The Economics and Feasibility of Electricity Generation using Manure Digesters on Small and Mid-size Dairy Farms

by
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Forward:

The thrust of this paper has been significantly revised since the project was first conceived. The initial aim was to assess the economic viability of electricity generation using methane from manure digesters on dairy farms under different electricity rate regimes. The initial idea was a simple one. If electric companies (transmitters and distributors) buy and sell electricity to the same generator/user at different rates, there is *potential* for significant economic inefficiency. It was my hope that a sense of the magnitude of this inefficiency could be assessed. The assessment would begin with the determination of the number of generators likely to operate under different pricing regimes. Taking the price regime wherein electricity would be purchased and sold at the same price to be the efficient benchmark, an estimate of the cost inefficiency from extant price regimes could be recovered.

As I have learned more about digesters, three points have emerged that speak to the inadvisability of using such an analysis to determine appropriate rate structures. The first, is that there are significant external benefits to producing electricity using digesters instead of coal. This means that the marginal social benefits of using biogas to generate electricity instead of coal are positive, implying that an otherwise efficient rate structure will err against biogas.

The second consideration is that manure digester technology is still in its infancy. In the U.S., there are almost as many different digester designs as there are manure digesters. In 1994, there were only 25 digesters operating on commercial farms in the U.S.[1] Today that number is up to 32, although only 14 of them are on dairy farms.[2] Many of those digesters that are in operation are supported by research grants and "green power" prices for their electric output. The diversity of design is appropriate given the diversity of farm size, location, management, energy needs and climate, as well as the potential gains from further experimentation. However, it does make identification of a "typical" digester difficult, and prediction of adoption levels nearly impossible. It also means that entering into the digestion/generation business today is a risky proposition and that the risk is likely to decline significantly as the data and experience accrued by early adopters leads to improved design and operating guidelines. The existence of substantial external learning-by-doing benefits from the investments of early adopters implies that the pricing scheme conventionally regarded as efficient (wherein the distributor pays a buy-back rate equal to its selling price) would only be appropriate if accompanied by subsidies to early adopters. The asymmetrically large risks faced by early adopters are likely to reinforce the need to subsidize them.

The third realization is that it is not useful to consider a farm's digestion/generation operations merely as an appended operation that could marginally improve its bottom line. The economic linkages between digester and dairy operations are significant and complex. For example; the profit potential of a digester/generator depends critically on the quantity and quality of the manure and bedding that it must digest. In particular, there is evidence of economies of scale in the digestion/generation process, in large part due to the substantial fixed costs (with respect to size) of building a generator and equipping it to supply power to the grid. At the same time, smaller farms,

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[1] Oregon Office of Energy.
[2] EPA (2001).

which pay higher rates for purchased power, and use more energy per unit of dairy output, might stand to make relatively larger cuts in the costs of their dairy outputs. Thus, the impact of digestion technology and rate structure on the competitiveness of dairy farms of different sizes is, at least in theory, a qualitatively open question. And if the distribution of farm sizes is revised, then the predicted patterns of adoption must be revised as well.

Even if this issue could be adequately resolved empirically, and a policy maker's preferences with regards to farms size were clear to begin with, the interconnectedness of digestion and dairy operations has another influence on the policy debate. Manure digestion is extremely helpful in the elimination of odors. This could substantially reduce the legal costs, barriers to, and reasons to dislike, larger dairy farms. For all the above reasons, the impact of digester technology cannot be seriously assessed unless close attention is paid to its likely impact on dairy operations, the distribution of farm size and the economic implications of such distributions. Furthermore, while standard economic arguments suggest that the benchmark efficient pricing scheme, propped up with some lump sum subsidies to deal with potential externalities, should still be optimal, agricultural policies tend to be evaluated largely in terms of their distributional impact. Given the plethora of other distortions to the distribution of agricultural production over farms of different sizes, it is not obvious that rationalizing the price system for electricity sales promises obvious efficiency or equity gains.

These concerns have led me to conclude that assessment of the correct rate structures for electricity produced from agricultural biogas should not be attempted outside of a complete model of a multi-output dairy farm, or in the absence of good, representative estimates of the parameters of the system.

Instead, this paper will serve as a first pass at the economics of digester/generators. It is hoped that the calculations and insights will be of interest to potential adopters and policy practitioners alike, even though they will not yield strong conclusions for the reasons presented above.

Some of the information presented in this paper was picked up in discussion with experts, from a tour of Tinedale Farm, and from a presentation by Dr. Robert Fick at the annual meeting of the Wisconsin chapter of the ASAE. Numerical values presented without citation fall into this category.

I. Introduction: The economics of digesters.

The Benefits:

A digester/generator produces multiple outputs. It is capable of extracting electricity, cleaner solid effluent suitable for use as fertilizer or bedding, heat and water from farm effluent. It allows for easier compliance with environmental safeguards, and eliminates much of the odor resulting from farm operations.

The waste heat, cleaner water, odor reduction and environmental benefits are non-market goods and are difficult to price. The waste heat can only be used in close proximity to the generator and attains economic value dependent upon how it is used. Typical uses include heat for the milking parlor or a green-house, refrigeration, or the drying of solid waste for bedding. The cleaner water may be reused for the flushing of stalls, and is unlikely to be in demand off the farm. Hence the value of the water is equal to the value of the water demand and effluent disposal costs that it eliminates. These vary greatly across farms. The value of odor reduction is notoriously difficult to gauge. I have heard a digester operator equate it to the legal fees that it might help to avoid, although the potential inaccuracies from such Coasean logic should be obvious. The social and private benefits of compliance with environmental safeguards differ. The private benefits will depend, amongst other things, on the nature of environmental law and its enforcers. The debate over the new rules on non-point source pollution in Wisconsin is indicative of the uncertainty and difficulty inherent in the enforcement of such measures, and therefore the costs of compliance and non-compliance.

The value of the solid waste generated by the digestion process will also depend on what is done with it. Typically, it is spread on fields, or dried to produce stall bedding or marketable fertilizer. Having already alluded to a value for environmental benefits, the correct value to ascribe to the cost of marginal units of manure formerly spread on fields is zero. The logic is simple. Larger dairy farms have more manure than should sensibly be spread on their fields. While on smaller farms the value of the manure that becomes unavailable for spreading is positive, it is likely to be small given that much of the solids are returned to the field post-digestion, and that the marginal productivity of manure as fertilizer is unlikely to be huge. The digester does not add significant value to this manure. However, solid waste that is dried for use as bedding, or sold as fertilizer, can be valued at its price on the open market.

