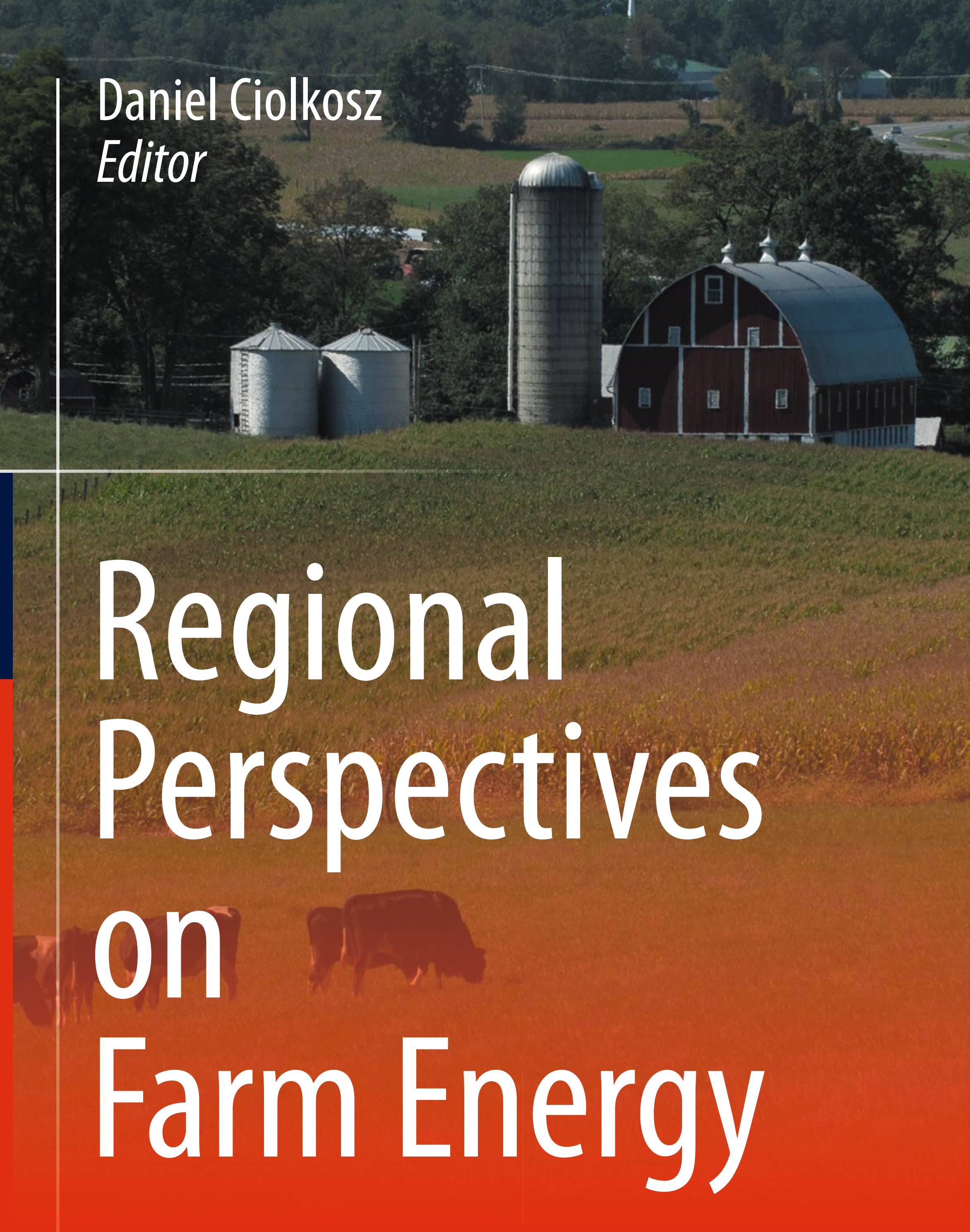

Daniel Ciolkosz
Editor

Regional Perspectives on Farm Energy

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Contents

Chapter 1
Energy Use on the Farm

Daniel Ciolkosz and Aluel Go

1.1 Introduction to Topic

In a broad sense, farms have always been “energy driven“, since they function by transforming solar energy into stored chemical energy via photosynthesis (i.e. the growing of crops). For some farms, this stored energy is the final product, in the form of hay, grain, plant fibers and the like. However, many farms carry out further “bioprocessing“ to move the stored energy into the form of milk, meat, animal-based power, etc. Additional, less obvious uses of solar energy on the farm include the warming of greenhouses through solar gain and the use of wind (which is a byproduct of solar radiation on the earth) to ventilate agricultural structures.

Farm Energy: Electricity or fuel used to carry out work or provide heat on the farm

However, such a philosophical approach to farm energy, while interesting, is usually of limited practical use. Instead, when we speak of energy use on the farm, we usually are using a narrower sense of the word “energy” in terms of electricity or fuel (solid, liquid, or gaseous) that is used to carry out work or provide heat on the farm. Farm energy can be produced by biological organisms (i.e. animal driven farm implements or compost-based heating systems), but it is usually produced by

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mechanical devices (i.e. motors, engines, boilers). Energy use on the farm has two main purposes: replace labor and perform tasks that cannot be done otherwise.

1.2 Uses of Farm Energy

1.2.1 Replace Labor

Consider that a ¼ horsepower (hp) electric motor can perform work at the same rate as an adult while using about 2 kwh of energy per day, which would cost 15–25 cents.

From this example, it is easy to see why work done by motors and engines is almost always a cost effective alternative to human labor. The increase in farm energy utilization during the twentieth century, coupled with developments in agricultural mechanization, was the primary driver of increased "per farmer" productivity of farms. This in turn allowed for a dramatic shift in human population away from rural areas and to the cities. It is difficult to overstate the profound effect that farm energy use has had on society today.

1.2.2 Perform Tasks That Cannot Be Done Otherwise

Refrigeration, heating, data storage and communication are all tasks that intrinsically require energy – often in the form of electricity. The ability to cool, heat, and automatically control farm operations has allowed for unprecedented improvements in farm productivity and product quality. Future improvements to farm productivity may very well come primarily from "smart agriculture" concepts that rely on big data, artificial intelligence, and other data-driven approaches that require energy in order for them to function.

1.2.3 Embodied Energy

There is arguably a third use of energy on the farm, namely to provide resources that could not be created otherwise. Analysts and academics often refer to "embedded" energy, or energy that is utilized to create materials and products that are utilized by farmers. A major example of this is nitrogen fertilizer, which is typically manufactured using an energy-intensive process. Chemical pesticides and herbicides are also often very energy intensive. These embedded energy uses are usually not included when analyzing an individual farm's energy use patterns - instead, they are classified separately. However, embedded energy use is worth considering if one is concerned about the overall impact of the agricultural sector on the global energy system.

Farmers and society in general are increasingly concerned about the impact of energy use on the ecosystem, as many forms of energy tend to result in air, water, and or land pollution. Because of this, significant effort has been made to identify and develop sources of energy that are more benign or can even be beneficial to the physical environment. Often these "gentler" energy sources are renewable, in that they depend on steadily replenished feedstocks of sunlight, wind, biomass, or geothermal energy. Farmers sometimes opt to switch to renewable energy sources for their operations, but usually not unless a cost advantage can be gained.

Farm energy use has another strategic value, in that farms are typically located at the extreme far points of the energy supply network. Thus, conservation and strategic energy use on the farm can have disproportionate benefits on the overall energy supply system.

While cost is a primary consideration when farmers select an energy source, other factors can come into play as well. This includes environmental impact (discussed above), reliability/robustness of supply, stability of prices, and convenience of use. The last factor (convenience) is important in that most farmers do not have excess time or "personal energy" available to devote to the management of their energy supply.

1.3 Energy Use and Resilience

Resilience is defined as the ability to provide acceptable performance in the midst of abnormal events. It is a key factor that contributes to the long-term success of any operation. Farm energy resilience, then, can be defined as the ability of a farm to continue operating in the face of abnormal energy issues. When one considers the critical nature that energy plays in the modern agricultural enterprise, it is clearly important that farms have a high degree of energy resilience, so that they can adapt to unusual variations in energy availability or unexpected changes in energy requirements on the farm. Possible unexpected energy "issues" on the fam can include:

- Loss of service reliability,
- Escalation of prices,
- Changing energy needs, and
- Changing market requirements.

These issues all translate into uncertainty about future operations. This is especially challenging given the dynamic energy environment in which farms operate, including unexpected or uncontrolled variations in climate (temperature, humidity, cloudcover, etc.), changes to technology, variability in the market and economy, changes in regulations, and changes to the body of knowledge available to the farmers.

In spite of this dynamic environment, the mindset and approach to farm energy has usually been static, with farm energy analyses and plans often based on an assumption of steady state farm operations, steady state energy resources, unchanging technology and steady state objectives for the farm. While this approach simplifies one's approach to farm energy, it is not always the most resilient way to address the topic.

Opportunities for a more resilient approach to farm energy do exist, however. Some of the things that can be done include:

- Future projections of performance - this can be a challenging task, since the future is generally quite uncertain. However, by examining current trends in energy availability, pricing, and markets, farms can often position themselves strategically to have a higher likelihood of success.
- Improved energy efficiency – while improved energy efficiency is often justifiable on a current economic basis, it also has the effect of reducing overall energy use, which in turn makes the farm more energy resilient by reducing the impact of energy price or availability fluctuations.
- Energy risk identification and mitigation – HACCP (hazard analysis and critical control points) is a common method used to reduce risk in food processing operations. A similar approach can be used to analyze a farm's energy utilization system to identify potential problems before they happen and develop a plan for preventing those potential problems from becoming actual problems.
- Design for "Soft" failure – Farm facilities that are less susceptible to catastrophic disaster when energy supplies are interrupted will be notably more resilient than those that rely on unchanging, uninterrupted energy systems. An example of low resilience would be poultry broiler houses that rely on fan-driven ventilation to cool the houses. Even a short interruption of power can result in sufficient buildup of heat in these densely occupied structures such that the birds expire from heat stress. A more resilient design would, for example, include retractable side walls that automatically open in the case of a power interruption. Design for soft failure generally adds cost to a facility, and so the benefit of this greater resilience must be weighed against those higher costs.
- Consider non-monetary as well as monetary performance – Analyzing a farm's energy system on a cost-only basis may not capture the full impact of resilience. For example, the impact of energy-based disruptions on customer loyalty, employee satisfaction, or owner stress is not easy to translate into a traditional balance sheet analysis. However, they are real impacts that can make the difference between long term success and failure of a farm.

Currently, there are not standardized practices for analyzing and optimizing farm energy resilience. However, the process generally begins with identifying energy risks for the farm, establishing projections of energy needs, availability, and costs, developing strategies for mitigating risks, and finally carrying out a cos/benefit analysis.

1.4 Current Status in the Region

The agriculture sector in the Northeast US[1] is extremely diverse. Thus, it is no surprise that farm energy use in the region is likewise varied. The predominance of "plain sect" farm communities (i.e. "Amish") adds an additional unique characteristic in that many of those farmers have restricted themselves as to the types of energy they use. This makes it very difficult to draw general conclusions about farm energy use. However, some salient points can be made when considering the various sectors of agriculture in the region. Energy use for farms is generally classified as being either "Field Operations" (i.e. plowing, harvesting, irrigation) or "Headquarters" (i.e. Barn, Storage Equipment, Manure Handling).

1.4.1 Energy Costs

The cost of energy, on a per-unit-basis, varies depending on the type of energy as well as location. Table 1.1 shows average energy costs in various states in the region for common fuels used by farms.

Since different forms of energy are sold by different units of measure, it is often useful to convert them to a "cost per gigajoule" basis so that they can be compared on a more equal footing.

$$C_{UG} = C_T * G_T * E \tag{1.1}$$

where

C_{UG} = Cost per useful gigajoule of energy ($/GJ)
C_T = Cost per typical unit of sale ($/gallon, $/kWh, $/cord, etc.)
G_T = Number of gigajoules in that fuel, per typical unit of sale (GJ/gallon, GJ/kWh, GJ/cord, etc.)
E = Efficiency with which fuel is used (decimil)

These equivalent costs, averaged for the entire region, are shown in Fig. 1.1.

Electricity is often the most expensive form of useful energy available to farms in the region, but is also the most readily available and the most useful. It can be readily utilized to provide heat, cooling, data manipulation and storage, and operate motors to perform a variety of tasks. Cordwood is often the least expensive form of energy, but it is generally only useful for providing heat, and the amount of labor usually needed to use the fuel (stacking, stoking, etc.) is not trivial. Natural Gas is typically the least expensive form of fossil fuel energy, but its usefulness is generally limited to providing heat, and natural gas is very limited in terms of its

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[1] For the purposes of this document, a broad-ranging definition is used for the term "Northeast United States, including states from Virginia northward, and as far west as the Mississippi River.

