and therefore combustion, the UI has focused particularly in sustainable combustion fuels. These fuels come from industrial processes, dedicated energy crops, and landfill diversion. They have a number of general advantages over fossil fuels, and particularly coal. Fuel diverted from landfills reduces the many negative environmental impacts of landfills. Locally-sourced biomass provides business to local land owners, in a market – electricity fuel production – that has not previously existed in Iowa. Bioenergy grasses reduce land degradation and improve water quality, two major problems caused by Iowa's row crop production. Compared to coal, many biomass fuels produce fewer harmful pollutants during combustion, cost less, and reduce maintenance requirements for power plant equipment.

In the last 15 years, UI Facilities Management has added oat hulls, wood chips and miscanthus bioenergy grass to their fuel portfolio. These biomass fuels together were responsible for 15% of the University's energy generation in 2015 (Andersen, 2017). They have learned that the successful integration of a biomass fuel depends primarily on the proximity, availability, reliability, and affordability of the fuel supply, as well as fuel properties that affect transportability, storage, handling, emissions, and environmental impact (UI Biomass Fuel Project Supporting Materials; Christiansen, 2016; Patersen, 2016; Andersen 2017). These characteristics for each fuel are reflected in Table 1, and they are discussed in more detail in the following sections.

Table 1: Summary of fuel characteristics that impact sustainability and implementation.

	Oat Hulls	Wood Chips	Miscanthus	Pellet
Proximity	Good	Fair	Variable**	Variable
Availability	Good	Poor	Good	Good
Reliability	Good	Poor	Good	Good
Affordability	Excellent	Variable	Fair	Good
Energy Density	Poor	Good	Fair	Excellent
Transportability	Fair	Good	Fair	Excellent
Environmental Impact (Sourcing)	Excellent	Variable	Good	Variable
Environmental Impact (Emissions)	Excellent	Fair	Good	Variable
Fuel Handling	Excellent	Good*	Fair	Excellent

*High quality wood chips are almost indistinguishable from coal in material handling, but high quality chips are expensive and difficult to obtain or produce.
**Depends on processing requirements and location of processing plant.

Oat Hulls

Oat hulls are a byproduct of processing oats for food products. They have been used in several markets around the world. Prior to partnering with the University, the Cedar Rapids Quaker Oats plant processed oat hulls with sulfur dioxide to produce fufural, which was used in the chemical industry as a motor oil additive. A relatively high sulfur-content byproduct of this process, called resifil, was burned at a Cedar Rapids power plant. In 2001, the fufural industry was lost to overseas competition, and the power plant that previously burned resifil chose to cut the fuel from its portfolio to reduce sulfur emissions. Facing a tipping fee if they could not find another use for the oat hulls, Quaker offered them to the UI at a price far lower than that of coal, UI's main energy fuel at the time.

Resifil was tested at the power plant, with less than impressive results. Although the University's boiler was able to maintain low sulfur emissions burning the fuel, the material – similar in consistency to coffee grounds – was difficult to mix evenly with coal, causing problems in several stages of material handling. Raw oat hulls were tested next. Co-firing 50% oat hulls by weight reduced emissions of particulate matter by 90%, heavy metals by 65%, polycyclic aromatic hydrocarbons by 40%, and carbon dioxide by 40% compared to coal alone (Al-Naiema et al., 2015). Raw oat hulls also have a lower sulfur content than resifil and saved energy and money by eliminating the resifil production process at Quaker Oats. However, raw oat hulls required a new custom-designed pneumatic fuel handling and injection system. University engineers and contractors designed, procured and installed this new system.

Overall, the transition to combusting oat hulls as a regular fuel required modest changes at the UI and took less than 3 years from conception to running the fuel. Although the technology to make the transition was available in other contexts, there was considerable investment in custom-designed material handling systems and adjustments to boiler conditions. The implementation required time investments from numerous UI and Quaker Oats employees, but no positions were permanently altered to accommodate the new fuel. Oat hulls save the UI $500,000 per year and displace 30,000 tons of coal per year (Facilities Management, 2016). The only opponents identified are those who oppose any kind of combustion, in favor of wind and solar energy.

Although the Quaker Oats plant is only 28 miles from Iowa City, the low density of oat hulls requires almost daily deliveries of the fuel. The urban location of the UI power plant makes this level of truck traffic somewhat undesirable. The fuel is available in significant quantities; Quaker Oats guaranteed 40,000 tons of oat hulls in 2016. Oat hulls are available reliably; any interruptions due to Quaker Oats plant shutdowns are planned well in advance. For the UI, these circumstances mean reasonable transportability, volume of supply, and reliability.

Review of this transition project showcases the capability of engineers and operators to undertake large, complex projects given support from their managers and University administrators, as well as flexibility to work through system implementation. Projects like the Oat Hulls implementation often rely more on contractors, which costs more money for the University and can sometimes result in more difficult transition because outside contractors are less familiar with University systems and practices (Milster, 2017). The University received two Governor's Iowa Environmental Excellence Awards in 2004, and the Effective and Innovative Practices award in 2005 from the APPA: Leadership in Educational Facilities (University of Iowa, 2015) for the implementation of oat hulls.