The value of the electricity produced is determined by the interaction of three factors: the rate structure, the farm's load curve, and whether it may direct power that it generates to the grid and its own operations at will.

The Costs:

The fixed costs associated with on-farm digestion and electricity generation are difficult to estimate. Due to the wide range of possible designs and operating conditions, meaningful estimates of the cost of building digester/generators of differing capacities are unavailable.[3] Given the rarity of on-farm generation, the transaction cost associated with

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[3] Dr. Robert Fick suggests a capacity cost of approximately $660 per cow, although the assumptions underlying the calculation are not readily available. Tinesdale Farm, a 1,800 cow dairy farm estimates total capital costs of about $1,000 per cow.

the negotiation of a contract with a power distributor is high, but inestimable. Maintenance costs are similarly elusive.

In fact, the only input into the process that it is possible to cost is energy. Engineers at two independent organizations have confirmed that digesters consume about one third the amount of electrical energy[4] they are capable of producing, regardless of size. The constancy of this relationship is because the vast majority of the input is used to achieve digester temperature, which is roughly linear the amount of manure to be regulated.[5]

Benefit-Cost Analysis:

Given the dearth of sensible estimates, it is impossible to conduct a full cost benefit analysis. Instead, given differing assumptions regarding the electricity sale and purchase contract I calculate the net revenues that a farm could achieve on its electric generation, inclusive of saved electricity costs and net of energy inputs. From here on, I will refer to this figure as the *electric margin*. This is all that may be calculated with any sense of realism, given the numbers available to me. Given the electric margins, I analyze the likely interactions between the terms of the contract to buy and sell electricity on farms of different sizes.

II. A Description of the System:[6]

A digester is often described as an extension of the digestive system of the herd itself. Manure is flushed or scraped from the stalls along with a certain amount of bedding. This waste is then heated and added to a series of tanks (usually two), where other waste, such as newspaper, may be added. In the tanks, solids may be separated out and water removed. The temperature of the manure is typically maintained at 95-105°F, although two stage digesters exist that start the manure off at about 130°F and then move it down to 95°F. Bacteria in the tanks digest the manure in an anaerobically (in the absence of oxygen), releasing gas. The gas is composed of roughly 55 percent methane, with the remainder composed mainly of carbon dioxide, as well as some hydrogen sulfide and traces of other gases. The collected gas is transferred to some sort of engine and generator. Some farms use a standard engine with a generator, while others use a micro-turbine. A micro-turbine is essentially a jet engine connected to a generator. The micro-turbine enjoys a slightly higher electrical efficiency than the heat engine: about 28% vs. 23%. It also is efficient in the capture of waste heat, capturing about 37% of the heat potential of the gas as usable heat energy. Despite these advantages several farms use heat engines. This is because micro-turbines cost more to install and because parts and technicians to work on micro-turbines are not easily found.

The following flow-chart depicts the system along with its most important state and control variables. The loading rate of manure, its temperature, dilution and the proportion of it that is frozen dictate the amount of energy needed to heat the digester to

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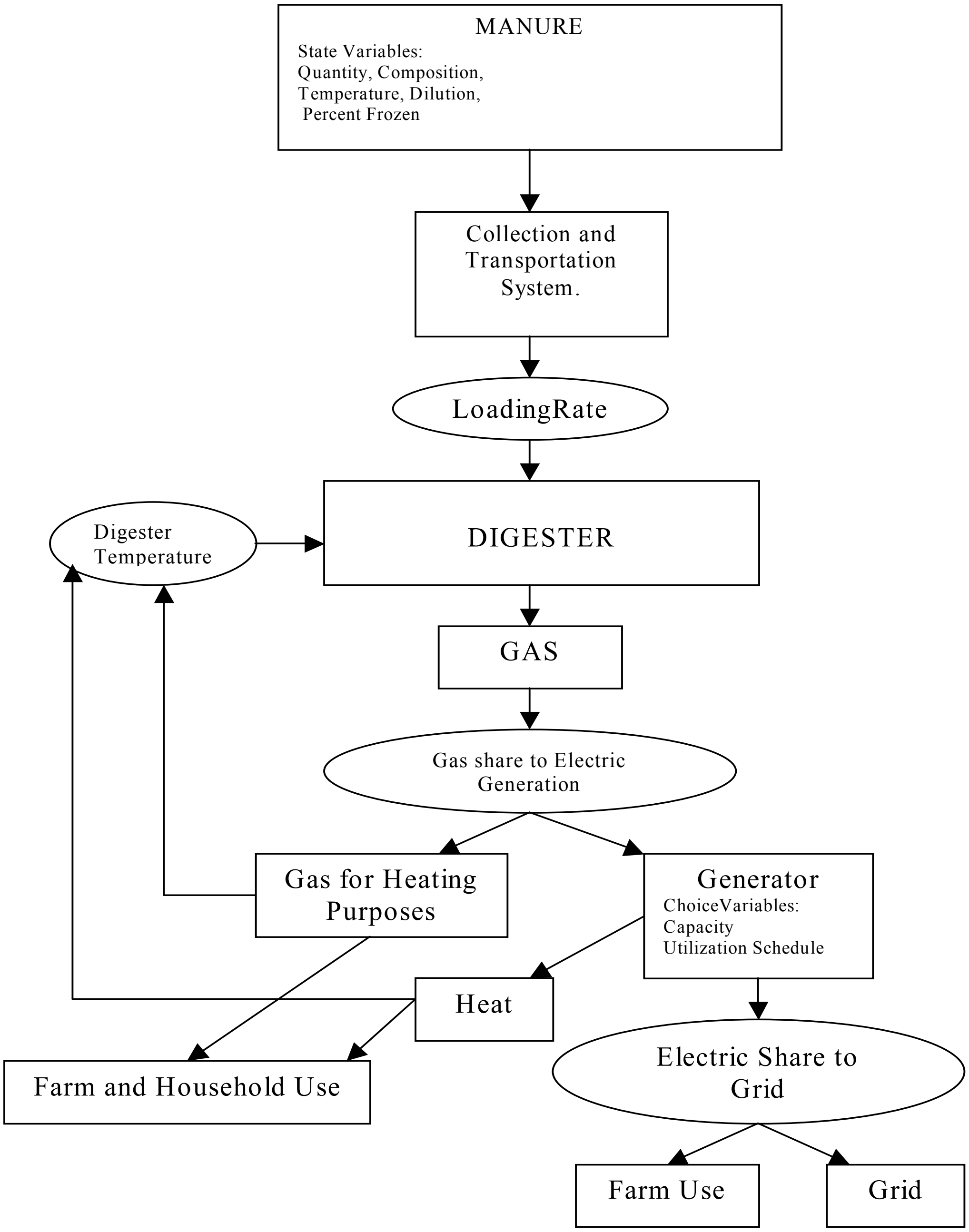
[4] The somewhat surprising fact that a number of farms use electricity rather than gas to maintain digester temperature, is due to the favorable electrical price structure that helps make digesters financially viable in the first place.