Table 1.1 Energy costs by state

	Electricity	Propane	Heating oil	Natural gas
Connecticut	$ 0.212	$ 2.59	$ 2.74	$ 15.78
Delaware	$ 0.125	$ 2.62	$ 3.06	$ 17.39
Illinois	$ 0.128	$ 1.51	$ -	$ 9.70
Indiana	$ 0.123	$ 1.80	$ 2.46	$ 11.38
Kentucky	$ 0.106	$ 2.10	$ 2.36	$ 14.58
Maine	$ 0.168	$ 2.47	$ 2.54	$ 16.44
Maryland	$ 0.133	$ 2.64	$ 3.16	$ 14.34
Massachusetts	$ 0.216	$ 2.75	$ 2.73	$ 14.17
Michigan	$ 0.155	$ 1.70	$ 2.29	$ 9.45
New Hampshire	$ 0.197	$ 2.84	$ 2.71	$ 14.59
New Jersey	$ 0.154	$ 2.87	$ 2.96	$ 10.39
New York	$ 0.185	$ 2.51	$ 2.98	$ 13.44
Ohio	$ 0.126	$ 2.01	$ 2.34	$ 11.46
Pennsylvania	$ 0.139	$ 2.18	$ 2.70	$ 13.02
Rhode Island	$ 0.206	$ 3.10	$ 2.90	$ 15.45
Vermont	$ 0.180	$ 2.78	$ 2.60	$ 14.28
Virginia	$ 0.117	$ 2.66	$ 2.71	$ 13.74
West Virginia	$ 0.112	$ -	$ -	$ 11.60
Wisconsin	$ 0.140	$ 1.47	$ 2.23	$ 8.58
Region Average	$ 0.154	$ 2.24	$ 2.39	$ 13.15
USA Average	$ 0.129	$ 1.95	$ 2.79	$ 11.99
Data Year	2018	2020	2020	2020
Units	cents/kWh	$/gallon	$/gallon	$/kcf

Source: EIA (2020)
Electricity and Natural Gas prices are based on average residential rate

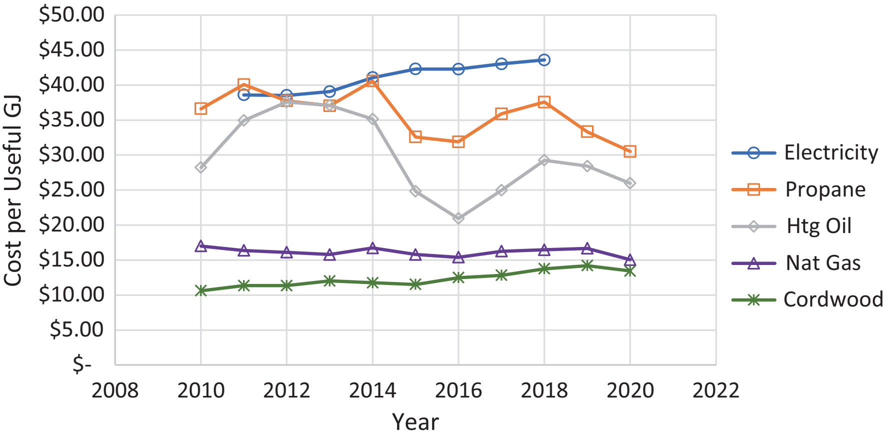

Fig. 1.1 Equivalent energy costs for northeast United States (EIA 2020; Ciolkosz 2021)

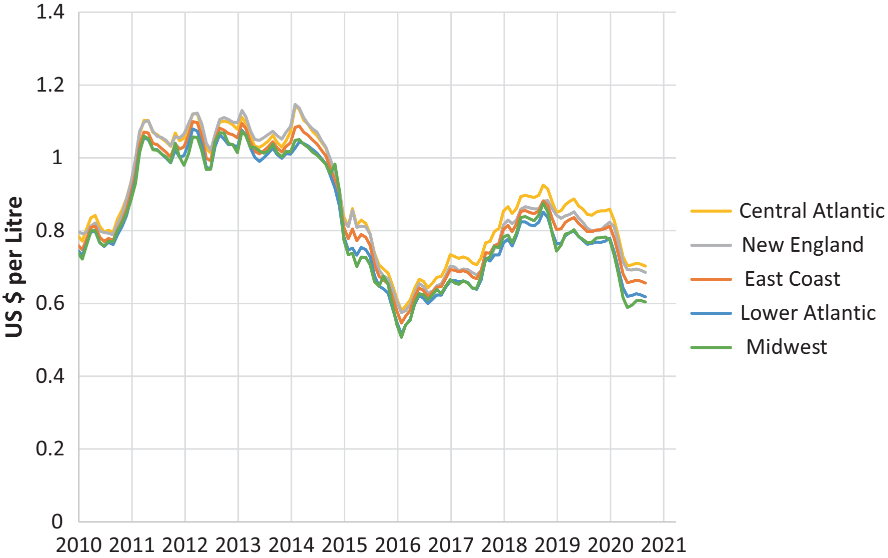

Fig. 1.2 Cost of diesel fuel ($ per gallon) in regions of the northeast United States (EIA 2020)

availability to farms in the region. A notable exception is those farms in areas such as Western PA and Eastern Ohio where natural gas wells may be located directly on farms, providing readily available and low cost gas fuel. Propane and heating oil tend to be available at a cost in-between that of electricity and that of natural gas.

Diesel fuel is the most common fuel for tractors and other field equipment. Its price over time, for areas in the Northeast US, is shown in Fig. 1.2.

Diesel fuel costs can be fairly erratic, impacting the economics of field operations significantly. While costs vary somewhat across the region, they tend to track similarly over time, and correlate fairly well to the commodity price of crude oil over time.

1.4.2 Energy Expenditures

Total farm expenditures for energy are summarized in Table 1.2 on a per-state basis.

On average, farm energy expenses are less than 10% of total expenses for farms in the region. However, this total can vary, with some farm types being much more energy intensive than others. If we make some very general approximations about energy expenditure data and equivalence of energy use to human labor[2], we can

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[2] Gas Fuel Oil expenses are estimated to roughly consist of 5.2 kWh of useful energy per dollar, and 2/3 of utility costs are for electrical energy at a rate of 5.3 kWh of useful energy per dollar. One

Table 1.2 Farm energy expenses by state

	Gas, fuel, oil		Utilities	
State	Per Farm	Pct of Tot	Per Farm	Pct of tot
CT	$ 5061	4.98	$ 2937	2.89
DE	$ 8702	2.31	$ 9329	2.48
IL	$ 8039	4.37	$ 3124	1.7
IN	$ 6523	4.05	$ 3215	2
KY	$ 2970	4.8	$ 1700	2.75
MA	$ 3348	4.92	$ 3176	4.67
MD	$ 5822	3.68	$ 4521	2.85
ME	$ 4763	6.17	$ 3417	4.43
MI	$ 6580	4.35	$ 4000	2.64
NH	$ 2467	4.83	$ 1948	3.81
NJ	$ 5179	5.03	$ 3359	3.26
NY	$ 7130	5.51	$ 3796	2.93
OH	$ 4239	4.21	$ 2360	2.34
PA	$ 4662	4.16	$ 3632	3.24
RI	$ 2989	5.3	$ 2167	3.84
VA	$ 3589	4.52	$ 1847	2.33
VT	$ 5142	5.37	$ 3781	3.95
WI	$ 6567	4.41	$ 4210	2.83
WV	$ 1635	5.75	$ 894	3.15
AVE	$ 5022	4.67	$ 3338	3.06

Source: USDA (2019)
Note: "Utilities" includes electricity, phone, and water and as such includes more than just energy cost

estimate that each farm in the region uses energy that is equivalent to about 76 laborers. This estimate, while based on a variety of assumptions and estimates, illustrates the dramatic importance of energy utilization not only to the success of farming, but also its impact on the fabric of society, with its mostly urbanized population being supplied food by a relatively small rural population.

Sector-specific energy utilization data are not collected by the US Ag Census, but representative energy utilization information can be summarized from various energy audit programs that are run by public and private organizations in most states. The following sections provide a discussion of energy issues and trends for the major agricultural sectors in the region. Energy utilization is reported in terms of an "Energy Utilization Index", which normalizes energy use against productivity of the farm. EUI values used in this analysis are summarized in Table 1.3.

EUI values are a composite of all primary energy used on the farm, converted to units of kWh then divided by farm productivity. Thus, for example, diesel fuel used in field crop production would be converted to units of kWh based on the energy

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full time laborer provides work at a rate of 2 kWh of useful work per day, or 500 kWh per year. These values are approximate, and are meant to only be of a representative and illustrative nature.

Table 1.3 Energy utilization indices for different Ag sectors

Ag sector	EUI units of measure
Dairy	kWh per milking cow per year
Poultry: broilers	kWh per broiler
Poultry: layers	kWh per layer per year
Beef	kWh per animal capacity per year
Swine	kWh per animal capacity per year
Greenhouse	kWh per square meter of heated greenhouse per year
Grain Drying	kWh per bushel of grain dried
Field Crops	kWh per productive acre per year
Tree Fruit	kWh per bushel

content of the fuel. These EUI values do not take into account variations in farm design or management. Thus, values can vary widely if, for example, seasonal production is employed on some farms and year-round production on others. The EUI values also do not take into account energy used outside the farm gate, such as for transportation of goods to market. Thirdly, EUI values do not take into consideration the efficiency with which the energy is used. Thus, farms, can reduce their EUI value by improving the efficiency of the energy-using equipment that they operate. However, they do provide a reasonable comparator that allows farmers to assess the status of their individual farm's energy efficiency relative to other farms in that sector.

In summary, farm energy use averages less than 10% of total expenditures in the region. While this may not seem large enough to justify attention from farmers, the low margins of agriculture and strategic nature of agricultural energy loads make farm energy utilization an important topic. Furthermore, energy utilization varies widely from farm to farm, indicating that not only are low efficiency farms spending a larger portion of their budgets on energy, but they could likely reduce their energy use (and costs) dramatically through careful energy use planning.

However, the diverse nature of the agricultural sector in this region precludes the widespread adoption of "one size fits all" assumptions about farm energy utilization, and each ag sector has unique energy needs and opportunities.

1.4.3 Energy Sources

A wide variety of energy sources are used on farms in the region, depending on local availability and other regional characteristics. Some of the more common energy sources used on the farm include the following:

Electricity Electricity is almost universally available on farms, although it is usually limited to single phase 120/240 V service. Larger farms will sometimes be eligible for three phase service. Depending on the farm's location, electrical service may be provided either by a regulated public utility company or a rural electricity cooperative. Rate schedules and rules for farm customers vary widely depending on the service provider, and may include provisions for selection of a specific electricity provider (i.e. a "deregulated" system).

Natural Gas Natural gas, however, is not commonly available on farms in the region, as distribution networks are generally limited to urban areas. However some farms that are located in gas-producing regions may have a gas well on site that provides natural gas for use by the farm. Also, some farms with large heat requirements (i.e. greenhouses) may choose to locate their operations in proximity to a natural gas line, to allow them to take advantage of the (usually) attractive pricing of this energy source.

Propane and/or Fuel Oil Propane (and to a lesser extent, #2 fuel oil) is the more common fuel for applications that might otherwise use natural gas, and is delivered to farms via road transportation and stored on site in tanks. Liquid fuel for field operations (i.e. diesel fuel, gasoline) is also typically delivered by truck, and stored on site in bulk tanks.

Biomass Biomass, in the form of cordwood or wood chips, is widely available throughout the region, and often represents an "opportunity fuel" for farmers, in which they can obtain very affordable prices from local processers. Many farms have woodlots that are used to supply heat for the farmstead. Some also utilize their woodlot to meet needs for space heat and/or process heat in the farming operation. Biomass can also be grown agronomically on the farm, such as when waste corn is used in stoves or furnaces to provide heat. Wood pellets are widely available throughout the region and can be purchased and stored in bulk for use in boilers or furnaces on the farm.

1.4.4 Energy Use Patterns

Energy use by farms can often be characterized in terms of repeatable patterns of use, which in turn can provide insights into the manner in which energy is used as well as the opportunities for improving the farm's energy management. These patterns often take the form of a base load, temperature dependent loads, production dependent loads, and time-dependent loads.

Base Load The base load is the amount of energy utilized regularly, on a daily basis regardless of other factors on the farm. An example of this is the energy needed to heat water for washing milking equipment. Since washing must take place every day and uses the same amount of hot water each day, the energy needed for the hot water will be the same on every day.

Temperature Dependent Load Temperature dependent loads are those energy requirements that rise or fall as the outdoor temperature varies. The classic example of a temperature dependent load on a farm is for ventilation fans, since the fans will operate more when temperatures rise, and will operate less when temperatures drop. Figure 1.3 shows a graph of daily energy use on a farm as a function of outdoor air temperature, illustrating both the base load and the temperature dependent load for the farm. The temperature dependent load in this case is likely due to ventilation fans in the barn, and occurs as outdoor temperatures rise above about 55 °F (13 °C). The base load, of about 360 kWh per day corresponds to lighting, manure handling, milk cooling, and other loads that occur every day regardless of outdoor temperature. Note that there is some scatter of data points in the temperature-dependent load profile, indicating that other factors also impact daily electricity use on the farm. Figure 1.4 shows the heating fuel usage (gallons per day) on a poultry farm. In this case, no heating fuel is used at outdoor air temperatures above about 52 °F (11 °C), but increases in a linear fashion as outdoor temperature drops below that point. The relationship shows very little scatter, indicating that fuel use in this case is exclusively a function of outdoor air temperature.

Production Dependent Load Production dependent loads are those energy needs that vary as a function of the amount that is being produced on the farm. Fuel use for field operations is a good example of a production dependent load, as the amount of fuel needed will be proportional to the tonnage of crop that is being produced. Milk refrigeration load also tends to be production-dependent, with energy use proportional to the amount of milk that is cooled.