Woodchips

In 2012, the Johnson County Conservation Board approached the UI about utilizing biomass from dead and invasive, non-native trees from Kent Park and Ciha Fen. Two major difficulties arose with wood chips from these timber stands: chip quality and moisture. To avoid blockages and damage to equipment at the power plant, the wood chips must be smooth and consistent in size and shape, similar to coal. Chips of this quality require a high-grade wood chipper (about 700 hp) that can cost around $1 M. The second issue is that chips from live trees are high in moisture, which reduces their heating value and increases PM emissions from the plant (Anderson, 2017). Despite challenges, the Kent Park and Ciha Fen projects provided over 3,200 tons of woodchips, which is roughly 27,500 MMBTU, or 1% of the power plant's annual output. Integration of wood chips also reduced a modest reduction (6%) in metals in stack emissions (Al-Naiema et al., 2015).

Prompted by the Kent Park and Ciha Fen projects, the UI sought waste streams of kiln-dried wood. A pallet manufacturer and recycler just over 80 miles from the UI was able to provide a steady supply of kiln-dried, high quality wood chips from retired pallets. These woodchips cost as much or slightly more than coal, but they have a particular unexpected advantage in power plant maintenance: they effectively polish coal dust off of power plant conveyors, reducing required cleanings from twice a day to about twice a week.

The UI has also explored fuel from dead trees removed from city property, which has increased due to the Emerald Ash Borer that appeared in Iowa in 2010. The City of Iowa City typically cuts and chips dead and dying trees at the site of the tree to avoid the inconvenience and cost of cutting, loading and transporting logs on busy city streets. The chips produced by the city's chipper are not acceptable for the power plant's handling systems. The City and the UI have explored purchasing a chipper capable of producing fuel-quality wood chips, but they have not found an investment/ownership structure that works for both entities.

This project emphasized the benefit of procuring fuels with physical characteristics similar to coal. With these fuels, processes in the power plant beyond the boiler require very few alterations and cost the University fewer man-hours and less money.

Miscanthus Bioenergy Grass

The miscanthus bioenergy grass pilot at the UI – jointly managed by Repreve Renewables and the UI – began in 2013 with a 16-acre field, and expanded to 550 acres by 2016, with the goal of up to 2500 acres by 2020. This goal would provide roughly 25% of the UI's fuel needs. Ferman Milster, an engineer in the Office of Sustainability, initiated the project with support from facilities management. The UI partnered early in the project with Emily Heaton, a researcher specialized in miscanthus at Iowa State University, and Repreve Renewables, a biomass company based in North Carolina. These partners assisted in finding land owners interested in leasing land for miscanthus production, making decisions, and troubleshooting difficulties with the crop and supply chain.

Similar to wood chips, miscanthus is currently mixed with coal at the fuel yard before being delivered to the power plant. The percentage of miscanthus that can be used in this way is limited by the energy density of the chopped grass. To overcome this limitation, the grass can be included as a feedstock in a high energy density pellet fuel, which is profiled next.

This project, more than those before it, relied on the University's firm and explicit long-term sustainability plan. Developing contracts with local land owners, establishing miscanthus fields that could be harvested annually for the next 15 years, and investing the capital time and money required to integrate miscanthus into power plant operations all required significant foresight. Uncertainty surrounding long-term institutional commitments can contribute to the abandonment of potentially viable and sustainable energy fuels.

Landfill Methane and Energy Pellets

In 2007 the University proposed a pipeline to carry methane from the Iowa City landfill to partially power its Oakdale research campus (SCS Engineers, 2010). The landfill currently produces about 310,000 MMBTU of landfill gas (LFG) annually that is flared onsite, and it is expected to continue producing enough LFG to remain a viable energy source, "for decades after… capping of the landfill," which is expected to be in 2019 (SCS Engineers, 2010). There was considerable discussion of the project between the University, the City of Iowa City, and Alliant Energy, and MidAmerican Energy, but in 2008 the project was abandoned largely due to the prohibitive costs of the pipeline installation and the difficulty of developing an investment and ownership plan for the project.

To avoid the complications previously encountered with the pipeline proposal, more recent efforts to use the landfill methane have explored high-energy processes that can be located at the landfill. One option under discussion is construction of a pelletizing plant that would use various renewable feedstocks to produce an energy dense pellet to fuel the UI main power plant. Feedstocks could include oat hulls, woodchips, and miscanthus, as well as many other materials that are otherwise not suitable fuels due to low density or material handling limitations.

In addition to organic feedstocks, most energy pellets must also include a plastic binder to achieve a reliable, energy dense fuel pellet. Although many studies show the safety of combusting these plastics and the EPA has approved many such pellets as a non-waste alternative fuel under the Alternative Fuels Program (40 CFR 241), the public remains wary of the idea of combusting plastics. Unfortunately, this misplaced concern may prove to be an obstacle in implementing this fuel that has potential to end the UI's dependence on coal.

Energy Control Center

The University of Iowa's Energy Control Center (ECC) is less about *control* and more about *information*, according to its manager, George Paterson (2016). The system accesses over 100,000 data collection points across the campus that are used to monitor, analyze and predict energy usage (University of Iowa Facilities Management, 2012). Data from the ECC is used in various ways by University engineers, consultants, utility operators, and others. Engineers access data to plan and implement new projects like those described in the previous sections, consultants to complete audits, and utility operators to assess and improve the efficiency of energy systems. Under normal operating conditions, access to this data improves efficiency of operations and maintenance projects. In the event of a malfunction, information from the ECC might alert operators to a problem that could otherwise remain unnoticed for days. With more information about campus systems, malfunctions are diagnosed and repaired more quickly.