[5] Parsons (1984), p.25. See section IV of this paper for details.

[6] The reader interested in a more detailed description of the digestion process is referred to Parsons (1984).

the desired temperature as well as the rate of gas production. Once generated, the gas may either be used to generate electricity, or to fuel other processes on the farm – typically heating. As all the farms that I know about use all their gas to generate electricity I assume that this will be the case in my study, although one should note that depending on the cost of heat relative to electricity, it may be optimal to use some of the gas for heating instead. In the process of generating electricity, a fair amount of waste heat is generated which can be used for ambient heating, the drying of solid effluent, and maybe even to heat the digester. As the value of non-electrical outputs of the digester is beyond the scope of this study I do not consider the optimal use and value of this heat. The electricity, once generated may be applied to off-set the farm's own electricity requirements or be sold via the electric grid.



III. Calculation of the Total Available Energy:

The amount of energy available for resale can depend on two factors. The first is the heat energy available given the maximum rate that at which gas can be generated on a continuous basis, which I shall refer to as the *electric power potential* of the farm. The second is the amount and timing of electricity use for the farm's dairy operations – the load curve.

Electric Power Potential:

The gross amount of energy that may be generated on a farm is best approximated as linear in the number of cows. This is because the amount of gas generated per pound of manure and the heat value of that gas are not dependent in any well understood fashion on the amount of manure, and the amount of manure is linear in the number of cows. Despite the apparent simplicity, the range of values obtained in operation for the amount of energy available per cow varies tremendously.

Robert Fick at Alliant energy reports that European generators obtain 0.15 kW of electrical power per cow on a continuous basis, while their American counterparts manage 0.2 kW (or 4.8 kWh/day). The difference probably owes to differences in animal size and feed. These figures correspond to generators using micro-turbines, with an assumed efficiency in electricity generation of 28%. This suggests that American digesters generate gas with a power potential of 0.71 kW on a continuous basis (or 17.14 kWh/day).

These numbers are significantly higher than the conventional wisdom used to suggest. Parsons (1984) suggests a gas yield of 54 cubic feet per cow per day. Combined with an estimated heat value of 600 Btu/cubic foot (which may be a little high) this yields a power potential of 0.4 kW on a continuous basis (or 9.49 kWh/day). Assuming a standard heat engine and generator with an efficiency of 21%, we are left with 0.083 kW continuous (or 2 kWh/day). With a micro-turbine this would amount to 0.112 kW continuous (or 2.66 kWh/day).

The discrepancy seems to arise from the estimated gas yield. Haubenschild Farm[7] reports an average daily gas yield of 139 cubic feet per cow. This more than doubles their design estimate of 65 cubic feet/cow. They also report average electricity generation of 5.5kWh per cow per day, using a standard heat engine – which unsurprisingly also more than doubles their design estimate. Similarly, Craven farms used a design estimate of 65 cubic feet/cow, although they do not report the rates they have achieved.[8]

Based upon this information, it seems likely that Dr. Fick's estimate is appropriate. While the reasons for the variation in gas yield are yet to be clearly explained and may be related in part to the addition small quantities of other digestible wastes such as newspaper, it seems likely that the gas yield attainable will, in the long run, converge on a figure that allows for continuous electrical output of approximately 0.2 kW per cow.

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[7] Nelson and Lamb (2000)

[8] Oregon Office of Energy

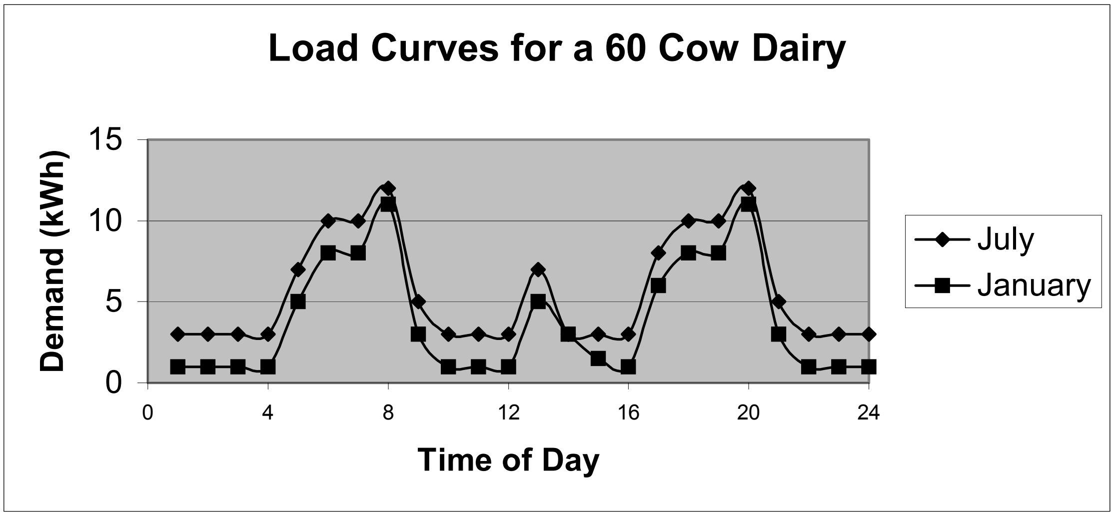
For future use I define the term *electric power potential* (EPP) as the maximum amount of electrical power that can be generated on a continuous basis for a given number of cows (assuming that generator capacity is sufficient). For our purposes, this will therefore be the number of cows multiplied by 0.2 kW.