Time Dependent Load Time dependent loads are those that vary over time. Depending on the farm operation, these loads can vary over the course of a day (i.e. milking center energy use is higher during milking sessions than between sessions), over the course of a week (i.e. farm chores that are carried out by salaried employees Monday through Friday, but not on weekends), or seasonally (i.e. fuel use for hay production, which occurs at intervals during the growing season).

The nature of a farm's energy use patterns can be assessed by analyzing the energy use records of the farm, along with temperature, production, and related data for that facility. Graphs such as that shown in Fig. 1.3 can be generated for a farm, with best-fit trend lines used to estimate the average performance of the facility. Furthermore, the trendlines can be used in conjunction with "typical meteorological year" weather data for that location to estimate the average energy use for the farm. However, some energy loads will have multiple dependencies, such as a combined temperature- and production-dependent characteristics. An example of this would be refrigeration of fruit and vegetable crops. The refrigeration load is proportional to the amount of crop being stored, but it is also affected by outdoor temperature since refrigeration efficiency improves as outdoor temperatures drop. Furthermore, farm operations have a tendency to change over time, so that farm energy use data from recent years may not be indicative of future performance. Lastly, many farms

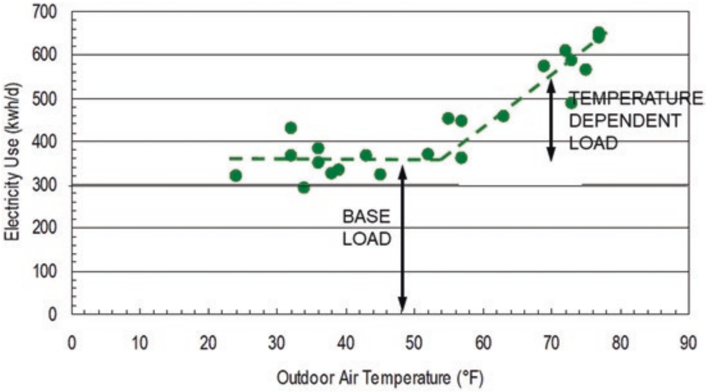

Fig. 1.3 Dairy farm typical daily energy use vs. outdoor temperature

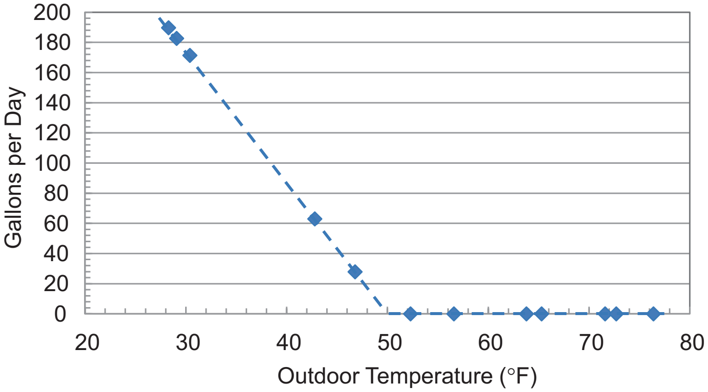

Fig. 1.4 Poultry farm typical daily energy use vs. outdoor temperature

are served by a single energy supply that is used both for the farm business and for the farmstead home, and it is not always easy to separate farm energy use from domestic utilization. Thus, it can often be a challenge to determine the magnitude of each effect from analysis of a farm's energy use records, and submetering may be needed to gain a clearer picture of energy use trends.

Example: Energy Use Estimation

Based on the energy use trends shown in Fig. 1.3, estimate the daily energy use by the farm during a week in which the daily average temperatures are 48 °F, 53 °F, 72 °F, 74 °F, 67 °F, 64 °F, and 51 °F.

First, we need to determine the best fit line for the energy use as a function of outdoor temperature. In looking at the graph, we can see that when average outdoor temperature is 53 °F or below, energy use is a steady 359 kWh d^{-1}. At temperatures above 53 °F, energy use follows a linear trend according to the following equation:

$$E = -300 + 12.24 * T$$

where

E = *daily energy use (kWh)*
T = *outdoor air temperature (°F)*

With this information, the expected energy use over the course of the week can then be calculated as follows:

Day 1: E =	359 kWh (temperature is 53° or below)
Day 2: E =	359 kWh (temperature is 53° or below)
Day 3: E = −300 + 12.24 × 72 =	581.3 kWh
Day 4: E = −300 + 12.24 × 74 =	605.8 kWh
Day 5: E = −300 + 12.24 × 67 =	520.1 kWh
Day 6: E = −300 + 12.24 × 64 =	483.4 kWh
Day 7: E =	359 kWh (temperature is 53° or below)
Average: E =	466.8 kWh d^{-1}

1.5 Outlook for Future

Farm energy utilization promises to remain diverse in the coming years, with each agricultural sector and each farm having unique energy needs and utilization patterns. A long term trend of improved efficiency is likely, given the ongoing incentives and programs available to farmers for upgrading inefficient equipment, as well as the likelihood that older, less efficient operations will be slowly replaced with newer, more efficient facilities. Increased automation could lead to increases in energy use in some cases, and improvements in efficiency in other situations. Regardless, the "resource rich, cash poor" nature of the agricultural sector dictates that changes will be gradual and follow a risk-averse strategy.

As agricultural operations consolidate and expand to become more competitive and spread fixed cost through economies of size/scale, there is a point when energy cost indices may increase rather than continue a decreasing trend as you expand operations. This has been observed in Michigan dairy farms with herds over 450 cows and milk 3x a day who have a higher energy cost per cwt of milk produced compared to smaller herds. When milking operations continue round-the-clock milking, lights, ventilation, refrigeration systems and machinery are often running non-stop,

As greenhouses expand into longer growing periods or diversify into retail activities, their energy cost per square foot will go up which makes energy expenditures an even more significant management factor.

The increase of energy consumption in agricultural operations is also fueled by farmers' desire to reduce operational risk as they face more erratic and changing weather patterns. Installation of grain dryers and irrigation systems have steadily increased in recent years and despite the economic stress currently faced by the region's farmers, this trend continues. The consequence of this is stressing energy supplies that will prevent further expansion of activities unless the energy infrastructures are upgraded and expanded in rural areas.

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Chapter 2
Energy Efficiency – Smart Metering

Edward Johnstonbaugh and Xinlei Wang

2.1 Introduction to Topic

In the United States, the 100-year-old electric grid has been getting an upgrade for modernization with new technology – SMART grid. The smart grid allows for a more efficient and reliable electricity distribution system, includes system communications between different pieces of the grid and the control centers, multiple supply sources of electricity to a given point, isolation of faulty equipment along the grid, and automatic reset switches along the grid to aid in power outages. This upgrade allows renewable energy sources, such as wind and solar energy, to be added to the grid and ensures backup electricity sources in case of a storm or emergency situation. The smart grid will reduce energy costs, enable demand-side management and cut carbon footprint.

Smart meters are critical components of the smart grid that are visible to the residential and business customers. In order to measure electricity usage in every home or business unit, utilities have long used old analog meter or an earlier version of a digital meter. These devices record the amount of energy consumed in each home so the utility company can provide billing for its customers. In order to get accurate consumption information, the utility company must send meter readers to your house or building to confirm your energy usage each month.

Smart meters are very similar to the traditional meter in that they measure and record energy consumption data. But these smart meters are able to record more frequent energy usage and communicate remotely with the power company every

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15 minutes to one hour. This means that meter readers no longer need to come to your home or building to record your electricity usage. Smart meters are also able to alert the power company automatically if there's a power outage in your area. Smart metering data provide utilities with detailed outage information in the event of a storm or other system disruption, helping utilities restore service to customers more quickly and reducing the overall length of electric system outages.

Another big benefit of a smart meter for consumers is the ability to track energy usage. The smart metering provides you with real-time energy consumption data accessible from your computer or smartphone and allows you to keep track of your energy spending. By providing detailed information about consumption patterns, smart meters allow consumers to make informed decisions to alter usage and lower electricity bills. By utilizing this data, you can manage your energy usage smartly and can plan ahead for those times when the rate is high or low based on new time-based rate programs to reduce peak demand and manage energy consumption and costs. Depending on your local electricity rates, energy during peak hours can cost up to four times as much as energy during off-peak hours. In the farming sector, savings of between 5% and 15% are possible with a simple rates optimization structure. You can also forecast what your next bill will look like.

Is there any downside about smart metering? Across the nation there's a lot of controversy surrounding the implementation of smart meters. One issue has been the fact that some smart meters have caught fire. The issue is more likely be caused by faulty meter panels on the home, not the smart meter itself. Millions of smart meters have been deployed throughout the United States and very few have caught fire. Another issue with smart meters is the amount of radiation they emit. Some people claim the meters cause dizziness, memory loss, headaches or even cancer. However, these claims aren't backed by science. Smart meters use the same technology as cellphones, which have relatively low radiation levels, but these advanced meters have a radiation threat that's even lower than a cellphone. Smart meters are typically placed outside the home, in the back or side of the property in places people don't usually hang around. So the risk of exposure to radiation is even lower than cellphones.

2.2 Current Status in the Region

Installations of Advanced Metering Infrastructure (AMI, smart meter) have more than doubled since 2010 (Table 2.1). According to the Federal Energy Regulatory Commission (FERC), there were 86.8 million smart meters operating in 2018, out of 154 million meters in the U.S., giving them a penetration rate of 56.4%. About 88% of the installations were residential customer installations.

Residential smart meter penetration rates vary widely by state. Washington, DC, has the highest AMI penetration rate at 97%, followed by Nevada at 96%. Six other states had a residential AMI penetration rate higher than 80% in 2016: Maine, Georgia, Michigan, Oklahoma, California, and Vermont. In 2016, Texas added the

Table 2.1 Smart meter installations in the U.S

Year	Residential	Commercial	Industrial	Transportation	Total # of Smart meters	Total # of meters
2010	18,369,908	1,904,983	59,567	67	20,334,525	
2011	33,453,548	3,682,159	154,659	7	37,290,373	
2012	38,524,639	4,461,350	179,159	35	43,165,183	
2013	47,321,995	5,770,067	248,515	845	53,341,422	138,070,832
2014	51,710,725	6,563,614	270,683	916	58,545,938	144,268,972
2015	57,107,785	7,324,345	310,889	813	64,743,832	150,813,765
2016	62,360,132	8,119,223	342,766	1,345	70,823,466	151,332,419
2017	69,474,626	9,060,128	365,447	1,389	78,901,590	152,110,274
2018	76,498,388	9,932,993	411,287	1,489	86,844,157	154,068,551

Source: *U.S. Energy Information Administration, Form EIA-861, "Annual Electric Power Industry Report"*

most residential AMI meters of any state, installing smart meters on more than 200,000 customer accounts.

In Illinois, Commonwealth Edison Company (ComEd) provides electric service to more than 4 million customers across northern Illinois, or 70 percent of the state's population. ComEd has begun work to install more than 4 million smart meters at all homes and businesses in the ComEd service territory by 2021.

Differences in smart meter penetration rates are often driven by state legislation and regulation, as some states require that regulators approve utilities' cost recovery mechanisms for metering projects. The Smart Electric Power Alliance publishes reports on state-level actions on advanced metering, among other topics.

2.3 Outlook for Future

New residential smart technologies are allowing consumers the opportunity to better manage their electricity usage. While smart thermostats have been available for several years, they are now joined by smart lightbulbs, smart plugs, smart fire detectors, and more. Many of these devices can be synced and controlled by an app on your smart device. Learning how to take advantage of these technologies can help you better control when and how much energy you consume.

Smart technology can assist in the safety, comfort, and convenience of your home. The Seniors Independent Living Collaborative has information on how senior citizens can take advantage of smart technology to age in place, with applicable information for consumers of all ages.

The rapid development of new technologies for the Internet of Things (IoT) has had a major impact on the smart metering market.

2.4 Conclusions and Summary

In summary, a smart meter provides four key benefits: 1. you have more control over your energy use to help you save money; 2. the utility company can provide better service by automatically sending meter readings, helping eliminate estimated bills and the need for a meter reader to visit your home or building; 3. smart meters allow utilities to better monitor the electric system through demand-side management and demand response to reduce peak loads, remote connect-disconnect option, fraud detection and prevention of outages; 4. It will help utility companies to restore service to customers with quicker response times during outages.

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Chapter 3
Energy Efficiency – Equipment Use and Installation

Scott Sanford and Aluel Go

3.1 Introduction

Energy on the farm is used by a wide variety of equipment to carry out necessary functions. This equipment can be efficient or inefficient, depending on its design, appropriateness for the task at hand, and manner in which it is used. Agricultural Enterprises have many opportunities to increase the energy efficiency of operations. It doesn't have to cost much money. It can be as simple as turning off the lights when not needed, or as costly as purchasing the latest refrigeration technology. There are usually things that all types of agricultural enterprises can do to reduce equipment energy use without compromising product quality or productivity. For example:

- Dairy farmers can install refrigeration heat recovery to pre-heat a portion of their hot water needs,
- Crop farmers can increase the use of minimum or no-till crop production,
- Livestock farms can use energy-free water fountains,
- Potato and onion growers can use variable speed controller on fans so the air flow can be reduced once the crop is cooled,
- Maple syrup producers can use reverse-osmosis units to reduce the amount of boiling required and
- Grain dryers can utilize heat recovery or in-bin cooling to reduce the energy require to dry grain.

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Before discussing sector-specific energy efficiency strategies, it is appropriate to devote some attention to specific equipment types, lighting, refrigeration, motors, heating, and energy recovery, as these technologies apply to most sectors of agricultural operations.

