Farm-level feasibility of bioenergy depends on variations across multiple sectors

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Abstract
The potential supply of bioenergy from farm-grown biomass is uncertain due to several poorly understood or volatile factors, including land availability, yield variability, and energy prices. Although biomass production for liquid fuel has received more attention, here we present a case study of biomass production for renewable heat and power in the state of Wisconsin (US), where heating constitutes at least 30\% of total energy demand. Using three bioenergy systems (50 kW, 8.8 MW and 50 MW) and Wisconsin farm-level data, we determined the net farm income effect of producing switchgrass (\textit{Panicum virgatum}) as a feedstock, either for on-farm use (50 kW system) or for sale to an off-farm energy system operator (8.8 and 50 MW systems). In southern counties, where switchgrass yields approach 10 Mg ha\textsuperscript{-1} yr\textsuperscript{-1}, the main determinants of economic feasibility were the available land area per farm, the ability to utilize bioheat, and opportunity cost assumptions. Switchgrass yield temporal variability was less important. For the state median farm size and switchgrass yield, at least 25\% (50 kW system) or 50\% (8.8 MW system) bioheat utilization was required to economically offset propane or natural gas heat, respectively, and purchased electricity. Offsetting electricity only (50 MW system) did not generate enough revenue to meet switchgrass production expenses. Although the opportunity cost of small-scale (50 kW) on-farm bioenergy generation was higher, it also held greater opportunity for increasing farm net income, especially by replacing propane-based heat.

Keywords: biomass, bioenergy, bioheat, land use

Online supplementary data available from stacks.iop.org/ERL/8/015005/mmedia

1. Introduction

Interest in, debate over and investment towards bioenergy have increased dramatically over the last ten years [1–5]. in response to diverse goals. These include net reduction of greenhouse gas emissions, diversification of energy portfolios, and efficient use of resources, including waste materials. However, the future magnitude of bioenergy production is unknown, partly due to uncertain supplies of biomass feedstocks. Several studies have estimated potential supplies [6–8], predominantly for conversion to transportation fuel (i.e. cellulosic ethanol). These studies have focused primarily on land available to produce biomass, and the potential yields of biomass on those lands. This information is critical but not sufficient to predict actual biomass availability,
since land managers typically must address multiple goals and constraints on land use. Fewer studies have analyzed costs of biomass production and/or provision [9–13]. Most of these are studies of biomass production for electric power, similar to the case study of heat and power presented here.

Comparisons between cost of biomass production and cost of fossil fuels can frame further analysis of bioenergy system feasibility. However, feasibility of specific bioenergy projects depends on many additional factors, including energy conversion efficiencies, capital costs, biomass delivery and storage costs, economies of scale, and environmental goals. Biomass producers, policymakers and other stakeholders need to know how this broad set of physical, agronomic, technical and economic factors interact in order to plan bioenergy related activities. Volatile and nascent markets for biomass feed stocks [10, 14] underscore the need for sensitivity studies that integrate the factors listed above.

We analyzed potential bioheat and power production from switchgrass (Panicum virgatum) in Wisconsin (US) as a case study of bioenergy feasibility. Wisconsin currently imports nearly all of its electricity and heat feedstocks, (i.e. coal, natural gas, fuel oil) [15], and development of bioenergy has been a goal of recent state administrations [16]. Switchgrass was chosen for the case study because its extensive native range includes Wisconsin [17, 18], and its performance as a bioenergy feedstock is well known both for biofuels and for bioheat and power [19–21]. We analyzed bioheat and power because of the greater land-use efficiency of these applications relative to biofuels [22], and due to relatively high heating needs in Wisconsin.

The goal of the case study was to find sets of physical, agronomic, technical and economic conditions that allow farms to produce biomass feedstock at a profit, while observing best practices for perennial cropping. These conditions define bioheat and power ‘feasibility’ in the study. The sensitivity of profit to these parameters was also analyzed. The general approach comprised three parts: (i) characterization of expected switchgrass yield and production, (ii) analysis of switchgrass production costs, and (iii) analysis of expected farm profit from biomass production given three bioenergy conversion systems of different types and sizes. The smallest system was for on-farm heat and power generation, while the two larger systems required sale of biomass to off-farm energy system operators, but in all cases the farm gross income from bioenergy activities was bounded by the prices of competing energy types. Because annual farm profit (or net present value) from bioenergy was the main unit of analysis, we used the Wisconsin farm records from the 2007 USDA Census of Agriculture to populate the study [2].