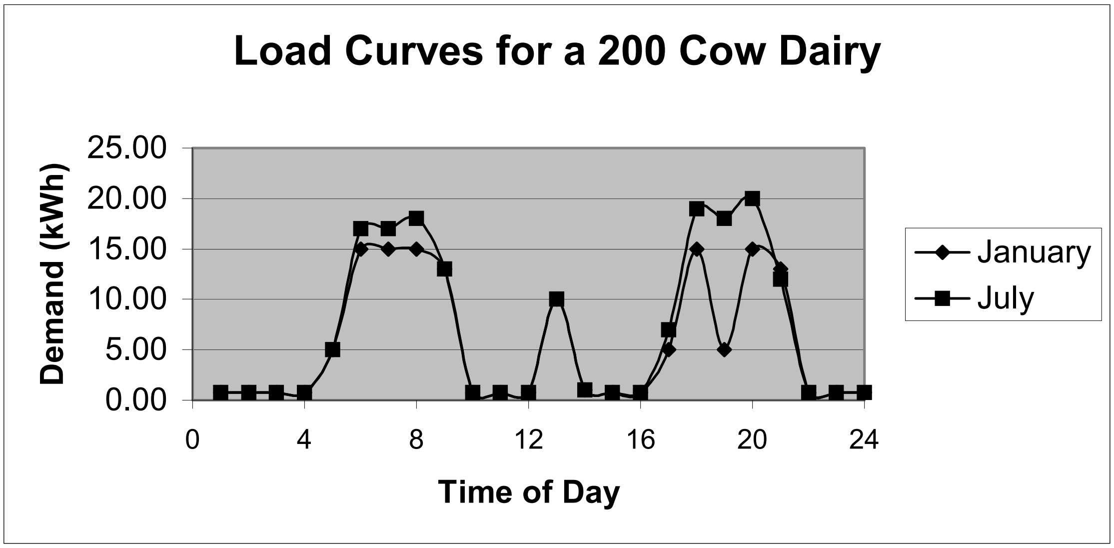
As seen above, the electric power potential depends on whether a standard heat engine or a micro-turbine is chosen for generation. The heat engine carries an electrical efficiency of between 21% and 25%, while the micro-turbine has an efficiency of approximately 28%. The difference is negligible compared to the uncertainty in gas production levels. Micro-turbines, however, are useful for their heat capture capability. An estimated 37% of the total heat potential of the gas may be collected when using a micro-turbine. The low quantity and quality of the waste heat that could be captured off a standard engine means that the amount of heat actually recovered by farms using them varies more for economic than engineering reasons. Farms often find it cheaper to vent waste heat than to use it. Hence the efficiency of heat capture is immensely variable in practice, and a representative estimate of the amount of heat *actually* captured off a standard heat engine is available.

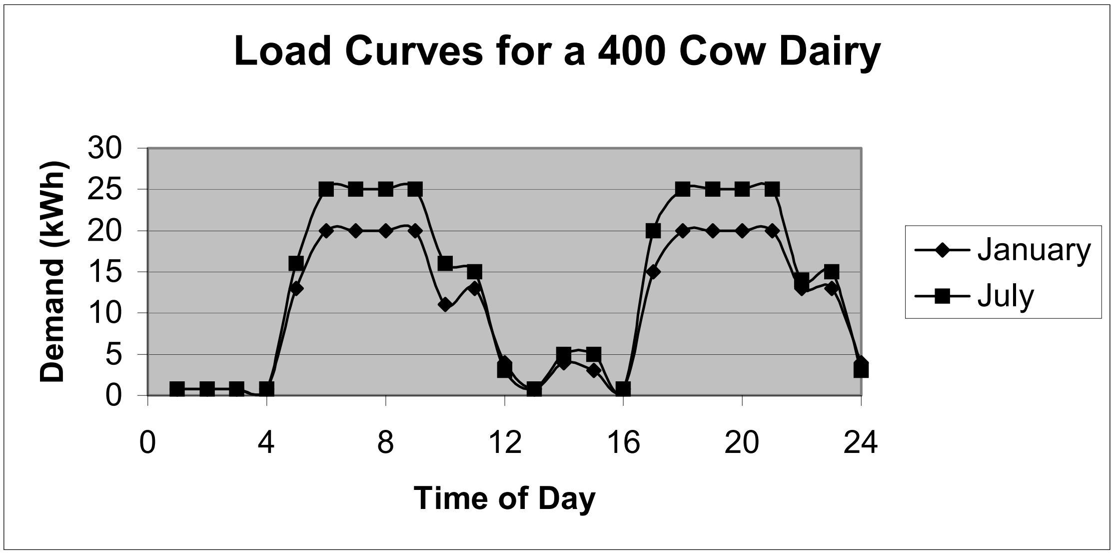
The Load Curves:

The load curves used in my calculations come from Peebles and Reinemann (1994). They estimated load curves for dairy farms with 30, 60, 200 and 400 cows using the TRNSYS simulation package. Two sets of results are presented in their work, one for an inefficiently configured farm, and one that is efficiently configured. I use the estimated load curves for the efficiently configured farm. This may bias my results against the feasibility of digesters, as less efficient farms have larger electricity bills and can therefore save more money by generating their own electricity. Peebles and Reinemann provide 24 hour load curves only for a typical day in January and July. I estimate the load curve for a typical day in the missing ten months by assuming that the demand at a particular hour of day is the average of the January and July demands for that hour, weighted linearly by proximity to the date. Also, for reasons to be presented below, I do not consider a 30 cow farm.

The load curves used in the paper are presented below:







The total estimated annual electricity consumption levels are presented in table 1.

TABLE 1: ANNUAL ELECTRICITY CONSUMPTION FOR DAIRY OPERATIONS

Number of Cows	Total Annual Electricity Consumption (kWh)	Annual Electricity Consumption per Cow (kWh/cow)
60	41,365	689
200	55,152	276
400	104,826	262

Note the considerable economies of scale in electricity use. These will play a significant role in determining which farms are likely to derive a competitive edge in the dairy markets as a result of the introduction of digesters.

IV. Calculation of the Electric Margin and output levels:

The value of the electrical output of a generator will depend on four factors: The number of cows, the electric rate structure, the rules regarding how the electricity is used, and the capacity of the digester/generator system.

The analysis will proceed as follows: For a farm of any given size, a range of generator capacities will be proposed. The optimal utilization under each potential price and use regime will be determined, and an electric margin will be calculated *taking the capacity as given*. If data on capacity costs and the value of non-electric outputs were available then the optimal capacity could be determined. This last step is not possible for me currently.

Pricing and Flexibility

I consider two different sets of rules governing the use of the electricity. Under the *inflexible* regime farms are constrained to either using all of the electricity they generate themselves, or to selling it all back to the electric grid. They do not have right, or the technology to direct electricity to different uses at different times. Under the *flexible* regime, on the other hand, a farm is at liberty to direct electricity to wherever it may be most profitably applied. I consider these two regimes because the latter is available in Minnesota[9], while it has been suggested to me that the former is the only likely regime on offer in Wisconsin in the near future.