It is valuable to note that energy efficiency is not about making any sacrifices but making educated choices. Energy efficient equipment generally has low management requirements so it shouldn't add to daily workloads if it is implemented effectively.

The economics of installing high efficiency equipment and appropriate sizing can be affected dramatically by the timing of the upgrade. The best time to invest in energy efficiency on an existing farm is usually when a piece of equipment needs to be replaced (worn out, need more capacity, etc.), as the cost of replacement is already a requirement, and the additional cost needed to select a high efficiency device will be only a fraction of the total cost. Investing in energy efficient equipment is also strategically beneficial if done when expanding or remodeling a facility. That being said, sometimes it is not worth it to wait. Lighting is an example of something that is very economical to upgrade because of advances in lighting technology in the last 10 years.

In some cases, there are also secondary benefits from selecting energy efficient equipment such as reducing soil erosion and compaction if using minimum tillage methods for the production of row crops, or reducing labor and equipment costs because of a reduction in the number of operations required to plant a crop. Upgrading a farm's lighting can have secondary benefits in terms of enhanced visibility and improved worker safety in agricultural operations.

There are also indirect benefits of energy efficient equipment such as reduced greenhouse gas emissions (which can help to curb climate change), less particulate matter in the air (which is a benefit to people with asthma), and less haze so you can see your favorite vista or sunsets.

This chapter discusses some of the primary strategies that can be used on farms to improve the efficiency of the equipment that they use to carry out the business of the farm.

3.2 Lighting

Lighting is important on a farm for working safely in the early morning or after sundown, or for doing detailed work indoors. Lighting is also needed to facilitate visual tasks by livestock, and can be used to increase production, modify the behavior of an animal or cause the start of estrus cycles. Controlled Environment plant production relies heavily on daylight and or artificial lighting to provide energy for photosynthesis as well as to regulate flowering and other plant responses. Lighting efficiency for human or animal vision is usually measured in units of "lumens of light output per watt of input electricity". Efficiency for plant production is usually measured in units of "Photosynthetic Photon Flux (PPF) per watt of input electricity". PPF is, in turn, measured in units of "micromoles of photons (400–700nm) per second". Overall efficiency of a lighting system is equal to the efficiency of the light source multiplied by the efficacy of the luminaire (reflector, lens, etc.) and the fraction of the emitted light that reaches the desired target. This in turn should be adjusted by a "light loss factor" to account for reduced performance on account of aging and the accumulation of dirt and dust.

$$E_O = E_S * E_{LO} * CU * LLF \tag{3.1}$$

where

E_O = overall system efficiency (lumens of useful light per input electrical watt)
E_S = efficacy of light source (lumens generated per input electrical watt)
E_{LO} = Luminaire Optical Efficiency (decimil)
CU = Coeffcient of Utilization (fraction of emitted light that reaches the target area)
LLF = Light Loss Factor (fraction of emitted light from old, dirty system relative to when new)

Lighting technologies have advanced significantly in the last 10 to 15 years with the introduction of compact fluorescent lamps (CFL) in the early 2000's to the introduction of Light Emitting Diodes (LED) lamps in the 2010's. LED replacement lamps use about 15% of the energy an incandescent lamp would use but last 25,000 to 50,000 hours versus about 1000 hours. Some LED fixtures are rated for as much as 100,000 hours of life. Today, LED lamps are the most efficient method to use for most lighting applications and their energy efficiency is expected to continue to climb to about 200 lumens per watt versus 15 lumens per watt for an incandescent bulb and 90 lumens per watt for a T-5 fluorescent lamp. Manufacturing and sales of some of the old types of lamps are being discontinued because of the advantages of the LED lamps. Incandescent bulbs, mercury vapor lamps and some types of fluorescent lamps have largely been discontinued. LED lamps also have good color rendering characteristics so colors seen by the human eye are closer to what would be seen using sunlight. Many agricultural buildings are under lit, relative to current recommendations for vision. Replacing conventional lighting with LEDs is often carried out with three objectives in mind: increase light levels, use less electricity and reduce maintenance costs. LEDs are cold hardy, outputting about 10% more light at 0 °F (−18 °C) than at 75 °F (20 °C) which makes them ideal for barns and outdoor lighting. Specialized LED lighting also has the potential to enhance agricultural production with the use of customized spectral output that is especially suitable for animal (i.e. poultry) or plant production (Sanford 2014). Regular cleaning of lighting systems is an important maintenance step that keeps light levels at their optimum in the often dusty and dirty environments that are found on farms. With usually damp, dusty with large electrical motors present being operated that can cause significant voltage drops, commercial grade LEDs are often appropriate,

3.3 Refrigeration

Refrigeration is a critical tool on the farm for maintaining the quality of milk, high value crops and seed material while allowing extended shelf life for fruits and vegetables. The main purpose of refrigeration is to reduce the temperature in a space, and in turn slow bacterial growth, respiration and other chemical reactions that lead to deterioration of the biological material. Agricultural refrigeration is often somewhat unique in that most refrigeration systems create very dry storage conditions, while Ag commodities often require more humid conditions for optimal storage life and quality.

Efficiency of a refrigeration system can vary widely depending on the type of compressor, size of coils, type of defrost system, type of refrigerant, air distribution fans, and manner in which the system is operated. Unfortunately, efficiency ratings are not easily obtained for refrigeration equipment, in part because of the wide range of configurations and uses for a given system. In general, scroll compressors are more efficient than reciprocating compressors, and should be selected when possible. Water cooled compressors are likely more efficient that air cooled compressors as water is a better carrier of heat than air. Chillers are an even more efficient option especially for larger operations given their greater capacity.

Electric heat defrost systems are the most energy intensive, whereas hot gas defrost is more efficient. Systems with smaller distribution fans can benefit significantly by upgrading their fan motors to Electrically Commutated (EC) motors. Regular cleaning of the refrigeration evaporator and condenser coils is critical to maintaining high efficiency operation (Sanford 2004a).

Insulation of the refrigerated space is an important component to any on-farm refrigeration system. Insufficient or poorly installed insulation leads to excess heat gain and increased energy use by the refrigeration system. Existing refrigeration systems should be inspected for old insulation that has lost some of its insulative value, broken or missing weatherstripping around doors, and signs of "thermal bridging" (locations where structural members are providing a low-resistance pathway for heat gain. An Infra-red camera can be very useful for identifying problem spots.

Another opportunity for efficiency improvement is by reducing the internal heat load caused by lighting inside the refrigerated space. Upgrading lighting to higher efficiency (i.e. LED) light sources and addition of occupancy sensors to turn the lights off when not needed will both reduce the heat load to the refrigerated space.

3.4 Motors

Electrical motors are used in many settings on the farm to perform mechanical work. In the Northeast United States, this includes the operation of milk vacuum pumps, irrigation pumps, fans, feeders, manure scrapers, silo unloaders, and manure transfer pumps. Many types of motors are available on the market, classified according to their full rated output (kW or hp), electrical supply (voltage, single phase or three phase), rotational speed, starting torque, and other characteristics. Motors used on the farm are often specially rated “farm duty” motors designed for high starting torque and rough operating conditions. While high efficiency motors are widely available, it is not always possible to obtain motors whose operability rating is compatible with farm use. Also, the additional cost of a high efficiency motor is not always easy to justify if the motor is used for a smaller fraction of the year. Often, the only economical time to upgrade to a high efficiency motor is when the old motor wears out and must be replaced. While three phase motors tend to be more efficient than single phase models, most farms in the region tend to be supplied only by single phase electricity. Most utilities limit the size of electric motors being operated on a single-phase service ranging from 15 to 25 hp. They may increase this size limit if soft start, low torque motors with variable frequency drives are used.

Motors tend to operate most efficiently when at or near their full load. Thus, another efficiency measure is to replace motors that are grossly oversized with a properly sized replacement. Sometimes, depending on the use of the motor, it is possible to connect a variable speed drive (also known as a variable frequency drive) to an oversized motor and reap energy savings (Fig. 3.1). These measures are usually only cost effective if the motor is used a great deal (~6000 hours per year).

Small (fractional horsepower) motors have traditionally been rather inefficient. The recent development of electronically commutated (EC) small motors has resulted in dramatic improvements (up to 40%) in efficiency, and small motors that run for many hours per year can often be a cost effective target for an upgrade. When considering a motor upgrade, it is important to work closely with the motor manufacturer to ensure that the replacement motor is fully compatible with the current system.

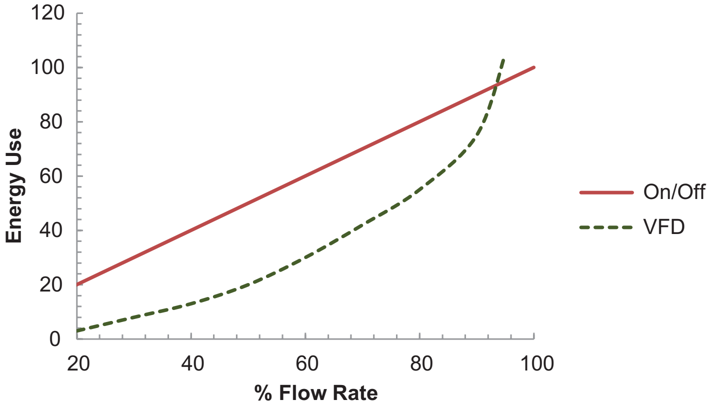

Fig. 3.1 Example of energy impact of on/off control vs. variable frequency drive control for a pump

3.5 Heating

Heating systems are used to provide hot air, water, or steam for a variety of agricultural uses. The efficiency of the boiler or furnace should always be considered when selecting new equipment. Traditional, non-condensing boilers tend to have a maximum efficiency of about 80%. Condensing boilers are becoming more common, and have efficiencies of over 90% (Sanford 2003a). Electrical resistance heating is essentially 100% efficient, but the cost of electricity is often much higher than that of other fuels. Heat pumps can be used to heat air or water, and have an effective efficiency that can be 2–4 times that of electrical resistance heating. The most common heating needs on the farm are for heating wash water or for heating barns or greenhouses during cold, winter conditions (Sanford 2004c). In the Northeast and Midwest United States, greenhouses are especially reliant on space heating in winter, and it is not uncommon for 75% of all greenhouse energy use to be devoted to space heating.

Common strategies for improving the energy efficiency of heating equipment include upgrading to higher efficiency devices, or reducing heat losses through improved insulation and reducing air infiltration as well as incorporating heat recovery systems. Regular maintenance and testing especially with older boilers can also improve efficiency. As with other equipment, heating equipment tends to operate at its most efficient when at or near its maximum rated output. Thus, it may be worthwhile to use multiple boilers to meet a facility’s heat load, and stage their operation so that individual boilers are running at capacity for a larger portion of the time. Improved heating controls can also improve energy efficiency of heating equipment by more precisely controlling temperatures, anticipating increases or drops in heating load, and allowing for advanced control strategies such as nighttime setback or reduction of temperatures when the system is not in use.

AFUE (Annual Fuel Utilization Efficiency is the “Ratio of heat output of the furnace or boiler compared to the total energy consumed by a furnace or boiler.” (U.S. Dept. of Energy). AFUE of 90% means that 90% of the energy of the fuel becomes heat for the facility and the other 10% escapes up the chimney or elsewhere. It does not include heating loss from system, age of boiler/system, fuel cost or equipment features.

There are numerous manufacturers producing high-efficiency heating and cooling equipment. The table below shows what efficiency levels are recommended for new central equipment and how to find a listing of qualifying systems (Table 3.1).

3.6 Energy Recovery

Agricultural equipment, such as engines, motors, coolers, refrigerators, heaters and boilers, all generate heat as a byproduct of their operation. When practical, efforts should be made to recapture that heat and put it to use. This can take the form of a

Table 3.1 Target heating system efficiency recommendations

	Gas furnace (AFUE)	Oil furnace (AFUE)	Gas boiler (AFUE)	Oil boiler (AFUE)	Air source heat pump (HSPF)	Ground source heat pump (COP)
Market range available	78–96%	78–95%	80–99%	80–90%	7.7–10	2.5–3.2
ENERGY STAR	90%	83%	85%	85%	Split system: 8.2 Single package unit: 8.0	Open loop: 3.6 Closed loop: 3.3 DX: 3.5
CEE Tier 2	92%	N/A			8.5	N/A
CEE Tier 3	94%				N/A	

Note: 1) If you live in a *mild climate* for heating, purchase products at the ENERGY STAR level; 2) If you are looking to buy a gas furnace or heat pump and live in a *cold climate*, purchase the highest *Consortium for Energy Efficiency (CEE) Tier* that is economically feasible. These tiers are determined by the Consortium for Energy Efficiency (CEE)

sophisticated condenser heat recovery system, or something as simple as blowing warm air from the equipment room into an adjacent work space during the cold winter months. Energy recovery can often be one of the most cost effective strategies for improving farm energy efficiency.

Utilization of energy recovery can also occur in the opposite direction, namely by utilizing a cold mass (usually well water) to remove unwanted heat, and in so doing to reduce the energy required for refrigeration. This is most commonly employed in the region in the form of well water precooling of milk, but could be applied to other scenarios as well (Sanford 2003b).

3.7 Conclusions and Summary

There are many things that can be done to reduce the equipment-related energy inputs for the production of food and fiber. Sometimes it may require an investment in new technology and sometimes it just involves changing a setting or modifying a habit. There is something that practically every agricultural enterprise can do to save energy which will have a positive return on investment no matter where energy prices are.