Switchgrass production costs and profit were calculated for each farm but here the results are presented by county; this protects the privacy of Census participants but still shows spatial patterns of bioenergy feasibility across the state. The data used to calculate production, cost and profit were chosen (or adjusted) for the year 2007 whenever possible, so this case study represents a nearly present-day baseline of bioenergy feasibility, which may form the basis for evaluating future farm biomass policy tools.

2 Methods

2.1. Switchgrass yield and production

To predict switchgrass yields and their variability, a multiple linear regression model of annual switchgrass yield (Y, Mg ha$^{-1}$) was fitted using 112 field-trial observations [17, 18]:

\[
Y = -27.60 + 0.0106^* P + 0.0104^* G - 0.0536^* C
\]

where C is the corresponding soil clay content (% clay) and P is the April–September precipitation (mm). $G$ is April–September growing degree days ($0^\circ C$ base):

\[
G = \sum_{i=1}^{183} \left( \frac{T_{\text{max}}(i) + T_{\text{min}}(i)}{2} \right) \tag{2}
\]

where $T_{\text{max}}$ and $T_{\text{min}}$ are daily maximum and minimum temperatures in excess of $0^\circ C$, respectively, and 183 is the number of days from April–September, inclusive. April–September GDD and precipitation were chosen as independent variables because the growing season of switchgrass is April–September, and because these values had more explanatory power than annual precipitation and GDD. Similarly, inclusion of soil clay content improved the regression model $R^2$, while inclusion of silt and sand content did not. Yield observations were restricted to switchgrass stands at least one year old, of the nine highest-yielding varieties in the field trials (USDA hardiness zone four or five only). A linear regression was chosen over logarithmic or exponential forms because the environmental variables and yields in this study are constrained to a relatively narrow range of values, as opposed to the widely varying values in global studies of yield, which must often use other model forms [23]. The adjusted $R^2$ of the regression model is 0.830. This regression was used to produce a map of switchgrass yield for Wisconsin, based on 8 km × 8 km gridded surfaces of daily temperature and precipitation for 1950–2006 [24], and a map of soil % clay [25] re-gridded to 8 km. Median, 95th and 5th percentile yields were found for each grid cell using Monte Carlo methods [26], with growing degree days and precipitation as the sampled independent variables. County medians of each statistic were reported.

Yields and total production depend on the quality and amount of land available for growing switchgrass. However, assumptions about which farmland might be used can easily lead to complicated opportunity cost scenarios, and to debate about the societal value of growing energy feedstocks on cropland [27]. For this reason we modeled switchgrass production on Conservation Reserve Program (CRP) land, farmland which is not currently used to grow crops. CRP land is set aside by farmers for a variety of reasons, but normally because it is less productive and/or more vulnerable to soil erosion [28]. In many cases, establishment of a new switchgrass stand on CRP land would cause excess

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2 These records were provided upon request by the Wisconsin office of the National Agricultural Statistics Service (US Department of Agriculture).
erosion. It would also reduce other benefits of CRP, such as wildlife habitat and a proportion of soil carbon storage. To simulate switchgrass production without impact on the most vulnerable CRP lands, we used a dataset that gives, in each Wisconsin county, the proportions of land area available for biofuel production with ‘moderate’ versus ‘high’ erosion risks (see supplementary data available at stacks.iop.org/ERL/8/015005/mmedia). To predict yields on these lands, the modeled yields were reduced by 20% [29]. These data, together with county totals of CRP land area [30], were used to calculate county-level switchgrass production.

2.2. Switchgrass production costs

Two sets of switchgrass production costs were calculated for each farm; one assumed ownership of the necessary equipment, and one assumed contracted fieldwork (see supplementary data available at stacks.iop.org/ERL/8/015005/mmedia). In the owned-equipment cost scenario, 50% of equipment costs were allocated to switchgrass production. In both scenarios, the total cost was the sum of the cost of switchgrass establishment plus the annual costs of land; mowing, raking and baling; fertilizer, herbicide and application; and transportation. Historically, CRP payments have been reduced or forfeited due to biomass harvest, and so 25% reduction of 2007 CRP payments was assumed [31]. The lower cost scenario was chosen for each farm, which depended on the number of CRP hectares available, yield, and transport distance. The switchgrass yield for each farm was drawn from the county-level statistics described above.