The price regimes that I will consider fall into three categories. Either the price at which a farm may sell its electricity (p_s) exceeds, is equal to, or is exceeded by, the price at which it buys electricity (p_b). As an example of a price regime in the first category, I choose prices p_s = \$0.09 /kWh, and p_b=\$0.035/kWh. These *might* be representative of the prices faced by Tinesdale Farms, although small farms are unlikely to receive this preferential purchase price.[10] As examples of price regimes in the second category, I choose prices $p_s = p_b$ =\$0.067/kWh and $p_s = p_b$ =\$0.0725/kWh. The former is the price that dairy farms requiring less than 200,000 kWh annually pay to Alliant energy, while the latter are the prices Haubenschild farms actually faces. Finally, I choose two sets of prices in the third category. The first is p_b =\$0.067/kWh and p_s ==\$0.060/kWh, and the second is p_b =\$0.0725/kWh and p_s = \$0.02/kWh. The former is a price structure currently being considered by Alliant Energy for green power producers, while the latter is the price scheme that Haubenschild Farms planned for.[11]

To summarize, then, I consider two possible sets of rules – *flexible* and *inflexible*, and the following five price regimes:

TABLE 2: PRICE REGIMES

Name	*Prices*
Regime I	p_s = \$0.09 /kWh, p_b=\$0.035/kWh
Regime II	$p_s = p_b$ =\$0.0725/kWh
Regime III	$p_s = p_b$ =\$0.067/kWh

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[9] For example these rules are currently applied to Haubenschild Farms in Princeton, Minnesota.

[10] The price at which Tinesdale sells their electricity is confidential. Also, while I do not know their purchase price, we know that as a large farm they probably pay a commercial rate. Alliant Energy offers a commercial rate of 3.5¢/kWh to customers using more than 200,000 kWh annually.

[11] The scheme was subsequently improved so that $p_s = p_b$ =\$0.0725/kWh.

Regime IV	p_b =\$0.067/kWh, p_s ==\$0.060/kWh
Regime V	p_b =\$0.0725/kWh, p_s ==\$0.02/kWh

Optimal Utilization:

The logic here is a little tricky to work out, but quite unambiguous once it is done. I present it in a series of propositions.

<u>Proposition 1:</u> Farms facing price regimes I,II and III ($p_s \geq p_b$) will run their generators at full capacity and sell all of their electricity to the grid.

- Consider the inflexible case first. A farm facing $p_s > p_b$ that is inflexible must choose whether to use its power to off-set its own bills, or to sell to the grid. Clearly the latter is more profitable under this price scheme.
- In the flexible case, a farm facing $p_s > p_b$ still utilizes power for greater profit if it sells it, than if it uses it to off-set its own requirements.
- In either case, if $p_s > p_b$ there is no incentive to ever turn of the generator.
- Now, in the inflexible case, if $p_s = p_b$, then a farm choosing to use its electricity may end up being unable to find a use for all its power. However, if it sells to the grid it can always sell all of it. Thus its revenues will always be (weakly) larger if it sells to the grid.
- Finally, a flexible firm, facing $p_s = p_b$ will be indifferent between using or selling its power.

It is well worth noting that under regime I ($p_s > p_b$) there is an obvious incentive to cheat. A farm could conceivably purchase power and sell it back at the higher green rate. Regulators and distributors should beware of such power laundering schemes.

<u>Proposition 2:</u> Under price regimes IV and V ($p_s < p_b$), whether flexible or not, a farm with a capacity that is less than its minimum power demand will produce to full capacity and use all the electricity they produce themselves. The remainder of their power needs will be purchased from the grid.

- In this case there is no potential for excess capacity if the farm chooses to use its own power. Flexibility is not an issue because with $p_s < p_b$ a farm will always find it more profitable to use their power themselves.

<u>*NB:*</u> When we look at the data on load curves, we find that the minimum demands on dairy farms of all sizes covered are less than 3 kW. This is far smaller than the smallest micro-turbine available. It is also unlikely that anyone would consider installation of a heat engine that small. I therefore preclude analysis of this case for this paper. Note, however, that a larger farm – say one with 1,500 cows – with round the clock milking, could certainly find a generator smaller than its minimum demand.

<u>Proposition 3:</u> A farm with at least 60 cows will never install capacity that cannot be fully utilized all the time in steady state. In other words it will never employ a power capacity that is greater than the electric power potential (defined above).

- To see this, consider why a farm would wish to violate the proposition. We know that the total amount of energy that can be produced in a year is limited by the electric power potential. It therefore follows that a farm will only be interested in having capacity in excess of EPP if this allows them to burn more gas at times when it receives a higher price.

  - Proposition 1 establishes that without regard to capacity, a farm facing $p_s > p_b$ will sell all its power at the maximum price p_s. There is no incentive to selectively time generation here, as the value of generated electricity is not time-sensitive.
  - Now, if $p_s < p_b$, a firm will only have an incentive to selectively time its generation if EPP is less than its maximum demand. In this case, it could increase the value of its electricity by saving gas when demand is below EPP, and using it when demand exceeds EPP. Fortunately, as the following table shows, EPP exceeds maximum demand for all farms of at least 60 cows.

TABLE 3: MAXIMUM DEMAND AND ELECTRIC POWER POTENTIAL.

Number of Cows	**Maximum Demand on an hourly basis (kW)**	**Electric Power Potential (kW)**
30	11	6
60	12	12
200	20	40
400	25	80

- It follows that we never need to worry about generators with capacity in excess of EPP.

Note that this is a steady state result. Typically set-ups are designed with excess capacity in order to facilitate possible expansion.

This partly explains why I drop 30 cow farms from my analysis. A 30 cow farm would not even be able to power its own dairy operations and would therefore require a qualitatively different analysis from the other farms sizes. Furthermore, a digester on a 30 cow farm is unlikely to be economically viable under any realistic rate structure. This is due primarily to the declining average cost of digester size. AGSTAR recommends against the use of digesters on farms of less than 200 head.

Proposition 4: If $p_s < p_b$ a flexible farm with capacity in excess of minimum demand will run at full capacity. The generated electricity will be applied to their own use. Any excess supply will be sold to the grid, while any excess requirements will be purchased from the grid.

- As $p_s < p_b$, any energy requirements that can be met from the farm's own generation should be.
- Consider times when capacity exceeds demand. There is no point to saving gas for times when demand will outstrip generation, as capacity (being smaller than EPP by Proposition 3), not gas, will be the limiting factor.