In the region, upgrading lighting systems to high efficiency LED lamps is a clear opportunity for farms. In fact, without even analyzing a farm’s operations it is probably safe to tell them “If you haven’t invested in LED lamps, do it today!” They have a bright future, they will pay for themselves in the energy savings in a few years, have lower maintenance costs and provide better light quality.

New energy efficient technologies for agriculture tend to come in small steps. LED lighting is a recent technology step. It is likely that LED technology will mature over the next 5 to 10 years resulting in lamps that are twice as efficient as the ones of just 5 years ago with lifetimes 2 to 50 times longer.

Other future trends in equipment energy use in the region are likely to be slow and steady, as older equipment reaches the end of its useful life and is replaced by more efficient models.

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Chapter 4
Energy for Field Operations

Scott Sanford and Aluel Go

4.1 Introduction

Common field crops in the northeast quadrant of the United States include soybean, corn (maize), and wheat, as well as pasture and hay. Energy use in crop production will depend on the farm's cultural strategy (conventional, no-till, organic) as many energy intensive field operations (i.e. plowing, cultivation, mechanical weed suppression) can be exchanged for chemically intensive activities (i.e. "no-till" farming practices). Row crops are often grown in rotation with other crops. The crop rotation can have an effect on the indirect energy needed to grow a crop in the form of fertilizer and chemicals (i.e. pesticides, herbicides, fungicides). For crops such as corn, fertilizer is the largest indirect energy input in the form of natural gas used to make nitrogen fertilizer. If a legume crop such as soybeans or alfalfa is grown before corn, the amount of nitrogen fertilizer can be reduced and sometimes eliminated.

Direct energy use in field operations is dominated by tractor and harvester fuel use during field preparation, planting, crop maintenance and harvest. Typical fuel requirements have been estimated for many field operations, but actual fuel usage can vary depending on engine efficiency, equipment type, field topography, soil conditions and other factors.

This chapter examines several strategies that can be used to reduce energy use during field operations, and reflects on the current status and trends of field operation energy use in the northeast portion of the United States. The strategies

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discussed include Tractor and Implement Selection, Reduced Tillage, Gear and Throttle Optimization, Tillage Depth Management, and Tractor Maintenance.

4.2 Tractor and Implement Selection

Not all farm equipment is equal when it comes to energy use. Thus, by carefully selecting equipment with higher efficiency (but not sacrificing performance), farmers can reduce their overall energy use (and costs) during field operations. Efficiency data for tractors and harvesters are maintained by the Nebraska Tractor Test Laboratory, including data on fuel use vs. engine load. This information is invaluable for comparing different machines for their energy efficiency. As an example, Fig. 4.1 shows data for two tractors. While Tractor 1 has a higher maximum power output, Tractor 2 uses less fuel. This is illustrative of the principle that the smallest tractor that is able to do the job is usually the most efficient. This is essentially because the smaller tractor will need to use less energy to move its own weight around, and can thus use a higher proportion of its output to carry out the actual field operation. This principle carries over to most equipment, in that equipment that is operating at or near its capacity is usually more efficient than lightly loaded equipment.

Farm implements also vary widely in their energy requirements. Power use is usually expressed in units of Horsepower (hp) at the tractor PTO or drawbar, where

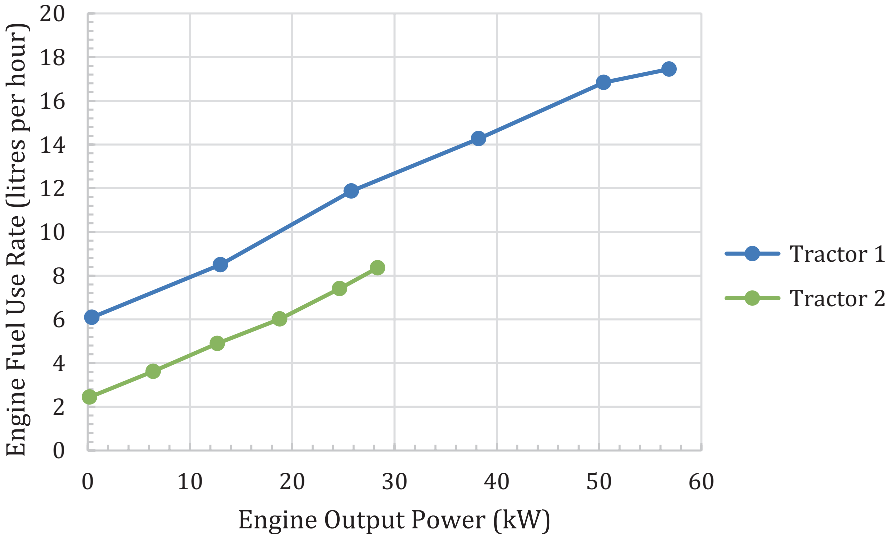

Fig. 4.1 Example tractor efficiency data for two tractors

1 hp. = 0.746 kW. Different designs of implements can have widely varying power requirements. For example, among the many different styles of mower (i.e. Sickle Bar, Rotary, Flail, Drum, Disc), power requirements can vary from less than 20 hp. to more than 100 hp. However, the speed at which it can be operated must also be taken into account when estimating energy use.

Total energy use by the implement can then be calculated as:

$$E = 0.746 * P / R \tag{4.1}$$

where

E = Energy use by implement (kWh per acre or kWh per hectare)
P = Power requirement by implement (hp)
R = Rate at which implement is drawn over the field (acres per hr. or hectares per hr)

While selecting the tractor and implement that use the least energy is generally the best strategy, additional factors such as equipment performance, ease of use and maintenance requirements should be factored into the overall equipment selection process.

Example: Tractor Fuel Use

A farmer owns the two tractors shown in Fig. 4.1 as well as a hay mower that requires 26 hp. of power to operate, and can safely mow the field at an average of 1.6 ha (3.9 acres) per hour using the larger tractor (Tractor 1), but only 1.3 ha (3.2 acres) per hour using the smaller tractor (Tractor 2), owing to stability issues while traveling over the field and turning at the ends of rows. Estimate the energy and fuel use when mowing a 17 hectare (42 acre) field. Which tractor is more fuel efficient for this operation?

(A) Energy Use by Implement
Using Eq. 4.1, energy use per hectare can be calculated as follows:

E = 0.746 kW/hp. * 26 hp. / 1.3 ha/hr.
E = 14.92 kWh per hectare

Multiplying by field size gives total energy use for the operation:

14.92 * 17 = 253.64 kWh total

(B) Fuel Use by Tractor
First, the power requirement of the implement must be converted from units of horsepower (hp) to kilowatts (kW):

26 hp. * 0.746 kW/hp. = 19.396 kW

Next, the time spent mowing the field can be calculated using the information given above:

Tractor 1: 17 ha / 1.6 ha/hr. = 10.62 hr.
Tractor 2: 17 ha / 1.3 ha/hr. = 13.08 hr.

Thirdly, Fig. 4.1 can be used to determine the rate of fuel use for the two tractors at the engine calculated output power of 19.396 kW:

Tractor 1: Fuel use rate = 10.1 litres/hr.
Tractor 2: Fuel use rate = 6.1 litres/hr.

Finally, fuel use can be estimated by multiplying fuel use rate by the time spent mowing:

Tractor 1 Fuel Use = 10.1 * 10.62 = 107.3 litres fuel
Tractor 2 Fuel Use = 6.1 * 13.08 = 79.8 litres fuel

So, Tractor 2 uses 107.3–79.8 = 27.5 litres less fuel to mow the field, which is an energy use reduction of 26%. However, note that this savings comes at a cost of increased time in the field (about 2.5 hours), which must also be taken into consideration.

4.3 Reduced Tillage

One strategy to reduce energy use during field operations is to reduce the amount and intensity of tillage operations (Table 4.1). Traditionally, soil has been tilled to create a seedbed suitable for germination, loosen compact soil layers, control weeds, insects and pathogens, incorporate crop and manure residues and facilitate water infiltration. However, there are disadvantages to tillage, including increased soil erosion from both rain and wind as well as soil compaction. Soil erosion, in turn, can result in loss of nutrients into surface water leading to algae blooms, fish kills and weed choked un-navigable waters. Reducing the proportion of the landscape that is tilled will reduce the erosion potential. Modern planting systems can create micro tillage zones and precisely place a seed in the zone while achieving high germination rates. These systems are referred to as conservation tillage or No-till systems. No-till does not mean, “Never Till”, but only till when necessary. It may be possible to only till once every 5 to 10 years to incorporate nutrients that are not water soluble. Reducing or eliminating some tillage operations saves time, reduces labor and equipment costs, conserves soil moisture, reduce soil compaction and saves energy. No-till systems can reduce fuel costs by about half compared to a conventional tillage production system. There are several types of reduced tillage systems, including no-till, strip tillage and ridge tillage. No-till only disturbs a narrow band (about 3/4 to 2 inches wide) where the seeds are planted and leaves 70% of the soil covered with crop residue (Simmons 2009) (Fig. 4.2).

Table 4.1 Typical fuel use for field operations

Field preparation – primary tillage		Field preparation – secondary tillage	
Moldboard plow	1.87 gpa	Disc	0.65
Chisel plow	1.09	Field cultivator	0.68
Offset discs	0.97	Spring tooth harrow	0.48
Subsoiler	1.56		
Planting		Crop maintenance	
Row crop planter	0.54	Pesticide spraying	0.13
Grain seeder	0.33	Spreading fertilizer	0.19
No-till seeder	0.43	Cultivator	0.42
Broadcast seeder	0.15	Rotary hoe	0.21
Harvest		Harvest (cont.)	
Small grain or bean combine	1.01	Mower/conditioner	0.66
Corn combine	1.37	Rake	0.24
Potato harvester	1.73	Baler (sm square)	0.69
Forage harvester/green chop	1.87	Baler (round)	0.80

Source: Helsel (2007)
Notes: diesel fuel use, average value shown, “gpa” = gallons of fuel per acre tilled

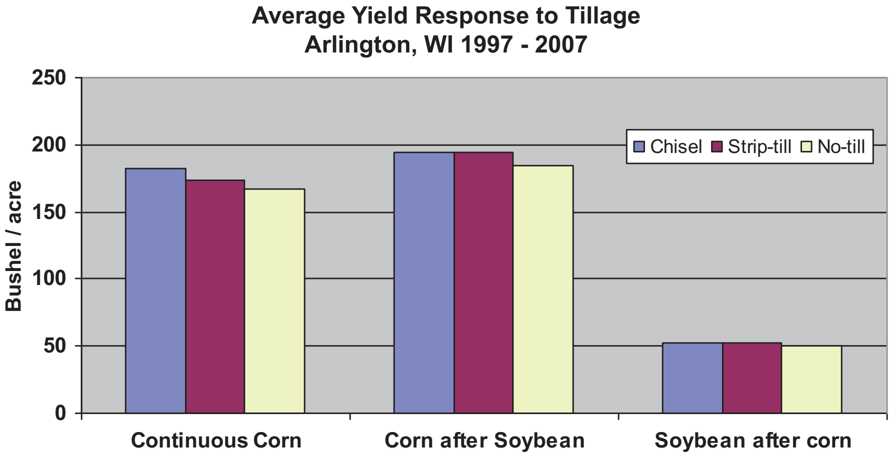

Fig. 4.2 Yield response to tillage (Wolkowski 2009)

Strip-tillage is a second method that is typically preferred on heavier poorer drained soils. It is a separate operation from planting and is usually done in the fall. One common approach is to incorporate or move crop residue to create a strip about 2 to 3 inches wide. Potassium and Phosphorous fertilizer is typically incorporated with the strip till operation. The advantage of strip tillage over no-till is that crop residue has been removed over the strip allowing the soil to warm faster in the

Table 4.2 Cost of production, COP

Crop/system	1997–2007 Ave yield (Bu)	2007 COP/acre ($/acre)	2007 COP/bushel ($/Bushel)
Continuous corn			
Chisel Plow (CH)	182	–	–
Strip-tillage (ST)	174	−$23.20	−$0.02
No-till (NT)	167	−$25.90	−$0.08
Corn after soybeans			
CH	194	–	–
ST	194	−$23.20	−$0.12
NT	185	−$25.90	−$0.03
Soybeans after corn			
CH	52	–	–
ST	52	−$11.20	−$0.18
NT	50	−$25.90	−$0.26

Source: Wolkowski (2009)

spring. This results in faster germination. However, it requires an additional trip across the field and works best with a Real Time Kinematic (RTK)-directed auto-steering to accurately place the seed in the strip at planting time. Also, reduced tillage operations typically require more chemical herbicides, as the weed-suppression effect of full tillage is no longer available.

Many studies have been done comparing conventional tillage cropping systems to reduced tillage systems. There is usually little to no significant difference in crop yields (Fig. 4.1) but there are significant differences in production costs, as illustrated in Table 4.2 (DeJong-Hughes et al. 2007; ASAE, R2020; Wolkowski 2009). Wolkowski found a $25/acre saving using No-till corn after soybeans, $23/acre savings using Strip tillage, a $25/acre saving using No-till soybeans after corn and $11 savings for strip-tillage compared to fall chisel plowing and spring cultivation before planting. These cost savings are due to reduced primary energy use and labor savings from the reduced tillage operations. Those cost savings are, in turn, offset in part by increased chemical costs, which are due in part to the “embedded” energy used to manufacture the chemicals. Overall, however, the energy impact of reduced tillage operations tends to be positive, and using less tillage to prepare a suitable seedbed saves money, time and reduces soil loss.