2.3. Bioenergy net income

To calculate the farm net income or loss from growing switchgrass, the details of each bioenergy system, and the type of heat and/or power it would replace, were considered (see supplementary data available at stacks.iop.org/ERL/8/015005/mmedia). Dry switchgrass energy content was assumed to equal 18.358 MJ Mg⁻¹ [32]. For the 50 kW CHP gasification system, biopower was assumed to replace electricity at the 2007 Wisconsin residential rate of $0.01087 kWh⁻¹ [33], and bioheat was assumed to replace heat from propane at $0.513 $⁻¹ [34]. Both the propane furnace and the bioenergy unit were assumed to operate at 80% efficiency. The cost of moving switchgrass bales to the on-farm bioenergy system was $2.20 Mg⁻¹ [35], but further transportation costs were omitted in the on-farm case. Switchgrass production cost was increased by a further 8.45% to account for 1–2% dry matter loss per month during a 6-month storage period [36, 37]. The 50 kW system was assumed to have a useful life of 20 years, and was 90% debt financed at 8% interest over 15 years, assuming 2% inflation.

The 8.8 MW CHP system uses thermal combustion in a circulating fluidized bed boiler. In this case, the farm net income model was based on switchgrass sales to an outside operator, so cost of transporting switchgrass bales off-farm (40 km) was included. The switchgrass price paid by the energy system operator was determined by the displaced net costs of electricity and heat from an 80% efficient natural gas-fueled system, assuming natural gas price of $1.31 per 1000 ft³ [38] and average 2007 Wisconsin commercial electric rate of $0.0871 kWh⁻¹ [39]. Capital recovery expense was included in the system operating costs:

\[ E = \frac{I^t (1 + i)^n}{(1 + i)^n - 1} \]  

where \( E \) is the capital recovery expense, \( i \) is the cost of capital (8%), \( n \) is the project life in years (assumed 20 years) and \( I \) is the capital invested. This switchgrass price scheme does not include profit for the energy system operator, nor any return on investment in the 8.8 MW system, and thus gives an upper bound on the biomass price that the operator may be willing to pay.

The farm net income impact of selling switchgrass for use in the 50 MW system was calculated as for the 8.8 MW system, except that electricity sales were the only system income source. The average 2007 Wisconsin industrial electric rate of $0.0616 kWh⁻¹ was used [40]. This retail rate represents an upper limit, since independent power producers’ sales to utilities are based on ‘avoided costs’ of electricity delivered to the grid, which do not include retail costs such as line charges and billing fees.

2.4. Net present value

NPV is an index of the opportunity cost of investment. Here it is used to indicate the relative risk of investing in switchgrass production for bioenergy. The real NPV of providing switchgrass for each bioenergy system was calculated, assuming a 20-year lifespan of the switchgrass stand [41]:

\[ \text{NPV} = \sum_{i=1}^{n} \frac{R_i}{(1 + i)^t} \]  

where \( R \) is the annual net cash flow, \( n \) is the term of the project in years (20), and \( i \) is the real discount rate (6.5%). Annual farm cash flows were calculated as described above, except that switchgrass establishment costs and 50 kW system down payment costs were allocated to year one only. Also no biomass harvest during switchgrass stand establishment, and thus no bioenergy income, was assumed during year one. Another, related index of investment favorability is the internal rate of return (IRR), which is the value of \( i \) at which NPV equals zero. Higher IRR indicates a more profitable investment. For the on-farm energy case (i.e. 50 kW CHP), IRR was calculated both with and without the purchase of the CHP system in order to evaluate the relative impact of buying a new energy system.

3. Results

Potential annual switchgrass yield varied widely across Wisconsin (figure 1(a)), with county median yields ranging from 4.3–10.8 Mg ha⁻¹ (figure 1(b)). Spatial yield variability was largely driven by the spatial pattern of April–September
Figure 1. Yield of switchgrass (Mg ha\(^{-1}\)) modeled in 8 km × 8 km grid cells (a) and aggregated by county (b).

Figure 2. Switchgrass production (Mg) by county assuming use of CRP land only (a), or 4% of farmland in each county (b).

growing degree days, although precipitation also influenced yield, as seen in the relatively arid counties in the east. Low soil clay content was associated with higher yield, as in isolated high-yielding counties in the central and southwestern parts of the state. All counties had similar temporal yield variability, with 90% confidence intervals of ∼6 Mg ha\(^{-1}\).