<u>Proposition 5:</u> If $p_s<p_b$ an inflexible farm with capacity in excess of minimum demand will either run at full capacity and sell all their power to the grid, or use all their power themselves, generating only exactly as much power as they need. The rest of the gas will be vented, or piped off for other uses on the farm.

- This should be obvious. The revenues from selling what can be generated using this capacity will be lower than those from using it due to the lower price, but higher due to the fuller utilization of capacity. Which option is selected is simply a quantitative matter, beyond the scope of current analysis due to the lack of detailed capacity costs.

It is tempting to speculate that a farm will always build sufficient capacity to fully utilize its EPP, or to satisfy its peak demand. Unfortunately, hypotheses concerning the optimal capacity cannot be examined in the absence of capacity costs.

Further, we should note that an inflexible arrangement, with $p_s<p_b$, under which the farm is required to sell all its power to the grid is likely to create too many complications to be practical. For, if the farm offered to sell its power to the grid, it would always have an incentive to divert power to its own farm and digester operations instead. As distributed generation grows, therefore, such contracts are likely to become extinct. In fact, probably for exactly this reason, I have been unable to find examples of anybody operating on such a pricing regime. Therefore, the only inflexible arrangement with $p_s<p_b$ that I consider, is one under which the farm may not sell electricity to the grid, but may use it to off-set its own power requirements.

Table 4 summarizes the optimal use plans.

TABLE 4A: OPTIMAL USE OF CAPACITY.

<table>
<tr><th></th><th>Flexible</th><th>Inflexible</th></tr>
<tr><td>$p_s>p_b$ (Regimes I and II)</td><td colspan="2" rowspan="2">Use the generator to full capacity. Sell all produced electricity to the grid. Purchase all required electricity from the grid.</td></tr>
<tr><td>$p_s=p_b$ (Regime III)</td></tr>
<tr><td>$p_s<p_b$ (Regimes IV and V)</td><td colspan="2">See Table 4B.</td></tr>
</table>

TABLE 4B: OPTIMAL USE WHEN $p_s<p_b$

<table>
<tr><th colspan="2">Capacity ≤ Minimum Demand (kW) – the irrelevant case for moderate sized farms.</th><th colspan="2">Capacity > Minimum Demand (kW)</th></tr>
<tr><td><i>Inflexible</i></td><td><i>Flexible</i></td><td><i>Inflexible</i></td><td><i>Flexible</i></td></tr>
<tr><td colspan="2">Use the generator to full capacity. Use all produced electricity and purchase the remainder from the grid.</td><td>Generate according to one's own needs. Use all generated electricity. Purchase any shortfall from the grid.</td><td>Run at full capacity. To the extent possible, meet own requirements from own generation. Sell extra electricity to the grid, and purchase shortfalls from the grid.</td></tr>
</table>

Digester Electricity Requirements.

As pointed out earlier, a digester requires about a third of the electrical energy it is capable of generating. The bulk of this energy is used to maintain the temperature of the manure in the digester. This is why the amount is independent of the amount of electricity actually produced. Even though I have allowed, in all the above arguments, for a farm to choose not to fully utilize all their EPP, the electric requirement for a digester depends essentially upon the amount of manure digested, not the amount of electricity generated.

Further, given the range of non-electric benefits from digestion, I assume that a farm will choose to digest all of its manure, regardless of the amount of electricity it chooses to generate. The adequacy of this assumption is impossible to test without information on the value of all the other outputs.

However, even though the electric requirement to heat the digester will be a constant with respect to capacity utilization for a farm of given size, it will vary with season. This suggests that we should consider whether these electric requirements are likely to lead to binding capacity constraints. I argue that they should not. We also need to consider at what price to value this heat requirement.

- If $p_s \geq p_b$, the farm will always sell as much electricity to the grid as possible, and satisfy all its electricity requirements by purchase (Proposition 1). It follows that the electricity to run their digesters will not even make use of their own capacity, leave alone exhaust it. Also, as the electricity to heat the digester is purchased, its cost is evaluated at p_b.
- If $p_s < p_b$ a farm will use its own electrical output, to the extent possible. Regardless of flexibility, it is my guess that farms of the size considered here function at minimum demand for long enough, and that the difference between the capacities considered and minimum demand is large enough, that they will always have the capacity to heat their digester by simply doing it off-peak. It follows that the requirement to heat the digesters will not exhaust capacity. There remains the question of cost. In the inflexible case, the farm may not sell its electricity anyway. Therefore, any excess electricity that can be generated carries no market value. A cost of zero for energy used to heat the digester is therefore assumed. In the flexible case, the off-peak generation that is used could, instead have been sold at a price of p_s. It is therefore valued accordingly.

The choice of electrical heating for the digester may seem surprising. It is a choice that is likely to be strongly influenced by the rate structure. Tinesdale Farm, for example, facing a significantly lower price for electricity purchased than for electricity sold, could more cheaply heat their digester using purchased electricity than using heat or gas output from their system. Haubenschild Farms, on the other hand, who may buy and sell electricity at the same price, have opted to reserve their excess electricity for the market, and instead heat their digester using waste heat from their generation process. The assumption that the digester will be heated electrically is therefore flawed. This said, there is no way around it for the time being. The heat collection and distribution systems required to heat the digester using electricity and waste heat are not likely to cost the same amount. Further, the quality of the waste heat matters greatly. Given these complications, resolution of this issue is beyond the scope of this paper. I simply assume here that powering the digester requires energy inputs equal to one third of its average energy output.

Choice of Capacities.

There are, to the best of my knowledge no digesters in the U.S. currently functioning on farms with less than 400 cows. Consequently manufacturers of micro-turbines do not cater to small capacities. The least powerful micro-turbine suitable for use with bio-gas on the market today is a 30 kW model on offer from the Capstone Turbine Corporation. Consequently, there are not a great deal of capacity choices currently available to dairy farms of the size I am interested in. However, I am assured by a Capstone representative that scaling up or down turbine sizes does not pose significant technical difficulty. Were there a market for other sizes, they could become available. Given the longer-term hypothetical view of this project, I therefore take the liberty of supposing that micro-turbines are available in a range of sizes.

I have already argued that a capacity in excess of *EPP* will not be selected. On the other extreme, if $p_s<p_b$ and a farm would like to use its generator to power its own dairy operations as well as the generator itself, the smallest reasonable capacity is one that provides sufficient electrical energy to run these systems. This provides the lower bound for capacities to be considered. We are concerned with total energy rather than power, because there is presumably sufficient flexibility in the timing of heat infusions to the digester.[12] One should note as well that if $p_s \geq p_b$, then all generated power will be sold, and there is no a priori sensible lower bound for capacity.