Before the ECC, power plant operators and engineers manually collected much of the data now readily available to them, identification of problems more often relied on customer complaints, and diagnosing problems required more time and on-site investigation. The idea of an Energy Control Center (ECC) floated throughout Facilities Management from power plant operators to the Associate Vice President and Directors, who all recognized the value of readily accessible information in facilities operations.

The creation of the ECC involved installing meters, automating controls, connecting and protecting a separate data server, purchasing modeling software from Rockwell Automation, and collecting access to all of those elements in a single room in the University Services Building. Although they improve overall functionality of the University's energy systems, each component of the ECC also adds complexity: meters can be costly, inaccurate (when a project requires very low tolerances), and difficult to access for calibration; the ECC server needs to be both accessible and secure, requiring robust firewalls and careful connections beyond them; and new software must be compatible with existing software while supporting new functionality. Two full-time employees and 2-3 student employees operate the control center and its various components, with support from other UI employees and outside contractors as needed.

The ECC is used to monitor energy consumption trends in all the buildings on campus. Real-time energy usage for each building is available online, along with historical data. These trends help identify maintenance issues that can cost hundreds of thousands of dollars a year. One leaking steam valve that was identified soon after the ECC was developed was estimated to cost $35,000 in energy losses every month! There were several more manual valves in the power plant that were overlooked until automation related to ECC development was installed. These valves, in the incorrect position, were estimated to cost the University $250,000-$500,000 a year. Aside from detecting malfunctioning systems, data collected by the ECC is used to construct building models, aid in completing various studies, and inform curtailment decisions.

However, savings and improvements from the creation of the ECC didn't come without growing pains. For instance, data collected in the ECC sometimes indicated a problem or opportunity that power plant operators believed to be impossible. This can happen because a certain measurement may not provide a full or accurate picture of power plant operations or meters can be inaccurate or faulty (Paterson, 2016). When data seemed to oppose operators' instincts, it was important for professionals looking at the data and operators working in the plant to communicate freely to find the error. Even considering these confusions, the ECC has more than paid for its installation and has been instrumental in providing information required for other sustainability initiatives and overarching plans like the 2020 Vision.

CHAPTER 3 METHODS IN MISCANTHUS SITING

This work supports miscanthus program development in two ways – by developing a map to inform miscanthus field siting and evaluating energy efficiency of miscanthus programs. The siting map helps decision-makers in new and expanding miscanthus bioenergy programs identify suitable fields based on factors that are expected to lead to reduced environmental damage, while limiting competition with high-commodity crops. The energy evaluation of miscanthus programs quantifies the effectiveness of the program to support long-term electricity or steam generation.

3.1 Miscanthus Field Siting

The miscanthus field siting map was created in ArcMap by combining datasets of factors that are expected to affect miscanthus program outcomes, according to a novel rating system, Miscanthus Suitability Rating (MSR). MSR addresses plant productivity, environmental impacts of nutrient pollution and the social and economic impacts of competing with high commodity crops. MSR targets land that has moderate land quality and requires tiling for full productivity in corn cultivation. Higher than moderate quality land reduces MSR because when planted on high quality land, miscanthus competes with high value commodity crops, which is a negative social outcome. Lower than moderate land quality land decreases MSR because miscanthus productivity will suffer, which is a negative economic outcome for the miscanthus program. Land that requires tiling to reach full productivity planted in corn earns a higher MSR because miscanthus is more resilient to field flooding than corn. Low productivity of corn due to flooding also decreases the opportunity cost of introducing miscanthus.

Corn Suitability Rating 2 (CSR2) (Burras et al., 2015) is used as a measure of land quality. Since many field characteristics that support high yields of corn also support high yields of miscanthus, we assume the metric is a reasonable basis for predicting miscanthus yield as well. Using CSR2 as a basis for MSR will aid implementation because many farmers already know the CSR2 of their fields and many researchers, agronomists, and other consultants know how to calculate CSR2. Using CSR2 also allows avoidance of competition with a high commodity crop by targeting moderate land quality.

Miscanthus and corn differ the most with respect to flooding. Corn, which experiences a fragile establishment phase after annual planting (Urban et al., 2015), is more often vulnerable to flooding than miscanthus, which is very hardy after establishment (Anderson et al., 2014). Also, miscanthus uses more water than corn, reducing water runoff yield by 30-60% (Le et al., 2010). Finally, field operations for corn are vulnerable to flooding every spring and fall, when tractors need to access the field for planting and harvesting. Miscanthus, however, is planted only once every 10-20 years in the spring, and annual harvest often occurs when the ground is frozen (UI Facilities Management et al., 2014).