4.4 Gear and Throttle Optimization

Typically, farm equipment is designed to be operated when the tractor is running at or near full throttle. If a tractor is oversized relative to the task, energy savings can be realized by using the strategy “shift up and throttle back” When this is done, the maximum power available from the tractor is reduced, but the amount of fuel used

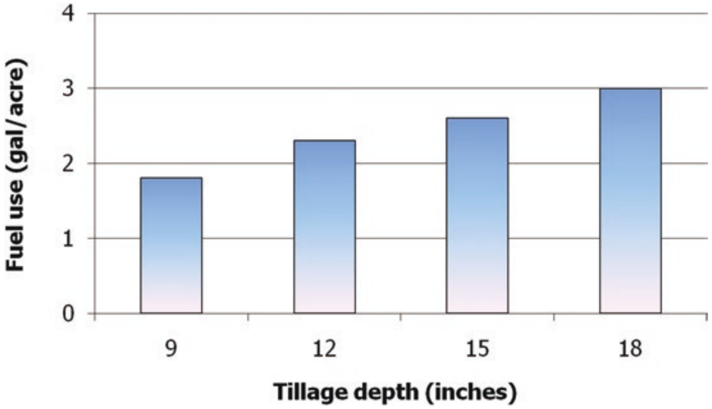

Fig. 4.3 Fuel use versus tillage depth for subsoil tillage (Shinners 1989)

by the tractor drops as well. This strategy was shown to reduce fuel consumption in 18 of 19 comparisons with an average saving of 26% (Hanna 2015). Operations that reduced energy use included planting, disking, field cultivation, stalk chopping, strip tillage and grain drilling.

Note that normal operating speed of a tractor generally corresponds to a PTO speed of 540 rpm. Throttling back the engine reduces PTO speed on most tractors, so it is not suitable for PTO-driven field operations unless the implement is modified to run either on the slower PTO speed or else the implement is provided its own separate shaft power in the form of a “pony” engine. This strategy is only applicable to older, geared transmission tractors, and is not effective on newer tractor designs that utilize Continuously Variable Transmissions (CVTs).

4.5 Tillage Depth

Tillage depth has a direct effect on fuel consumption. The depth of tillage versus fuel consumption were compared for field cultivation and disking and found to reduce energy use by 7–41% using shallower tillage depths. In one study, disking at 4 inch depth (10 cm) instead of 6 inches (15 cm) reduced fuel use by 28% while field cultivating at 3 inches (7.5 cm) instead of 4.5 inches (11 cm) saved 20% in fuel (Hanna 2015). Shinners (1989) found that increasing the tillage depth of subsoiling from 9 inches (23 cm) to 18 (46 cm) inches increased energy use by 60% (Fig. 4.3).

Table 4.3 Ideal range for wheel slippage

Surface type	Slippage range
Untilled soil	6–13%
Tilled soil	8–16%
Soft or sandy soil	12–22%
Concrete	4–8%

4.6 Tractor Maintenance

Tractor setup and maintenance can affect fuel use, and thus this is an important strategy for improving field crop energy efficiency. Common maintenance tasks include engine maintenance, tire selection and pressure optimization, and ballasting.

Engine maintenance can have a significant impact on fuel efficiency, and it is not uncommon for farmers to struggle to have time to carry out this important task. Simple, routine maintenance such as checking for leaks, adjusting carburetors/fuel delivery systems, checking timing and replacing bad plugs have anecdotally improved tractor fuel efficiency by as much as 50%, in some extreme cases.

Tractor tire pressure affects tractive efficiency and wheel slippage, which in turn affects energy use. The correct tire pressure should be determined for the tractor weight and tire size used based on the tractor operator's manual and the tire manufacturer's guidelines. Many manufacturers post tire pressure calculators on their websites. These pressure values may require adjustment based on field conditions and soil types.

If soil conditions are wet or marginal or the operation has higher drawbar pull, dual wheels will improve traction and reduce fuel usage. Hanna (2010) found a 4–12% increase in fuel consumption when single wheels were used (Table 4.3).

Tractor ballasting also has an effect on tractive efficiency and wheel slippage. Too little weight results in excessive wheel slippage and too much weight increases rolling resistance and soil compaction. The ideal amount of wheel slippage will depend on the surface, and general guidelines are given in Table 4.3. Two wheel drive tractors are ballasted differently than front wheel assist or four wheel drive tractors and semi-mount or mounted implements are ballasted differently than a trailing implement. Improper ballasting or inflation pressure of the tires can also cause excessive tire wear (Stombaugh et al. 2008).

4.7 Status and Outlook in the Region

The northeast and midwest portion of the United States is highly variable in its field operations. While the most common crops tend to be Corn, Soybean and Wheat throughout, the size of fields, topography and soil types tend to vary widely. Field equipment can also range widely, from very small, low budget operations that take advantage of niche markets and sweat equity to massive custom-hire equipment that depends on economies of scale to stay competitive. These wide variations in farming operations can often dictate equipment choices in spite of the energy implications. This diversity of operation is likely to continue in the region, although the trend is likely to be for major cash crops to trend towards larger operations while smaller farms gravitate towards specialty crops and markets. Many field crop operations are run as an integrated component of a dairy or other animal ag operation, and thus the needs of the animals will often dictate the crop strategy and related equipment choices. Variability of weather also tends to encourage the selection of oversized equipment, which is less energy efficient but allows farmers to complete their field operations during short windows of suitable weather.

Reduced tillage systems are growing in popularity as well, and are likely to continue to increase their presence in the region, especially on land that is highly erodible. However, the proven yields of full tillage farming, concerns about extensive chemical use, and the built-up knowledge base within the farming community regarding tillage farming are likely to slow the growth of this strategy within the region.

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Chapter 5
Energy for Dairy Farms

Scott Sanford and Aluel Go

5.1 Introduction

Dairy farms have many opportunities for heat recovery and reducing energy use. Milk harvesting operations (vacuum pump, milk pump, water heating and milk cooling) use about 60% of the energy used on a dairy (Table 5.1). The specific breakdown varies from state to state, perhaps due to variations in farm design, prevailing climate and local preferences.

These loads occur on a daily basis and tend to be proportional to the size of the milking system. Apart from the milking operation, energy is also used for lighting, ventilation, and waste management in the barn. Energy use can be reduced in all areas. An energy efficient dairy will use 750 kWh/cow-yr or less (Ludington 2003). Note that the EUI for dairy farms is on a "per cow" basis, with the assumption that associated crop production and heifer production occurs elsewhere or that the energy use for those activities has been subtracted prior to calculating the EUI.

Energy audits of dairy farms shows a wide range of energy use per cow. Based on reports from New York, Pennsylvania, Michigan, Wisconsin and Minnesota dairy farms, the annual energy use per cow ranges from 424 kwh/cow to 3800 kwh/cow. Some of this wide variation can be attributed to factors beyond the farmer's control, such as a low water table that leads to increased pumping requirements or average age of the farm equipment/faciliites. However, much of the variation can be due to the efficiency of the farm's design and operation (Table 5.2).

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Table 5.1 Typical breakdown of dairy farm energy utilization

	Minnesota (Ebinger 2015)	Michigan (Go 2018)	New York (Ludington and Johnston 2003)	Pennsylvania (Calehuff 2014)	Wisconsin (ECW 2005)
Milk vacuum pump	15%	13%	13%	28%	17%
Milk cooling	18%	24%	19%	39%	25%
Water heating	22%	16%	28%	9%	18%
Ventilation	18%	8%	16%	1%	19%
Lighting	13%	15%	18%	8%	15%
Feed motors		3%	2%	9%	
Manure handling		13%	3%	1%	
Misc.	14%	7%	1%	5%	6%

Table 5.2 Dairy energy utilization index values by state (kWh per milking cow per year)

State	Low	High
Pennsylvania	425	3800
New York	424	1736
Minnesota	800	1200
Wisconsin (adapted from Bolton 2009)	700	1177
Michigan	534	875

Energy utilization data are typically not broken down by operation size. EUI data that are broken down by operation size could help operators in making capital investment decisions based on how their operation's energy use compares to other operations of similar size. Van Zweden and Go (2018) analyzed the impact of EUI on herd size in Michigan, with the results showing a steady downward EUI trend as herd size increased and became more energy efficient up to 450 milking cows. At that level and above, EUI increased due to 24-hour continuous milking operations, 7 days a week without any pause or shutting down equipment due to three-a-day and even four-a-day milking for some groups.

Primary opportunities for energy efficiency on a dairy farm, based on recommendations made during energy audits in the region, are centered around the major energy users: vacuum pumps, refrigeration, compressed air, and engine block heaters (i.e. Van Zweden and Go, 2018). Lighting system energy efficiency is also a common opportunity but is discussed separately in Chap. 3.

5.2 Vacuum Pump Energy Efficiency

A vacuum pump is used to facilitate the harvesting of milk from cows but only a portion of the vacuum pump capacity is used the majority of the time. Traditionally, milking systems have achieved stable control of vacuum levels by bleeding air into the vacuum lines whenever vacuum levels exceeded the setpoint. As a result, vacuum pumps would run at 100% full load regardless of the amount of vacuum actually used by the milking equipment. In addition, it is not uncommon to encounter a milking system vacuum pump that is drastically oversized, especially since newer milking equipment tends to require less vacuum capacity to operate (Sanford, 2004b).

Installing a variable speed drive or "VSD" (sometimes called a "variable frequency drive") to sense the vacuum level and control the pump speed can reduce electrical usage by an average of 50% but ranges from 30% to 80%. The vacuum regulation is equal or better than conventionally regulated vacuum systems. Many styles of vacuum pump can be found on dairies in the region – variable speed drives work best if using a blower- or lobe- type vacuum pump. Other styles of vacuum pump may be less effective owing to limits of speed at which they can operate effectively. If a farm is milking 3 times per day or more than 6 hours per day, the investment in the variable speed controller will typically pay for itself in less than 5 years. In the Northeast United States, newer farms typically include VSDs as a standard design feature, but many older farms can still benefit from this upgrade.

Efficiency benefits can also result from regular maintenance of the vacuum system, as poorly maintained pumps will tend to use more energy to provide the same amount of vacuum. Air leaks in the vacuum system are an unnecessary waste of energy as well, and inspections and repair should be carried out regularly.

In the absence of a detailed engineering analysis, Eq. 5.1 can be used to estimate the annual electrical energy savings that can be obtained by adding a variable speed drive to a milking system's vacuum pump (from Ludington et al. 2004):

$$S = \left[C - \left(0.25 * U\right)\right] * 0.9 * H * 365 \tag{5.1}$$

where

S = annual energy savings (kwh per year)
C = capacity of vacuum pump (hp)
U = number of milking units in milking system
H = number of hours of operation per day

As a rule of thumb, milking systems require a vacuum capacity of 35 cfm (59 m^3/h) plus 3 cfm (5 m^3/h) per milking unit and any additional vacuum-activated devices. Pump efficiency can vary widely, with a typical range of 6–14 cfm (10–24 m^3/s) of vacuum available per hp. at a system operating point of 14 inches Hg of vacuum (47 kPa).

Example: VSD for Vacuum Pump

A dairy farm has a 7.5 hp. vacuum pump that has a pump efficiency of 10 cfm per hp., operating 8 milking units with no additional vacuum-operated devices, 6 hours per day. The farm does not currently have a variable speed drive (VSD) controlling the vacuum pump.

(A) Is the vacuum pump oversized?
(B) Estimate the annual energy savings to be gained by adding a VSD to the system.

First, the vacuum pump capacity can be estimated as follows:

7.5 hp. * 10 cfm/hp. = 75 cfm of vacuum available

The system's vacuum requirements can be estimated as:

35 cfm reserve +3 cfm/unit * 8 units = 59 cfm

Therefore, the vacuum pump is oversized by 100 * (1–75/59) = 27%.

Rather than purchasing a smaller pump, it is usually more cost effective to install a VSD.

Savings from the VSD can be estimated using Eq. 5.1:

S = [7.5 – (0.25 * 8)] * 0.9 * 6 * 365

S = 10840.5 kWh per year savings

5.3 Refrigeration Energy Efficiency

The refrigeration system for cooling milk is probably one of the most important pieces of equipment on a dairy farm. Refrigeration systems tend to vary widely from farm to farm in the region, but almost all utilize direct expansion systems, containing a compressor, condenser, evaporator and expansion valve (Sanford, 2004a). A low-cost way to get more cooling for the dollar is to clean the condenser unit twice a year and make sure it has free flow of air during the summer months. Cleaning the condenser takes about 30 minutes and can save 3–5% in electrical costs. Power sprayers should not be used on the condenser, it will bend fins and force dirt into the press fit connections between the refrigerant tubes and the fins. Use a Condenser Coil Cleaner detergent that can be purchased from refrigeration equipment supply companies. Disconnect power to the refrigeration system before cleaning and follow labelled directions.

Farms in need of a new compressor should consider upgrading to a "scroll" compressor rather than the more traditional reciprocating piston design. Scroll compressors are 15–20% more efficient than a standard "reciprocating piston" compressor. It's typically not economical to replace a working compressor so making the decision ahead of time to “plan the replacement” when the compressor must be replaced will ensure you capitalize on the opportunity to increase the energy efficiency when replacement is required.