Now, a 400 cow dairy, has an *EPP* of 80 kW (701,280 kWh/yr) and therefore a digester electricity requirement of one third that, or 26.67 kW (233,760 kWh/yr). It also requires an average 12 kW (104,827 kWh/yr) of electricity for its dairy operations. Given that the total average power requirement is 38.87 kW, I estimate the electric margin assuming capacities of 40, 50, 60, 70 and 80 kW. Similarly a 200 cow dairy, with an *EPP* of 40 kW and an average 6.3 kW power requirement for its dairy operations requires a total of 19.6 kW for dairy and digester operations. Hence, I consider capacities of 20, 30 and 40 kW. Finally, a 60 cow dairy, with an *EPP* of 12 kW and an average 4.7 kW power requirement for its dairy operations requires a total of 8.7 kW for dairy and digester operations. Hence, I consider capacities of 9, 10, 11 and 12 kW.

Results.

Tables 5a-c present the calculated electric margins.

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[12] Naturally there is more to this. The digester's heat requirements are likely to be considerably higher during the winter, increasing the possibility of capacity overloads. At the same time, dairy operations require more electricity in the summer, which may alleviate the capacity constraint.

TABLE 5A: *ELECTRIC MARGINS FROM A 60 COW DAIRY ($/YR):*

			Capacity (kW)			
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*9*	*10*	*11*	*12*
0.09	*0.035*	*Either*	5873	6662	7451	8240
0.0725	*0.0725*	*Either*	3178	3813	4449	5084
0.067	*0.067*	*Either*	2937	3524	4111	4699
0.06	*0.067*	*Inflexible*	2625	2698	2747	2771
0.02	*0.0725*	*Inflexible*	2840	2919	2972	2999
0.06	*0.067*	*Flexible*	2904	3503	4078	4629
0.02	*0.0725*	*Flexible*	2933	3188	3416	3618

TABLE 5B: *ELECTRIC MARGINS FROM A 200 COW DAIRY ($/YR):*

				Capacity (kW)	
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*20*	*30*	*40*
0.09	*0.035*	*Either*	11688	19577	27467
0.0725	*0.0725*	*Either*	4237	10592	16948
0.067	*0.067*	*Either*	3915	9789	15662
0.06	*0.067*	*Inflexible*	3695	3695	3695
0.02	*0.0725*	*Inflexible*	3999	3999	3999
0.06	*0.067*	*Flexible*	4791	10051	15310
0.02	*0.0725*	*Flexible*	4364	6117	7870

TABLE 5C: *ELECTRIC MARGINS FROM A 400 COW DAIRY ($/YR):*

					Capacity (kW)		
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*40*	*50*	*60*	*70*	*80*
0.09	*0.035*	*Either*	23376	31265	39155	47044	54934
0.0725	*0.0725*	*Either*	8474	14829	21185	27540	33895
0.067	*0.067*	*Either*	7831	13704	19577	25451	31324
0.06	*0.067*	*Inflexible*	7023	7023	7023	7023	7023
0.02	*0.0725*	*Inflexible*	7600	7600	7600	7600	7600
0.06	*0.067*	*Flexible*	7747	13006	18266	23525	28785
0.02	*0.0725*	*Flexible*	7841	9594	11347	13101	14854

To facilitate comparison, as well as to gain an appreciation of the likely impact of digester technology, rate structures and regimes on the competitiveness of dairy farms of differing sizes, tables 6 and 7 present the electric margins per cow and per unit of capacity.

TABLE 6A: *ELECTRIC MARGINS PER COW FROM A 60 COW DAIRY ($/COW-YR):*

			Capacity (kW)			
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*9*	*10*	*11*	*12*
0.09	*0.035*	*Either*	98	111	124	137
0.0725	*0.0725*	*Either*	53	64	74	85
0.067	*0.067*	*Either*	49	59	69	78
0.06	*0.067*	*Inflexible*	44	45	46	46
0.02	*0.0725*	*Inflexible*	47	49	50	50
0.06	*0.067*	*Flexible*	48	58	68	77
0.02	*0.0725*	*Flexible*	49	53	57	60

TABLE 6B: *ELECTRIC MARGINS PER COW FROM A 200 COW DAIRY ($/COW-YR):*

				Capacity (kW)	
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*20*	*30*	*40*
0.09	*0.035*	*Either*	58	98	137
0.0725	*0.0725*	*Either*	21	53	85
0.067	*0.067*	*Either*	20	49	78
0.06	*0.067*	*Inflexible*	18	18	18
0.02	*0.0725*	*Inflexible*	20	20	20
0.06	*0.067*	*Flexible*	24	50	77
0.02	*0.0725*	*Flexible*	22	31	39

TABLE 6C: *ELECTRIC MARGINS PER COW FROM A 400 COW DAIRY ($/COW-YR):*

					Capacity (kW)		
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*40*	*50*	*60*	*70*	*80*
0.09	*0.035*	*Either*	58	78	98	118	137
0.0725	*0.0725*	*Either*	21	37	53	69	85
0.067	*0.067*	*Either*	20	34	49	64	78
0.06	*0.067*	*Inflexible*	18	18	18	18	18
0.02	*0.0725*	*Inflexible*	19	19	19	19	19
0.06	*0.067*	*Flexible*	19	33	46	59	72
0.02	*0.0725*	*Flexible*	20	24	28	33	37

Table 7a: ***Electric Margins per kW of Capacity from a 60 Cow Dairy ($/kW-yr):***

			Capacity (kW)			
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*9*	*10*	*11*	*12*
0.09	*0.035*	*Either*	653	666	677	687
0.0725	*0.0725*	*Either*	353	381	404	424
0.067	*0.067*	*Either*	326	352	374	392
0.06	*0.067*	*Inflexible*	292	270	250	231
0.02	*0.0725*	*Inflexible*	316	292	270	250
0.06	*0.067*	*Flexible*	323	350	371	386
0.02	*0.0725*	*Flexible*	326	319	311	302

Table 7b: ***Electric Margins per kW of Capacity from a 200 Cow Dairy ($/kW-yr):***

			Capacity (kW)		
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*20*	*30*	*40*
0.09	*0.035*	*Either*	584	653	687
0.0725	*0.0725*	*Either*	212	353	424
0.067	*0.067*	*Either*	196	326	392
0.06	*0.067*	*Inflexible*	185	123	92
0.02	*0.0725*	*Inflexible*	200	133	100
0.06	*0.067*	*Flexible*	240	335	383
0.02	*0.0725*	*Flexible*	218	204	197