Therefore, CSR2 and tiling requirements determine MSR as follows:

$$\boldsymbol{MSR = c + d}$$

$$Where\ c\ is\ determined\ by\ the\ CSR2\ of\ a\ parcel\ of\ land\ and$$

$$d\ is\ determined\ by\ the\ drainage\ requirements, according\ to:$$

$$For\ (70 < CSR2 < 80), \qquad \boldsymbol{c} = 7$$

$$For\ (60 < CSR2 < 70\ AND\ 80 < CSR2 < 90), \qquad \boldsymbol{c} = 5$$

$$For\ (0 < CSR2 < 60\ AND\ 90 < CSR2 < 100), \qquad \boldsymbol{c} = 0$$

$$Requires\ Tile\ Drainage, \qquad \boldsymbol{d} = 3$$

$$Does\ not\ Require\ Tile\ Drainage \qquad \boldsymbol{d} = 0$$

MSR for non-agricultural land or fields smaller than 40 acres is 0 regardless of CSR2 and drainage. Only land that is currently planted in corn or in corn-soy rotation is considered to avoid the development natural ecosystems. The also ensures that urban areas and water bodies are not included in the map for obvious reasons. Land that does not fit this criterion is automatically set to MSR = 0.

Soil erosion and nutrient pollution are among the most environmentally damaging processes resulting from corn cultivation (Potter et al.,2006; Anderson et al., 2015). Both of these are exaggerated on fields that experience flooding (Ng et al., 2010; Smith et al., 2013). Tiling is becoming more common in flood-prone fields to avoid damage to corn, but tiling exacerbates nutrient pollution by carrying nitrates to waterways faster than they would be carried over land (David et al., 1997). Miscanthus requires less than half the nitrogen application of corn (63 lbs/acre compared to 110-114 lbs/acre (Laboski and Peters, 2012)), reducing the potential for nutrient pollution. In addition, miscanthus develops deeper, denser roots systems that increase infiltration and protect soil and compounds in the soil from runoff.

3.2 Miscanthus Supply Chain Energy Evaluation

Many evaluations of miscanthus bioenergy programs are based on cost (Heaton, 2004; Styles et al., 2008; Repreve, 2015) and emissions (Styles, 2007). EROI is another important factor in these evaluations. Regardless of associated costs and emissions, if it requires more energy to produce miscanthus fuel than it provides, it will fail as a primary source of energy. The loosely linked costs of energy fuels in different forms (transportation fuels vs electricity fuels) and the bias of policy incentives can mask a disadvantageous energy return, as in the case of corn ethanol (Murphy et al., 2011).

Energy calculations in this work are based on the processes and inputs outlined in the University of Iowa Power Plant’s (UIPP) miscanthus bioenergy business plan (UI Facilities Management et al., 2014). However, the energy evaluation tool is built to conform to other types of programs with only simple adjustments in parameters. The model is organized by steps in the miscanthus supply chain: Field Operations, Fertilizer, and Transportation (energy costs), and the

Power Plant (energy return). Field operations include tilling, planting, chemical applications, and harvesting. Embodied energy in rhizomes, fertilizer, herbicide, and insecticide are included. Embodied equipment energy is neglected, as most field operations use existing row crop machinery. A full crop rotation is considered to occur every 15 years.

According the to the UIPP business plan, new fields are cultivated twice, and then miscanthus rhizomes are planted at a density of 13,382 per acre. Insecticide is applied in the first year, and herbicide for the first two years to support reliable establishment of the crop. The crop is harvested with a forage chopper for the first time after the second growing season and then annually. Fertilizer is applied annually. Default rates for fertilizer components are 7 lb. per ton of yield from the previous season for nitrogen and potassium and 1.5 lb. per harvested ton for phosphorus.

The model does not include processing or storage needs for the crop. Storage needs are unique to each plant and can include field storage in ag bags, bales, or other storage options at the electricity generating unit (EGU) or other facility (Shastri et al., 2012; Chaoui and Eckhoff, 2014; UI Facilities Management et al., 2014). Processing may not be necessary for lower co-firing rates (less than ~10% miscanthus), based on preliminary tests at UIPP. This is also unique to each plant, based on the facility's conveyor systems, boilers, and other equipment. Transitioning to 100% miscanthus or other low density biofuel would most likely require densification, which allows more efficient storage and delivery of the fuel. Numerous densification options exist, all of which are relatively underdeveloped and are thus beyond the scope of this work. The energy required to run the plant and combust miscanthus fuel is assumed to be similar to that of coal and is neglected for this analysis. EROI comparisons to coal are made at the point of delivery to the facility.

Fuel usage assumptions for each field operation are shown in Table 2. Fuel consumption for transportation vehicles is based on 6 mpg average gas mileage and 23 tons of miscanthus in each load. Embodied energy for diesel fuel, field applications, and miscanthus rhizomes are shown in Table 3. Energy content of miscanthus fuel is assumed to be 8000 BTU/lb (University of Iowa Facilities Management, et al., 2014). Sources and statistical analyses for embodied energy calculations are shown in Tables 4 and 5.

Table 2: Fuel and energy inputs for miscanthus field operations. Sources and statistical analysis for these data are found in Tables 4 and 5.

Field Operation	**Diesel Usage (gal/acre)**	**Energy Usage (kWh/acre)***
Primary Tillage	1.45	60.02
Secondary Tillage	0.86	35.60
Planting	0.32	13.24
Spraying	0.125	5.17
Harvesting	2.83	117.13
Totals		
Year 1	5.835	240.51
Year 2	3.08	127.48
Years 3-15	2.96	122.31

***assumes 41.39 kWh/gallon diesel fuel**

Table 3: Average embodied energy in chemical field applications. Sources and statistical analyses are available in Tables 4 and 5.