The refrigeration system will have an air or water-cooled condenser to dissipate the heat extracted from the milk. A portion of the heat can be recovered and used for heating water in a refrigeration heat recovery (RHR) unit. A unit can typically replace 50% of the water heating needs on dairies (Sanford, 2003). These units are plumbed in series with the water heater, so water is pre-heated in the heat recovery unit before entering the water heater. RHR units are refrigerant to water heat exchangers with no moving parts. They require the same type of maintenance as water heaters; flush some water from the bottom of the tank monthly to keep minerals from building up.

Using well water to cool the milk before it enters the bulk tank is another energy saving option. A heat exchanger is used to transfer heat between the milk and the well water. With enough heat exchanger surface area and water flow, it is possible to cool the milk to within 3 or 4 °F (2–3 °C) of the well water temperature with a potential refrigeration system electrical savings of 60% in northern dairy areas. This will typically require the water flow to be two or three times higher than the milk flow rate. The typical 1 HP (~0.75 kW) milk pump has a flow rate of 35 gallons per minute (~130 litres per minute) which would mean you’d need a water system that can supply 70 to 105 gallons per minute (~250–400 litres per minute) of water flow. Few on-farm water systems have that high of a capacity. To alleviate this issue, a variable speed controller can be installed on the milk pump to pump the milk out of the milk receiver and through the precooler as slow as possible without letting the receiver overflow. In doing this, the water to milk flow ratio is increased which results in greater drop in the milk temperature. The water used for cooling can be used to water cows or for parlor cleanup so it isn’t wasted. Cows tend to drink the warmed water more readily, which often has a positive impact on milk production.

5.4 Compressed Air Energy Efficiency

Many milking parlors are equipped with milking unit take-offs, parlor gates or crowd gates that use compressed air to power cylinders or air motors. In time, air cylinder seals, pneumatic controls or fittings may leak as they age. Compressing air is only about 10% efficient based on the energy input versus the work performed by the compressed air to open a gate or retract cylinders. However, they rarely use a large amount of energy relative to other systems in the farm. Nevertheless, checking for air leaks annually and fixing them can be a useful and cost-effective energy savings strategy for these systems.

5.5 Tractor Block Heater Energy Efficiency

Another low-cost energy saving option for dairy farms in the cold winters of the Northeast US is to use time clocks on tractor block heaters. Dairies may need tractors or skid-steer loaders for feeding or manure removal. It takes about 2 hours to warm up an engine block to a temperature where the engine will start more easily in cold weather. A time clock can be used to turn on the block heater a few hours before it will be needed versus leaving it plugged in overnight or all the time. A pool clock timer costs about $25 and will pay for itself in as little as 20 days with the energy savings.

5.6 Recommend Energy Efficiency Measures

An analysis of Michigan dairy farm energy audits showed top four recommendations were lighting, variable speed drives for vacuum and milk pumps, equipment upgrades and weatherization. Figure 5.1 is a summary of the top energy efficiency measures recommended to Michigan dairy farms (Van Zweden, 2018).

Example: Dairy Farm Vacuum Pump Upgrade

A dairy in western New York State is milking 250 cows and moving from milking twice per day to three times per day. It takes 2–3/4 hours to milk the cows in a double 12 parlor and approximately 30 minutes for washing the milking system or 6–1/2 hours per day of run time for the vacuum pump. Planned increases in herd size will increase operation to 9–3/4 hours with the additional milking. The vacuum pump is a 10-horsepower blower type vacuum pump. Using an energy analysis tool, it is estimated that the vacuum pump consumes 30,000 kwh per year. If a variable speed drive is added to control the motor instead of using a conventional vacuum regulator, it would save 13,190 kWh per year. At $0.10 per kwh that is a savings of $1319 in electrical costs. The estimated installed cost of a variable speed drive is $5500. This would represent a 4.2-year simple payback on investment.

5.7 Regional Status and Outlook

The dairy sector remains one of the largest and most energy intensive portions of the region’s agricultural operations. However, long-standing slim margins and uncertainty of returns for dairy farms have exerted ongoing financial pressure that makes long-term investment challenging to justify. Overall, farm size has slowly increased over the years and is likely to continue increasing in response to economic

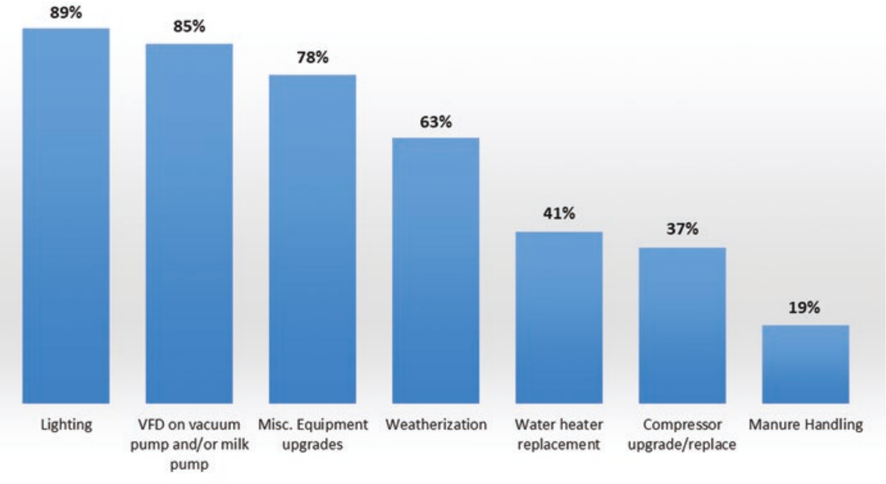

Fig. 5.1 Energy efficiency recommendations to Michigan farms (Xin, 2014)

pressures. As a result, automation is likely to become more common, in the form of robotic milking and other automated tasks on the farm. These trends tend to make viability more difficult for smaller dairy farms, which in turn makes it difficult to establish entry level opportunities for new farmers. Thus, there is a growing need for support for these smaller operations, in order to ensure long-term viability of the sector by bringing new farmers and farms into operation. Energy efficiency innovations that are suitable for smaller operations will be a notable need in the coming years.

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Chapter 6
Livestock Housing Energy

Scott Sanford and Aluel Go

6.1 Introduction

The housing of livestock is a critical component of the dairy sector, and is the central aspect of poultry, swine, and beef production. While some farms (especially beef farms) may keep their animals in the field much of the time, most farms utilize structures to provide improved environmental conditions for the animals. Energy is utilized to enhance the environmental conditions in the structures using lighting, ventilation and space heating. This chapter provides an overview of energy use by the poultry, beef and swine sectors, followed by discussion of energy efficiency opportunities for major energy-using systems.

6.2 Poultry Sector Energy Use

Poultry production at a commercial scale is exclusively an indoor operation. The most common operations are "layer houses" in which eggs are produced, and "broiler houses" in which meat chickens are produced. Other types of poultry operations include turkey, duck and pheasant production. Several variations of farm layout are utilized for layer houses, including caged and "free range" houses, with designs and management often dictated by companies that act as "vertical

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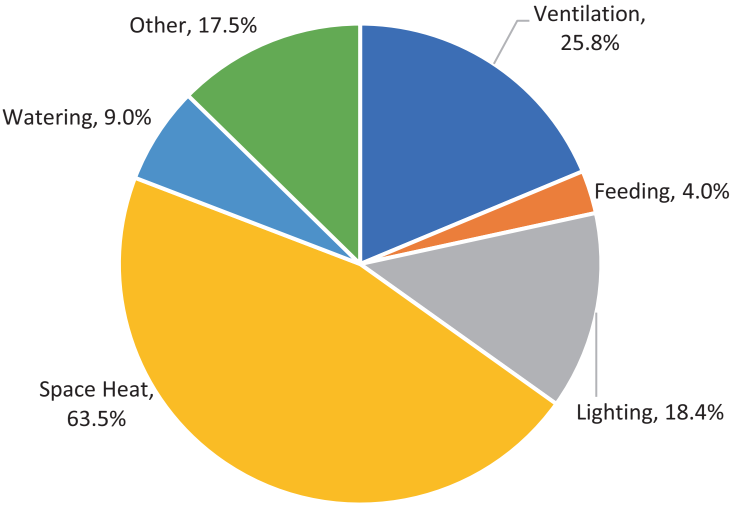

Fig. 6.1 Typical breakdown of broiler poultry farm energy use

integrators" in the industry. As such, energy use in the poultry sector varies widely, but tends to be dominated by heating, ventilation and lighting (Fig. 6.1).

In the case of layer facilities (egg production), refrigeration is also a large energy user. While the availability of data for poultry energy use is very limited, one study found annual energy use by poultry producers to vary from 2.1 to 6.1 kWh per bird capacity (Calehuff 2014). Another analysis (Xin 2014) reports electricity use of 4.9 kWh plus 0.076 gallons of propane per bird per year for commercial egg laying operations. This would be equivalent to 6.9 kWh per bird per year. Differences in energy use can be attributed to differences in farm design (i.e. natural ventilation vs fan ventilation) and operation.

The energy use in vertically integrated broiler operations in Kentucky is about 25% of the growers' cost, with 20–30% due to electricity and 70–80% from propane gas. Most of the electricity is for ventilation with some for lighting and feed handling. Monitoring of 12 houses found an average use of 30,000 kWh of electricity and 4750 gallons per house annually (Overhults 2014). Seven farms raised birds to 4 lb. and averaged 5579 gallons propane per house with a range of 3241 to 6836 gallons. Five farms grew birds to 6-1/4 lb. and used an average of 3926 gallons propane per year with a range of 2801 to 5863 gallons. Houses with higher propane use typically had un-insulated sidewall curtains. In recent years, most farms have removed the sidewall curtains and installed insulated wall sections to reduce energy consumption. Other popular energy efficiency improvements include attic air inlets to use the attic space as a solar preheater, adding ceiling insulation, installing mixing fans to push warm air towards the floor, replacing tunnel inlet curtains with insulated door panels and replacing old fans with high efficiency fans when replacement was needed.

In northern states with colder winters, infrared heating, ceiling curtains, sectional dividers and insulated walls on the north facing perimeter of facilities are energy efficient measures often used. With insulated side curtains and efforts to seal air leaks to close the building envelope, the need to reevaluate the ventilation and air exchange requirements is critical to adequately dissipate ammonia buildup for the safety of the birds and workers. Natural gas is the predominant heating fuel used where available.

6.3 Beef Sector Energy Use

Beef production in the region can vary widely in size and scope, ranging from a few feeder cattle being grass fed for local markets to large feedlots that supply mass market processors. Energy uses for beef production tend to be minimal, and focus primarily on feed storage and handling. Replacing heated livestock water fountains with energy-free waterers can reduce energy use.

Electric fences are used to control livestock be delivering an uncomfortable current flow through the body for a sufficiently short duration so as not to cause injury to the animal. There are three main parts to an electric fence: (1) The energizer (fence charger) produces a high voltage charge that only lasts a fraction of a second; (2) The fence is an extension of the high voltage terminal on the energizer. Types of fence material depend upon the animal to be controlled and whether permanent or temporary; and (3) The ground rods return the current to the energizer. They are necessary to complete the circuit.

Most early fence energizers were high impedance (resistance) units that worked over short distances when they were weed-free. Dry soil conditions had little effect on the effectiveness of high impedance units. Energizers today are generally of the low impedance type that deliver a very high current to the fence for a very short time. Even when some grass or other vegetation is touching the fence, the system can still deliver enough current to control livestock. However, if you skimp on the number of ground rods with a low impedance energizer, the current delivered to livestock can be drastically reduced (Surbrook et al., 2009).

One of the most important aspects of making sure an electric fence system works effectively is proper grounding of the energizer. If an energizer does not control livestock, the solution is not necessarily a more powerful energizer which would be a significant safety concern. Improving the grounding may be the lowest cost, most effective and most energy efficient means of improving the operation of the electric fence system. The grounding required by a fence energizer will vary depending on the soil type and moisture. For an average soil, it is recommended that a 5 Joule low impedance charger be grounded with three, 8-foot ground rods spaced at least 10 feet apart. Doubling the Joule output of the energizer would double the grounding needed. The best place for the energizer may be outdoors away from animal buildings and grounded equipment.

An improperly installed electric fence system can result in unintentional shocks to livestock at grounded equipment such as at waterers, feeders or even in a milking barn. The most frequent cause is improper grounding of the energizer. The energizer must have its own grounding electrode located well away from any other grounds or metal object in the earth (50 feet minimum recommended. An energizer must never be grounded to the farm electrical system grounds, to the utility system grounds, to metal water pipes, or to metal objects in a building such as stalls, fences, or dividers.

6.4 Swine Sector Energy Use

There are three main production systems in swine production: Sow production, which includes farrowing, gestation and breeding; nursery production (pigs raised from 12 to 25–50 pounds) and grow-finish production (pigs from 25–50 to market weight, usually about 280 pounds). Sometimes the nursery and grow-finish production are combined. Most swine production in the region is vertically integrated and consists of large, enclosed structures with controlled environments and automated feed and watering systems. As such, energy utilization involves ventilation fans, creep heaters, lighting, manure handling, cooling curtains, misters and feed handling equipment. Heat is used in winter months when the animals are still small and unable to generate sufficient metabolic heat to maintain temperatures in their facility. Energy use data for the swine sector in the region is limited and tends to vary. An analysis in the state of Michigan gives an average EUI of 115 kWh per hog (Go 2018). Based on farm financial records in Minnesota (Sharpe et al. 2018), energy is 2 to 5% of production costs while feed accounts for 60–70%. A 2015–2016 study of commercial swine farm energy use in Minnesota monitored two of each type of swine operation (Sharpe et al., 2018). The breeding to weaning operations housed an average of 2950 sows and used an average of 11.6 kWh of electric and 0.32 gallons of LP gas per head annually. The nursey operation housed an average of 6600 nursey piglets and used an average of 2.3 kWh of electric and 0.42 gallons of LP gas per head annually. The finish operation housed an average of 1730 feeders and used an average of 8.47 kWh of electric and 0.41 gallons of LP gas per head annually. The total energy use was equivalent to 53.5 kWh per market pig annually from farrow to market (Figs. 6.2, 6.3 and 6.4).