The state total and spatial pattern of switchgrass production varied depending on scenarios of land availability (figure 2). If all farmable CRP land was used, comprising 4% of total Wisconsin farm area, then total simulated annual switchgrass production was 1.8 million Mg, concentrated in southwest Wisconsin and along the Mississippi River. For comparison with a land availability scenario that is independent of the current spatial distribution of CRP land, switchgrass production was also simulated on 4% of farmland in each county. This comprises the same total land area as in the CRP-based production scenario. This second scenario gave total production of 1.0–1.2 million Mg depending on farmland quality. The overall production difference between the two scenarios was due to concentration of CRP land in the warmer southern half of the state.

The spatial pattern of switchgrass production costs was also driven by climate factors, with lowest costs per Mg of switchgrass in the high-yielding southern counties (figure 3). High-yielding and large farms achieved lowest production costs using owned equipment, while low-yielding and small farms minimized cost by hiring custom field work (see methods). For example, with a state median annual yield of 7 Mg ha\(^{-1}\), a minimum of 62 ha of switchgrass cultivation was required to use owned equipment economically. The yield and farm-area economies of scale combined to create lowest switchgrass production costs in the Central Sands eco-region. In these same counties, the importance of economy of scale is also seen in potato production [42], which requires extensive irrigation infrastructure.
The farm net benefit of producing switchgrass for bioheat and power was analyzed using three bioenergy systems of different types and sizes: 50 kW, 8.8 MW, and 50 MW. The 50 kW system was a combined heat and power (CHP) system. It was assumed to be operated on-farm for a twenty-year term, where it offset purchased electricity and heating fuel costs. When calculating the benefits of system operation, only those farms with sufficient CRP acres and yield to provide 389 Mg switchgrass per year were included (3018 farms). The advantage of using switchgrass instead of purchased fossil energy depended strongly on the opportunity to utilize bioheat (figure 4(a)). Farms can use bioheat for drying grain, heating houses, barns, greenhouses or water. Currently most Wisconsin farms use propane to meet heating needs. Assuming Wisconsin median switchgrass yield and farm size, 2007 electricity and propane prices, biomass use ‘breaks even’ with fossil fuel use at 25% heat utilization from the 50 kW CHP unit. This result is robust within the 90% confidence interval of switchgrass yield, but is quite sensitive to the percentage of heat utilization. The annual farm net income impact of generating bioheat and power also depended strongly on propane price (figure 4(b)). However, delivered propane is relatively expensive, and farms of median size and switchgrass yield could realize relative income gains from bioheat and power even at the lowest propane prices of the last decade.

Establishing a perennial switchgrass stand and purchasing a bioenergy system both entail risk; therefore we calculated the net present value (NPV, see methods) of the combined on-farm switchgrass and energy production project for a 20-year term (figure 5). The NPV was somewhat sensitive to switchgrass yield uncertainty, but more sensitive to discount rate; a modest real discount rate of 6.5% yielded unfavorable NPV in all counties. This was largely due to high expenses and no biomass harvest in the first year of the term. The spatial pattern of NPV followed the pattern of switchgrass production costs, since the basis for calculating bioenergy income did not vary over space.

For a farm with switchgrass yield of 7 Mg ha$^{-1}$ and 56 ha available for switchgrass production, able to use 25% of the CHP system heat, the IRR of on-farm bioheat and power production over a 20-year term is 2%. Most of the income from heat and power is needed to defray the cost of energy system purchase. For comparison, the IRR without purchase of a new 50 kW system is 148%.

The 8.8 MW system, also CHP, was sized for use by a business such as a hospital, or as part of a district heating system. In this case, the switchgrass producer would sell biomass to the bioenergy system operator or a biomass distributor. Including hauling costs for a 40 km trip, the state median switchgrass production cost was $78.22 Mg$^{-1}$. At this price, biomass use could roughly break even with fossil fuel.
use given 50% heat utilization, and ignoring profit margin for the switchgrass producer and distributor (figure 6). The 8.8 MW system required relatively high heat utilization to break even because it competed with natural gas use, which is cheaper than propane. The break-even scenario was robust to switchgrass yield, but sensitive to heat utilization and natural gas price. At 50% heat utilization from the 8.8 MW system, energy from natural gas would have been cheaper than bioenergy during nearly half of the last decade [38]. Low natural gas prices would depress switchgrass prices, so that producers would lose money at natural gas prices less than $11 per thousand cubic feet.