	Embodied Energy	**Variation**
Diesel Fuel	41.39 kWh/gal	
Nitrogen	9.58 kWh/lb	± 0.43 kWh/lb
Phosphorus	1.65 kWh/lb	± 1.30 kWh/lb
Potassium	1.36 kWh/lb	± 0.54 kWh/lb
Herbicide	30.50 kWh/lb	± 9.13 kWh/lb
Insecticide	24.02 kWh/lb	± 11.27 kWh/lb
Rhizome	0.042 kWh/rhizome	

The energy embodied in the miscanthus fuel before combustion divided by the sum of the energy inputs over the lifetime of the crop produces the EROI for the miscanthus program. Energy Inputs are greater in the first years of the crops life due to multiple field operations and chemical applications, while energy output increases from years 2-4 until the crop is mature. The reported EROI is averaged over 15 years of crop production. This value should be compared to the EROI of coal before combustion. Comparing the two fuels after combustion will require extensive tests at power plants firing varying levels of miscanthus and coal to characterize the fuel's (potentially non-linear) impact on power plant efficiency.

Table 4: Embodied energy in fertilizer components, herbicide and insecticide account for up to 79% of energy inputs.

	N Fertilizer		**P Fertilizer**		**K Fertilizer**		**Herbicide**		**Insecticide**	
	Value (kWh/lb)	*Source*	*Value (kWh/lb)*	*Source*	*Value (kWh/lb)*	*Source*	*Value (kWh/lb)*	*Source*	*Value (kWh/lb)*	*Source*
	9.529	4	1.201	4	1.241	4	35.293	2	35.293	2
	9.655	5	2.016	5	1.613	5	40.610	4	12.750	6
	8.543	6	4.561	6	0.176	6	29.988	6		
Average	9.242		2.593		1.010		35.297		24.022	
SD	0.497		1.431		0.609		4.336		11.272	

Table 5: Energy costs of field operations include cultivation, chemical application (fertilizer, herbicide and insecticide) and planting in the first year, chemical application (herbicide and fertilizer) and harvest in the second year, and fertilizer application

	Prim. Cultivation		**Second. Cultivation**		**Chemical Application**		**Planting**		**Chop (Harvest)**	
	Value (gal/acre)	*Source*	*Value (gal/acre)*	*Source*	*Value (gal/acre)*	*Source*	*Value (gal/acre)*	*Source*	*Value (gal/acre)*	*Source*
	1.5	1	0.7	1	0.15	1	0.5	1	1.9	1
	1.16	2	1.02	2	0.125	2	0.15	3	3.335	2
	1.7	3	0.85	3	0.1	3	0.3	3	3.25	3
Average	1.453333		0.856667		0.125		0.316667		2.828333	
SD	0.22291		0.130724		0.020412		0.143372		0.657347	

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CHAPTER 4 RESULTS

4.1 Miscanthus Resource Availability

Calculation of the MSR of fields across Iowa shows that siting miscanthus fields with consideration of field characteristics results in different targeted fields than working with climate-based models alone. There is enough high MSR land resource within 25 miles of Iowa's coal EGUs to displace 19% of the coal currently burned in Iowa. We can use this information to site new miscanthus programs, specific fields for miscanthus cultivation, third party densification facilities, and storage facilities.

Across the state of Iowa, there are 4,550,942 acres of high MSR (8-10) on 40+ acre contiguous fields for potential miscanthus cultivation, shown in Table 6 and the map in Figure 3. Every county has resource potential, with the most acres of highly suitable miscanthus fields concentrated in the Des Moines Lobe. Within 25 miles of all coal EGUs, there are enough acres of high MSR land to displace as much as 19% of the coal burned in Iowa, as seen in Table 6. Up to 43% of the state's coal consumption could be displaced with the resource within 50 miles of all EGUs. However, there is a dramatic incongruity between land resource and coal EGUs. This means that without transportation limitations, the state of Iowa could produce 170% of the state's coal consumption in miscanthus fuel, when evaluated in terms of energy content alone.

Table 6: Coal energy used and miscanthus resource available near Iowa's coal EGUs.