Table 7c: ***Electric Margins per kW of Capacity from a 200 Cow Dairy ($/kW-yr):***

			Capacity (kW)				
Selling Price ($/kWh)	**Buying Price ($/kWh)**	**Regime**	*40*	*50*	*60*	*70*	*80*
0.09	*0.035*	*Either*	584	625	653	672	687
0.0725	*0.0725*	*Either*	212	297	353	393	424
0.067	*0.067*	*Either*	196	274	326	364	392
0.06	*0.067*	*Inflexible*	176	140	117	100	88
0.02	*0.0725*	*Inflexible*	190	152	127	109	95
0.06	*0.067*	*Flexible*	194	260	304	336	360
0.02	*0.0725*	*Flexible*	196	192	189	187	186

V. Analysis and Conclusions:

The conventional wisdom holds that digester technology displays significant economies of scale with respect to farm size. This is due to installation costs that are fixed with respect to the size of the operation. Given the non-availability of measures of fixed costs that vary according to farm size, analysis of this issue is beyond the scope of this paper. However some educated guesses can be made.

In the case where $p_s \geq p_b$, at EPP, both the electric margin per kW of capacity and per cow are equal across farms of different sizes. This is because the farm simply generates as much electricity as it can and sells it. At a capacity equal to EPP, the amount of electricity that can be generated per cow, or per unit of capacity is constant across farm sizes, by construction. If the average fixed cost of a digester-generator indeed decreases in size, two unambiguous results follow:

- Larger farms will be able to make a larger profit margin on each kWh of electricity sold (because the electric margin per kW is constant while average fixed costs are declining).
- Larger farms will gain more of a competitive edge through the introduction of digesters than small farms. The reasoning is as follows: the per cow profit increase due to the introduction of a digester (equal to the constant electric margin per cow minus the declining cost of capacity per cow) is higher for larger farms, implying that if milk output per cow is roughly constant across farms of different sizes then the reduction in the break-even price of milk should be larger for larger farms.

Thus, the conventional wisdom is borne out in this case.

Conversely, however, if $p_s < p_b$, smaller farms *may* win out. If $p_s < p_b$, farms will dedicate as much generated electricity as possible to off-setting their own electric bills. Two hunches follow:

- The electric bill per cow is significantly higher for smaller farms, which explains why the electric margin per cow is much higher for a smaller farm in these price regimes. The reduction in a farm's costs per cow are higher for smaller farms. Again, if the milk production per cow is roughly constant with respect to farm size, it would seem that this reduction in costs would disproportionately assist smaller farms. Thus, smaller farms will unambiguously experience a relative competitive edge from rate structures in which $p_s < p_b$ *compared to those in which* $p_s \geq p_b$. However, on the flip side, the presumed declining average digester-generator capacity costs continues to aid larger farms. Therefore, it remains unclear whether under regimes with $p_s < p_b$ small farms will become more or less competitive with the introduction of digesters.
- Because a smaller farm is capable of utilizing a greater percentage of the electricity it produces itself, the margin per unit of capacity is also higher for smaller farms

Ceteris paribus, flexibility seems to do more for larger, than for smaller farms. To see why, note that if $p_s \geq p_b$ flexibility is irrelevant as all farms will sell all the produced electricity anyway. However if $p_s < p_b$, moving from an inflexible to a flexible contract allows farms to sell whatever electricity they cannot use themselves. As large farms have more excess electricity, they gain more when a market for it is created. To gain an appreciation for this numerically, compare the increase in electric margin (on an absolute, per cow, or per kW, basis) when switching from an inflexible to a flexible regime, across farm sizes.

Finally, we can gain a *very* loose sense of profitability. Given the probable declining average cost of building the system, it seems likely that Dr. Fick's estimated fixed of $660 per cow is a little low for the farms we are looking at. Tinesdale farm, with 1800 cows, invested about $1,000 per head. Given that this is one of the first generation of commercial digesters, I suspect that in the future the costs will come down. From this, I guess that $1,000 per cow may be an appropriate number for smaller farms. Given this, and assuming an interest rate of 10%, I estimate that in order to break even on the electrical output alone a farm would have to obtain an electric margin of at least $100 per year per cow. From table 6 it follows that a digester would turn a profit on its electric output alone at 10% interest only if p_s=0.09$/kWh. This is higher than a commonly quoted figure of 0.06$/kWh. However, if I reduce my estimated fixed cost to $660 per cow, all the farm sizes considered are able to turn a profit at 0.06$/kWh. Given my sense of the fixed cost structure, though, I am inclined to suggest that smaller farms will not be able to break even on their electricity supply alone at 0.06$/kWh.

All this said, it is imperative that conclusions about the economic feasibility and desirability of this technology not be drawn from these figures. In addition to electricity there remain five outputs of a digester that I have been unable to value: bedding/fertilizer, heat, water, odor reduction and environmental benefits. The addition of these benefits will make digesters economically feasible at less generous rate structures. Further, reducing odors and other externalities associated with dairy farming may make large dairy farms more acceptable. If so, this may help to reduce further the cost of milk if there are additional scale economies in the dairy sector to exploit.

The likely presence of scale economies in digester size also points to one important policy option. Smaller dairy farms could utilize cooperatively owned digesters to exploit potential scale economies. This might not just render them as competitive as larger farms. Under rate regimes where $p_s<p_b$, a cooperative of smaller farms would be able to generate higher margins than a single large farm with the same number of cows, as the cooperative would have larger electricity bills to off-set. This would improve the competitiveness of a cooperative of small farms even more than that of a single large farm. On the other hand, the cost of manure collection and potential difficulties in utilizing waste heat may negate these advantages.

One of the major lessons of this analysis is that variations in the contractual arrangements have an immense impact on the feasibility of digesters. The range of rate structures examined in this paper are drawn from reality, and environments that are deemed unsuitable for digesters under one rate structure are deemed suitable under another. The relationship between the rate structure and feasibility is empirically important.

Ironically, my analysis also suggests that a policy maker who is concerned solely with the promotion of smaller farms may wish to favor price schemes in which all farmers receive *less* for the power they produce than they would pay to purchase it, and have less flexibility in choosing what to do with it. The negative efficiency implications of such policies are obvious, potentially making the promotion of power cooperatives is a better option.

One of the reasons that policy makers purport to prefer policies that favor small farms, is their perceived environmental impact. If, however, digester technology turns out to display significant economies of scale, it could be the case that larger farms are capable of being greener – more capable of recycling their own waste - than smaller farms. A strange twist in an already emotionally charged debate.

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