The NPV of 20 years of switchgrass production for sale was calculated assuming that operators of the 8.8 MW plant would pay a switchgrass price equivalent to that of natural gas per unit of energy output. The county median NPVs for switchgrass production were relatively robust to varying discount rate (figure 7), because the farms had no cash outlay for a CHP system in year one, as was assumed in the 50 kW case. On the other hand, the zero discount rate NPV was less favorable in the 8.8 MW case than in the 50 kW case due to relatively lower gain from offsetting natural gas cost compared to offsetting propane.

The 50 MW system, such as may be operated by an independent power producer, generated electricity only [45]. As in the 8.8 MW case, the switchgrass producer would sell biomass to a distributor or bioenergy system operator. At a commercial electric rate of $0.10 kWh\(^{-1}\), the system operator could pay the switchgrass producer $83 Mg\(^{-1}\), which was the state median cost of switchgrass production plus 80 km delivery. This result was relatively robust to yield variations, but sensitive to electricity price. However, in 2007, the average industrial electricity rate was $0.06 kWh\(^{-1}\), and so the median NPV of selling switchgrass to a non-CHP power producer was negative in all counties at both discount rates.

The total possible heat and power production, assuming switchgrass production on Wisconsin CRP land only, is shown in table 1. Total annual bioenergy from the 50 kW on-farm system is based on annual switchgrass production of 1.2 million Mg from 3018 farms. Output from the larger systems is based on annual switchgrass production from all CRP land (1.8 million Mg).

4. Discussion and conclusions

This case study shows that the farm-level feasibility of biomass production for bioenergy depends upon several
costs, the annualized costs over a 5-year term averaged states. In the Great Plains field study of actual production are similar to those found in Illinois [9] and Great Plains [41] for bioheat Environ. Res. Lett. 8 that with state median switchgrass yield, at least 70 ha of land were needed to produce switchgrass at prices competitive with natural gas, assuming 50% bioheat utilization. This land-area threshold may be circumvented by to the advantage of attributing equipment costs (i.e. planter, sprayer, mower, rake, baler) over greater land area. This study indicated that with state median switchgrass yield, at least 70 ha of land were needed to produce switchgrass at production cost and component costs are similar to those found in Illinois [9] and Great Plains [41] states. In the Great Plains field study of actual production costs, the annualized costs over a 5-year term averaged $66 Mg$^{-1}$, using a conservative 10% discount rate (not including transportation cost). Similar treatment of our results gives annualized cost of $59 Mg$^{-1}$. Higher average yields in our study (7 versus 5 Mg ha$^{-1}$) give lower costs per biomass produced despite slightly higher labor and materials costs in Wisconsin. In the Illinois study, 10-year annualized production costs were $57 Mg$^{-1}$, excluding land rent, and assuming 4% discount rate. The remaining production costs were higher per hectare in Illinois, but average switchgrass yield was higher as well (9 Mg ha$^{-1}$).

In this study, available land was narrowly defined as land already set aside in CRP. This was done in order to estimate the farm-based bioenergy production possible without using croplands. However, CRP land is relatively vulnerable to erosion and generally less productive than prime cropland, and it is not clear which CRP land should be used to produce switchgrass [46]. The Biomass Crop Assistance Program (BCAP) [47], the USDA’s flagship policy tool for promoting bioenergy crop production, does not currently subsidize production on CRP land. We attempted to exclude the most vulnerable land from this analysis (see methods), but farm-by-farm distinction between land capability classes was not within the scope of this study. Given the possibility of future bioenergy crop production on non-prime farmland, more research on best management practices for switchgrass is needed. The yield models in this study were based on field trials at agricultural research stations (i.e. prime farmland), which used an average of 75 kg ha$^{-1}$ of nitrogen fertilizer during post-establishment years, as well as phosphorous, potassium, lime, and herbicides. It is not well known how this type of switchgrass management on CRP land would affect soil and water quality. Less intensive management would produce both lower costs and lower yields, which would propagate through the bioenergy feasibility analysis.