Plant Name	Coal Energy (MW)	25 Mile Buffer: High MSR (acres)	25 Mile Buffer: Resource (MW)	25 Mile Buffer: % of Coal Cap.	25 Mile Buffer: Exploitable Resource	50 Mile Buffer: High MSR (acres)	50 Mile Buffer: Resource (MW)	50 Mile Buffer: % of Coal Cap.	50 Mile Buffer: Exploitable Resource
*Lansing	249	903	2	1%	2	19,619	46	18%	46
Prairie Creek	164	37,818	88	53%	88	262,695	609	371%	164
*Riverside	125	23,234	54	43%	54	100,140	232	186%	125
*Walter Scott Jr Energy	1,517	27,450	64	4%	64	80,269	186	12%	186
*George Neal North	918	22,976	53	6%	53	59,122	137	15%	137
*Burlington	210	56,591	131	63%	131	130,370	302	144%	210
Ames Electric Services	105	286,448	665	630%	105	1,071,662	2,486	2359%	105
*Muscatine Plant #1	231	55,594	129	56%	129	203,678	473	205%	231
Ottumwa	746	42,101	98	13%	98	137,116	318	43%	318
*Louisa	746	71,266	165	22%	165	206,796	480	64%	480
George Neal South	644	22,944	53	8%	53	59,264	137	21%	137
AG Processing Inc	9	631,263	1,464	17229%	9	2,053,609	4,764	56050%	9
Cargill Corn Milling	37	39,603	92	250%	37	135,976	315	860%	37
*ADM Clinton	180	24,952	58	32%	58	55,458	129	71%	129
ADM Des Moines	8	104,719	243	3075%	8	472,422	1,096	13873%	8
ADM Cedar Rapids	260	35,531	82	32%	82	260,547	604	232%	260
Univ. of Northern Iowa	8	157,620	366	4876%	8	625,084	1,450	19335%	8
Iowa State University	46	294,270	683	1478%	46	1,093,820	2,538	5493%	46
University of Iowa	21	37,089	86	410%	21	242,784	563	2682%	21
TOTAL	6,224	1,972,372	4,575.77	74%	1210.7	7,270,432	16,867	271%	2,656
Not Site-Specific				1488%	19%			5370%	43%

*EGUs located near state lines, so full 25- or 50-miles buffers are not within Iowa and are not evaluated. These plants may have more resource available in neighboring states.

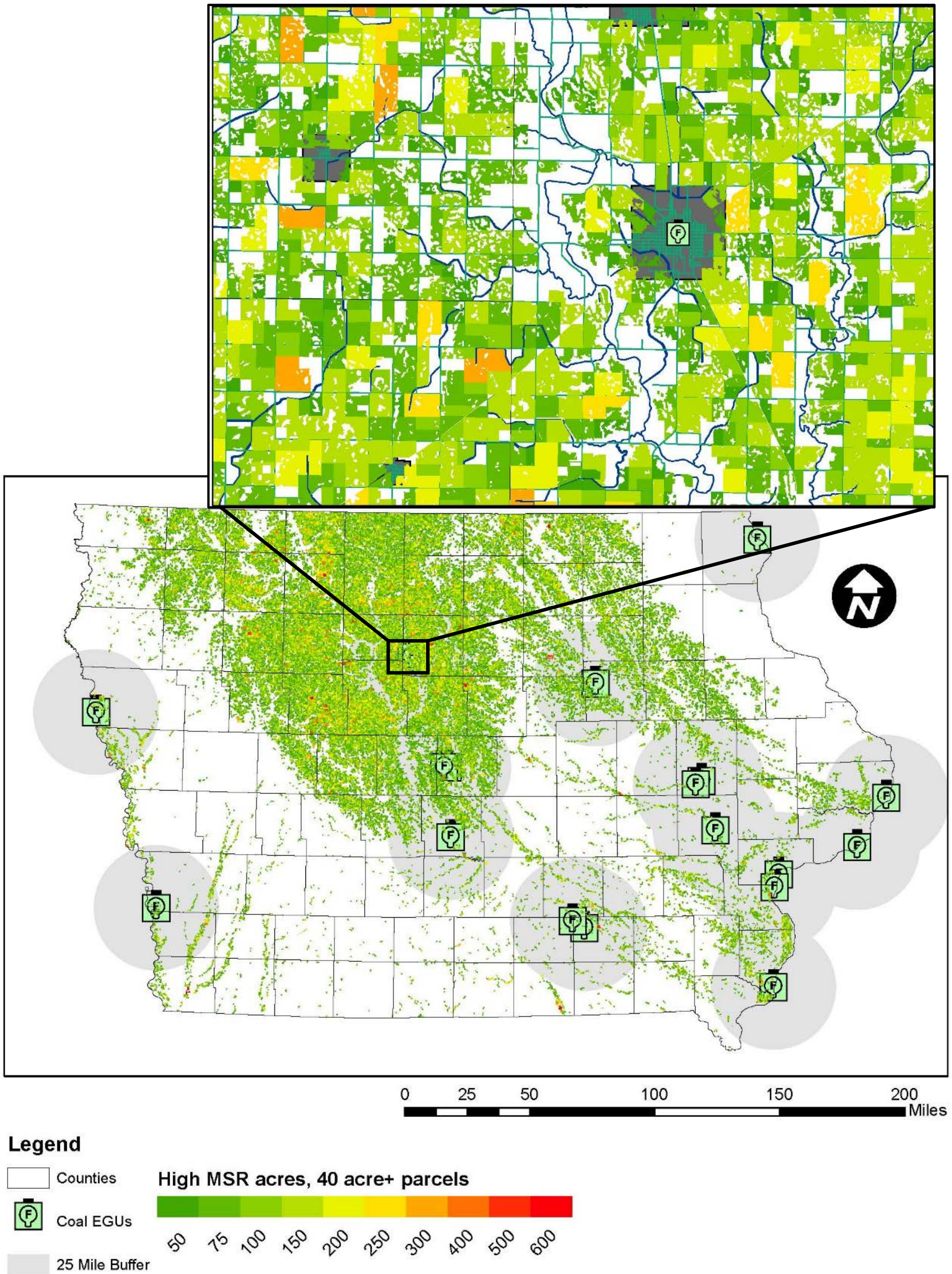

Figure 3: Highly suitable miscanthus fields and coal EGUs in Iowa

The inset in Figure 3 shows an example of the sub-field resolution around the most resource-rich EGU in Iowa, AG Processing, Inc. in Eagle Grove. The entire area shown in the inset can be assumed to experience roughly the same climate. This means that climate factors might indicate that AG Processing, Inc, should or should not pursue miscanthus bioenergy in their climate zone, for example, but will not help them choose which fields to target for miscanthus cultivation.

In contrast to Figure 3 that assumes miscanthus will be planted in place of a commodity crop on fields no smaller than 40 acres, Figure 4 shows potential citing of miscanthus as buffer zones between existing crops and waterways near Iowa City. These buffer zones would not increase field sizes (which could potentially worsen soil runoff and nitrogen pollution), but would instead replace a strip of land on which row crops were previously planted. As Gopalakrishnan (2012) argues, planting miscanthus in buffer strips between existing fields and water bodies has the advantage of retaining high returns from high commodity crops, while using strips of bioenergy crops to protect waterways from field run-off pollution. In this strategy, no fertilizer is applied directly to the miscanthus because it intercepts and utilizes fertilizer runoff from the adjacent field.

This buffer zone method could be especially useful in areas that are attempting to reduce nutrient pollution from fertilizer runoff. Sac, Calhoun and Buena Vista counties, for example, discharge agricultural runoff via field tile and drainage ditches into the Raccoon River, which supplies the Des Moines area drinking water. Des Moines Water Works has legally challenged the previously accepted exclusion of these discharges as non-point sources because of new drainage techniques that concentrate nitrate discharge (Beeman, 2015). Energy crop buffer zones may be an especially beneficial nutrient reduction strategy in these counties.

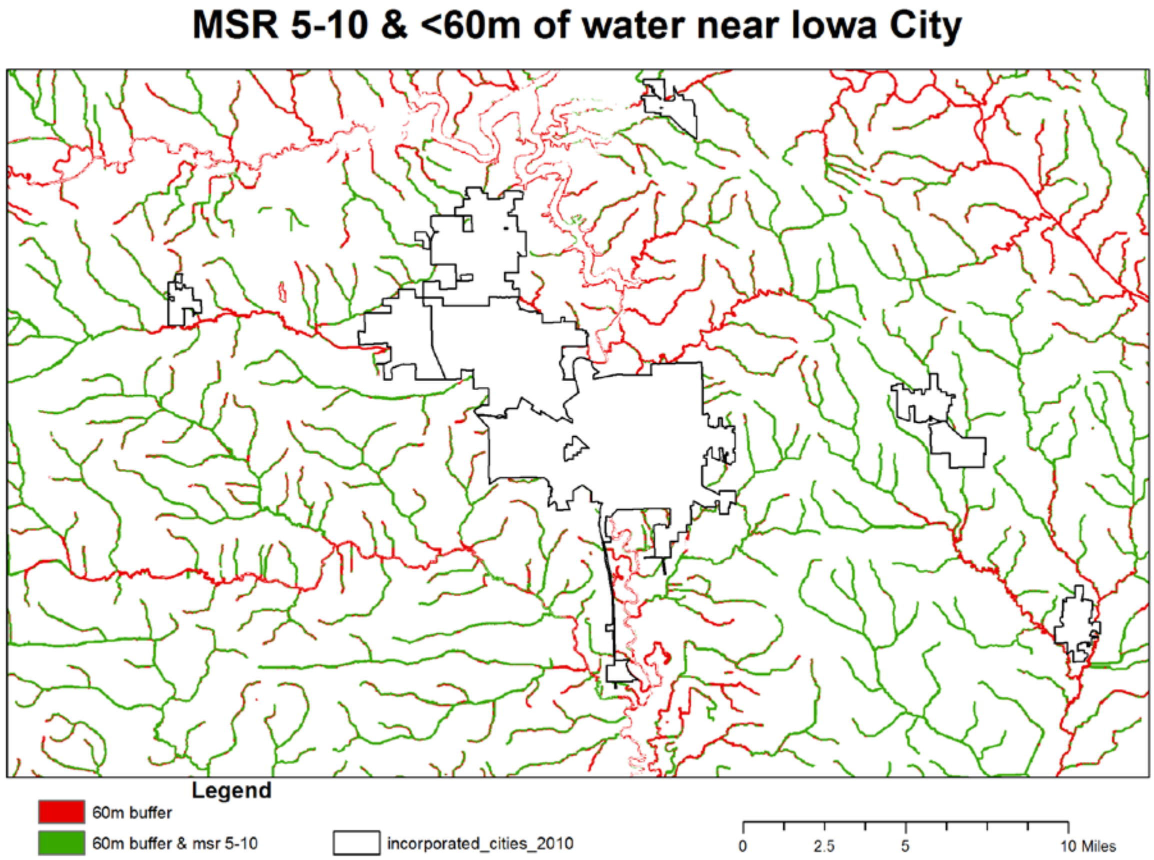

Figure 4: Riparian buffer zone potential. Green areas show land within 60 meters of water bodies are expected to produce at least moderate miscanthus yield. Red areas meet the water proximity criteria, but not the minimum MSR.