Feasibility of bioenergy feedstock production on crop-land would require a separate analysis. This case study assumed that no farm income (except CRP payments) was lost due to switchgrass production, but conversion from crops to switchgrass would forfeit the net income from crops. For example, the net profit from Wisconsin corn production (corn sales less operating costs) was about $450 ha$^{-1}$ in 2007 (see supplementary data available at stacks.iop.org/ ERL/8/015005/mmedia). The net profit from natural gas replacement by switchgrass would be about $700 ha$^{-1}$, while the net loss from coal replacement by switchgrass would be $300 ha$^{-1}$ (considering heat content only, not electricity generation). Thus, at current energy commodity prices, farmers cannot make money by growing switchgrass for bioenergy if switchgrass is competing with coal, and thus would fall far short of replacing the net value of corn production. On the other hand, natural gas replacement by switchgrass could provide more farm net income than corn if the farmer is willing to accept the risks of uncertain markets over the lifespan of the switchgrass stand, and the relatively high cost of switchgrass establishment in the first year.

Additional concerns about using cropland to grow biomass, such as increased food or feed commodity prices, also pertain, but are outside of the scope of this study.

Table 1. Total electricity and heat production from switchgrass grown on CRP land.

| Bioenergy system | Number of systems | Electricity (billion kWh) | Heat (million MMBtu) |
|------------------|-------------------|---------------------------|---------------------|
| 50 kW            | 3018              | 1.06                      | 12.7                |
| 8.8 MW           | 10                | 0.62                      | 21.3                |
| 50 MW            | 7                 | 2.45                      | 0.0                 |

Figure 7. NPV of producing and selling switchgrass for bioheat and power (8.8 MW system).
Heat utilization was another key element of feasibility. Even in the case of propane replacement, 25% bioheat utilization was required in order to break even in the median case. Offsetting purchased electricity was much less beneficial, because electricity is a relatively cheap commodity that benefits from economies of scale [48]. However, on-farm demand for heat varies widely between farms and between seasons, and careful evaluation is needed before establishing switchgrass for on-farm use. Forming partnerships with businesses that can utilize excess heat on-farm, such as greenhouses, can also create opportunities for profit.

Fossil energy prices also influence the feasibility of bioenergy projects. In particular, recent natural gas prices have fluctuated around the level that competes with combined bioheat and power as specified in this study. At 50% heat utilization, the operator of the 8.8 MW system in this study could pay farmers the 2007 state median switchgrass production price ($78–83 Mg\(^{-1}\) and compete with natural gas systems paying $11 per thousand cubic feet. However, commercial natural gas prices ranged between $6 and $16 per thousand cubic feet during 2000–2009, and were lower than the competitive $11 point for at least half of that period [38]. On the other hand, natural gas prices are projected to increase steadily in the coming decades [38], thus increasing the competitiveness of bioheat and power even in the absence of a strong market for CO\(_2\), or other policy tools to encourage perennial biomass crops.

The bioenergy production described here is dwarfed by Wisconsin’s overall heat and power consumption, which was 1418 million MMBtu in 2008 [15]. Thus, the potential of farm-based biomass production to offset overall energy use is small, even if some current cropland is converted to perennial biomass production. The advantages of farm-based bioenergy are more strategic and complementary to other types of energy in Wisconsin’s portfolio. One strategic advantage is farm risk reduction, since perennial crops are less vulnerable to weather extremes. For example, in all 60 Wisconsin counties with USDA corn yield records dating back to 1950, the coefficient of variation (CV) of annual yield is higher for corn than for switchgrass as modeled in this study, with average CV of 0.262 and 0.184, respectively. Offsetting rural propane use for heat is another strategic advantage for farmers, since it replaces expensive liquid propane deliveries with the most efficient energy conversion of biomass, i.e., to heat. It is also worth noting that the relatively modest NPV (~$100,000) and IRR (2%) of the 20-year, on-farm bioenergy project indicate a quite favorable investment, compared to the high-risk, low-profit enterprises common in farming. The value of the investment improves markedly where heat demand exceeds 25% of system heat production. If soil carbon sequestration by switchgrass stands could be monetized via carbon policy instruments or markets, the value of investment would improve further. All of these advantages apply especially in southern counties, which enjoy higher switchgrass yields. Farm-based biomass in the south could complement the relatively well-established use of woody biomass in the north [15]. The influence of such specific factors and thresholds over the feasibility of bioheat and power underscores the need for further careful, spatially detailed policy analysis at the state, regional and national levels.

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