4.2 Miscanthus Program Sustainability Evaluation

EROI is an important indicator of the sustainability of a fuel source over its lifetime and its entire supply chain. Assuming 20 miles of transportation and the chemical applications prescribed in the UIPP business plan, the UIPP miscanthus program has a predicted EROI of 45.38. Table 7 shows that this is a competitive energy return compared to other biofuels, other renewable energy technologies, and coal.

Table 7: EROI and land footprint for a variety of energy generation methods.

Fuel	**EROI**	**Min. Land Footprint (acres/GWh/yr)**
Coal	30[1]	
Miscanthus	57[2], 98[5]	23[3]
Switchgrass	73[5]	43[5]
Hydroelectric	49[1]	
Solar PV	3.9[1]	2[4]
Wind	16[1]	
Corn Ethanol	3.5[1], 1.07[6]	

1. Weissbach, 2013
2. Amaducci, 2016
3. UI Facilities Management, 2014
4. Ong et al., 2014
5. Amaducci et al., 2016
6. Murphy et al., 2011

Chemical applications account for 60-80% of energy inputs, depending on transportation and field operations. Reducing the amount of chemical applications, therefore, has a significant effect on the EROI. However, reducing chemical applications to reduce inputs can also reduce yield. Reducing herbicide and insecticide applications provide minimal benefit to EROI over the life of the program because these are only applied during establishment. The reduction of these applications, however, can dramatically harm the health of miscanthus rhizomes in the critical first years, jeopardizing future yield. Reducing fertilizer rates can dramatically reduce the energy inputs to the field, but also has potential to reduce yield. The impact of fertilizer on miscanthus yields is still unclear and heavily dependent on many site-specific factors (Danalatos et al., 2007; Amaducci et al., 2016).

Transportation up to 100 miles accounts for 7-25% of energy inputs, depending on chemical applications and field operations. Energy expended in transportation can be reduced by densifying miscanthus on or near the field, so that fewer trips are required to bring the fuel to the EGU. Shastri et al. (2011) found that distributing pre-processing can increase costs by 16-53%, but decrease the cost to farmers by 13-39%. Reducing the number of loads between field and EGU would reduce energy inputs by 0.295 kWh/ ton-mi. Field Operations account for 10-15% of energy inputs, depending on chemical applications and transportation. This part of the supply chain is already very lean, but can benefit from advancing tractor and machinery technology.

These findings and the development of the energy evaluation tool that can be adjusted to represent specific miscanthus bioenergy programs will provide decision makers with predictions of project outcomes, decreasing the risk of implementing these projects. Using the field siting tool to choose the most effective locations for miscanthus cultivation will improve the likelihood of successful establishment and greater yield over the lifecycle of the crop. Modeling the impact of changing program factors can help to target program funds at improvements that will most effectively improve EROI and lean inputs without losing productivity.

CHAPTER 5 CONCLUSIONS

This work consolidates documentation of the UI's major energy transition projects from 2003 to 2017. These projects are analyzed with frameworks from energy transition literature as well as a new sociotechnical configuration framework that identifies relationships between components in the configuration. These contributions can support learning within departments and knowledge-sharing between departments and with other institutions.

Consolidation and analysis of previous transition projects revealed discursive, institutional and technological factors that are particularly influential in the success of new fuel integration and transition projects. First, the detailed and measurable commitments in the 2020 Vision gave employees working on transition projects the ability to make informed decisions in longer term projects, such as miscanthus production. Publicizing these sustainability commitments also attracts professionals with similar values who will advance sustainable initiatives. Next, including people who are closest to the fuel operations, like power plant operators and professionals at the fuel handling facilities, in large projects often and early can save time and money for the University. Integration of new fuels is likely to be smoother when these employees are part of planning and development phases. Finally, sourcing fuels that behave similarly to incumbent fuels in power plant equipment reduces the technological changes required for the transition.

In service of the miscanthus program more specifically, this work developed the first state-wide siting tool to use field characteristics in determining suitability for miscanthus production in Iowa. This allows differentiation of field suitability within a single climate zone. The field characteristics considered can be reasonably expected to reduce nitrogen pollution and limit competition with high commodity crops as biofuel markets grow. This work also contributes to the published energy analyses of miscanthus programs, improving our collective understanding of miscanthus production in various settings.

Our analysis suggests that miscanthus can be produced in volumes to significantly reduce the amount of coal burned in Iowa, while improving energy efficiency and reducing GHG emissions. Seven of Iowa's coal EGUs have enough potential land resource within 25 miles to cover all the electricity they produce from coal. Within 50 miles of all coal EGUS in Iowa, 43% of statewide coal usage can be displaced by miscanthus. Without accounting for transportation limitations, there is enough land resource in Iowa to produce up to 170% of current coal usage in miscanthus fuel.

This work shows that miscanthus can be delivered to a facility at an EROI as high as 59, without processing. Chemical applications are identified as the highest energy input and a contributor of GHG emissions in the miscanthus supply chain. Further investigation into energy intensive fertilizer production and yield response to fertilizer may improve energy efficiency and decrease global warming impact of the program.

Current literature shows that miscanthus can support more wholesome wildlife habitats, can reduce nutrient and sediment pollution, and is a premier species among bioenergy crops. Coupled with existing studies of miscanthus, this work shows the favorable potential impacts of miscanthus in local settings and the sufficient potential of Iowa land resource to support the development of miscanthus bioenergy programs.

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