6.5 Lighting Energy Efficiency

Lighting systems tend to have three possible purposes in livestock housing systems. First, they can be intended to provide for human vision, as farmers carry out tasks in the facility. Second, they can be intended to provide for animal vision, allowing the animals to move, access feed and water, and carry out the daily activities normal for their species. Third, lighting systems can be utilized to trigger or control

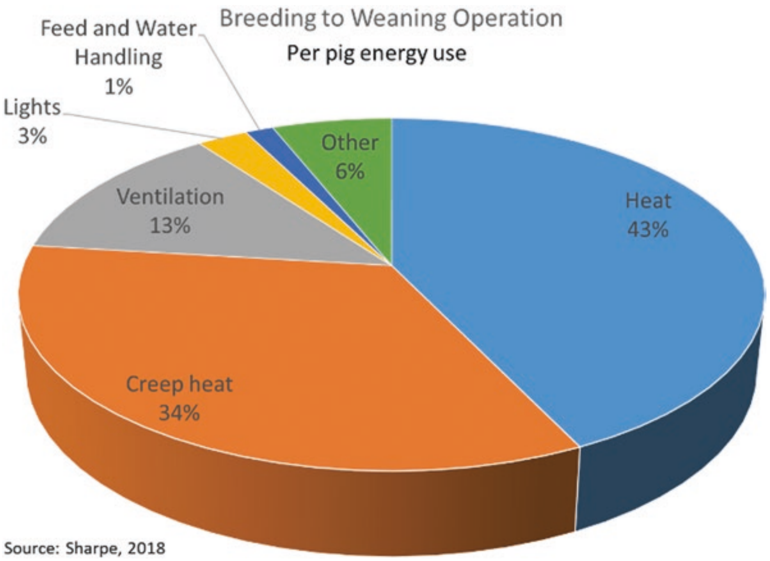

Fig. 6.2 Energy use distribution for farrowing operation

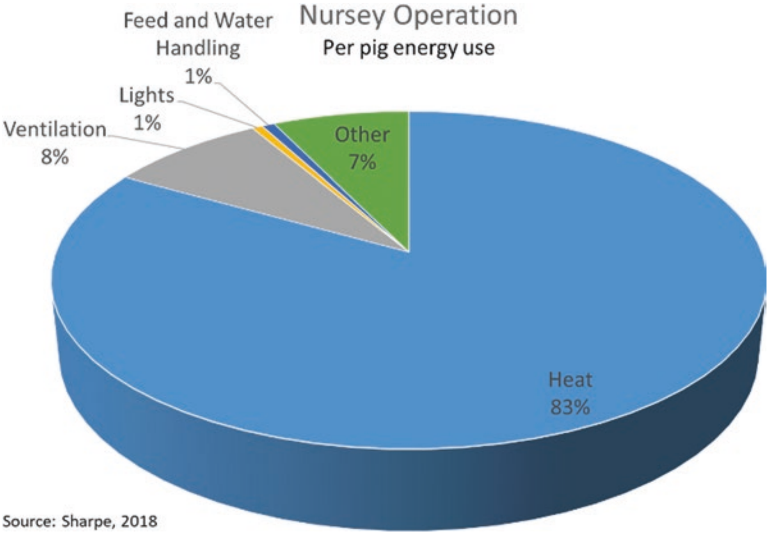

Fig. 6.3 Energy use distribution for nursey operation

non-visual responses, such as the enhanced milk production that occurs under long day lighting conditions especially during winter months. Lighting upgrades with LED have recently expanded to include automated control systems for light duration intensity and color rendition for poultry as well. A reddish light hue is used when the birds are usually young to enhance growth rates with a more aggressive

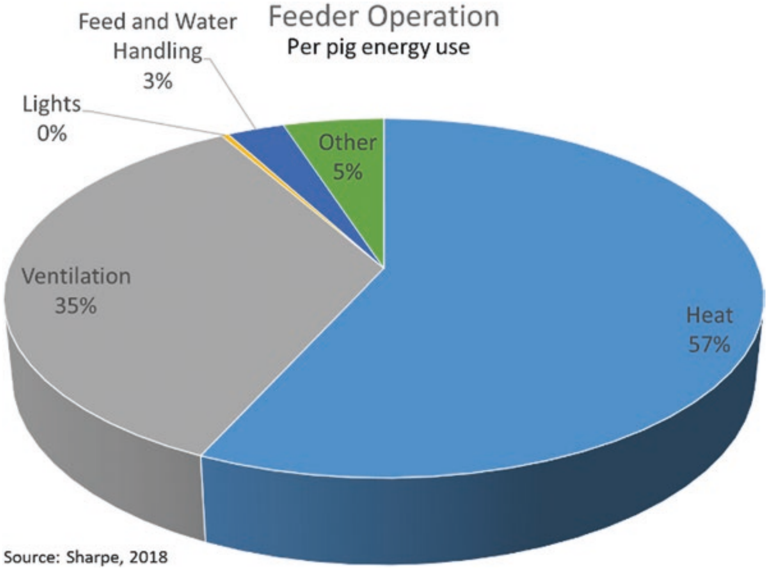

Fig. 6.4 Energy use distribution for grower-finisher operation

feed and water intake behavior. A bluish light hue is believed to keep mature birds calmer which reduces cannibalism and death rates. These often leads to increased overall productivity.

In general, it is assumed that an animal's sensitivity to electromagnetic radiation is the same as that of the human eye, and so efficiency is generally measured in units of "lumens per electrical input watt (LPW)". While many claims are made as to the special effectiveness of the spectral quality (i.e. individual wavelengths of light) for livestock, these putative benefits are not always easy to substantiate, and farmers should examine said claims with care. It is also worthwhile to note that a light source that generates light with a high LPW may not have a high efficiency in the barn if the optical efficiency of the luminaire is poor, or if accumulations of dust and grime inhibit the delivery of light to the task plane.

Four main strategies can be used to improve lighting energy efficiency in livestock housing. First, regular cleaning of lamps, reflectors, lenses, etc. can allow a higher fraction of the generated light to reach the task plane, resulting in a need for fewer luminaires to be used to achieve target light levels. This can be a very effective strategy in livestock housing facilities, as the dusty, dirty conditions tend to cause speedy accumulations of dust and grime on surfaces. Second, the existing lighting system can be replaced with a new one whose efficiency is higher. Third, advanced controls can be used to turn lighting systems down or off when not needed. Daylighting (the use of light from the sun and sky) is the last strategy, and can dramatically reduce lighting energy costs when utilized effectively. However, while daylight has traditionally been used either instead or in combination with electrical lighting, its implementation in livestock housing has not always been popular, in part due to a desire to precisely control light levels and photoperiods in the barn. Lighting as a percentage of total energy used for production is 1 to 3 percent in swine operations and can approach 18% on poultry operations.

6.6 Ventilation Energy Efficiency

Ventilation consumes a sizeable amount of energy on livestock farms. Fans are used for both circulating air within a building (mixing fans) and exchanging air (exhaust fans). The efficiency of a fan is affected by the motor efficiency, cowling around the fan, blade design, clearance between the blade end and the housing, shutters and diffusers. Diffusers on exhaust fans can reduce energy consumption by 12–23% depending on fan size. In general, larger fans and fans that have a diffuser will be more efficient. It is impossible to merely look at two different fans of the same size and type and tell which one is more energy efficient. However, there is independent lab testing of fans, and the data is available to the public for free at the BESS lab website (http://bess.illinois.edu/). There can be a 50% difference in energy consumption for a fan of the same size for the same purpose. Checking the energy performance before you buy could save you thousands of dollars in energy costs. Exhaust fans are rated in cfm per watt at a specific static pressure while panel and basket circulation fans are rated in thrust pounds force per kilowatt. A higher value represents a more energy efficient fan. Table 6.1 shows recommended minimum efficiency values for exhaust fans, while Table 6.2 gives recommendations for circulating fans.

If a farmer needs to replace a fan motor, replacing it with a motor from the fan manufacturer will ensure the fan efficiency is maintained. They may be more expensive because they contain more copper which is needed to manufacture a high efficiency motor (Sanford 2014).

Table 6.1 Recommended energy efficiency for Exhaust fans

Fan diameter	Efficiency range[a] CFM / watt	High efficiency[a] CFM/watt
24 inch	8.7 to 19.4	14 or higher
36 inch	9.4 to 23.0	20 or higher
48 inch	13.6 to 27	21 or higher
54 inch	19.8 to 33	23 or higher

[a] @ 0.05 inch water static pressure

Table 6.2 Recommended energy efficiency for circulating fans

Fan diameter (inches)	Efficiency range of tested fans (lbf/kW)	Recommended minimum efficiency (lbf/kW)
12	7.1 to 10.6	10
20	8.8 to 11.4	10.8
24	9.8 to 13.2	11.5
30	10.7 to 13.3	12
36 w/ guards	13.0 to 15.9	14.5
36 w/o guards	18.4 to 21.2	20
48	20.5 to 24.7	23.5
50–54	20.5 to 24.4	23.0

6.6.1 Exhaust Fans

Enclosed livestock housing will require a minimum ventilation rate to remove water vapor from animal respiration and ammonia gases from manure. The air flow rate will be based on animal species, age or weight, and type of bedding or housing type. The outside ambient air temperature is not a factor in determining the minimum air flow rate. Under ventilation can lead to respiratory disease issues and lower weigh gain.

Research has shown that ammonia level, even as low as 25 ppm can reduce body weight of broilers at 7 weeks of age (Miles 2004) but increasing ventilation can increase heating costs. Ventilation heat recovery systems allow higher air exchange rates without increasing supplemental heating energy. The heat recovery ranges from 35% to 70% depending on the technology used. These units will require maintenance to clean the heat exchanger surfaces so they do not become fouled with dust and debris. However, newer technology has automated washing and deicing of the heat exchanger to keep the performance from degrading.

Over ventilation (providing more airflow than is needed) can increase energy use in heated animal facilities such as swine farrowing or nursey barns or poultry broiler barns. Variable speed fans can be used to more precisely control the ventilation rate thus saving energy (Sanford, 2004).

Traditionally, basket or panel fans have been used for air circulation in a barn, whether it is to prevent stagnant areas in a barn or for summertime cooling. For summer conditions, circulation fans are typically spaced at ten times the fan's diameter in feet. Example, 48" fans in a freestall barn would be spaced every 40 feet (4-foot diameter × 10 feet per foot of fan diameter).

In animal housing with high ceiling, another type of fan can be used for circulation are high-volume, low-speed (HVLS) fans. These are large diameter ceiling fans (up to 24 feet diameter) that are mounted above the feed alley or over pens and are useful in dairy barns for summer air circulation or preventing winter air stagnation. One HVLS fan can replace approximately six 48-inch circulation fans in a 4-row freestall barn and reduce electrical use for cooling by about 65%.

Fig. 6.5 Heated livestock water fountain

6.7 Water Fountain Energy Efficiency

All livestock needs a clean, liquid form of water. In northern states, heated water fountains are needed to keep the water in the liquid form during the winter months. This requires energy and access to electrical power. However, there are energy-free water fountains available that don't need electrical power and can maintain ice free water even in sub-zero weather (Fig. 6.5). They do require a minimum number of animals per fountain and a large diameter insulated pipe that extends below frost level to provide some ground heat to keep things from freezing.

6.8 Space Heating Energy Efficiency

In some livestock operations, a heated draft free environment may be needed during the first weeks of life. Day-old chicks need a temperature of 95°F for the first week, 90°F the second week and 5°F less each week thereafter. Heating a broiler barn requires lots of energy but can be reduced by using brooder heaters, high efficiency heaters, well insulated walls and ceilings and minimizing over ventilation. Brooder heaters allow a small area to be heated with radiant heat rather than heating the entire building, thus saving energy.

For swine operations, piglets need a warm dry area to keep from getting chilled. They will need temperatures of about 90°F at birth and then slowly dropping to

82°F when weaned at 21 days. The sows need cooler temperature, under 60°F, or they will overheat causing them to lose body condition and have reduced milk production. Keeping the piglets warm and the sow cool can be accomplished with area heating such as heat lamps or heated floors in the creep area. A study comparing heat lamps to creep heating pads (MacDonald 2000) found the heat lamps were less expensive to purchase but more expensive to operate than electric creep heating pads. The piglet survival and weight gain were not significantly different between the two groups. The creep heating pads paid for themselves with the energy savings in less than 2 years. A hover or a covered creep area can allow the barn temperature to be reduced further, while maintaining enough warmth for the piglets.

Some poultry broiler and swine feeder barns have curtain sidewalls for summer ventilation. However, if barns are located in cold climates where heating is needed during the winter, they can increase the annual energy use compared to removing the curtains, insulating the sidewalls and operating the barn with tunnel ventilation during the summer (Overhults 2014).

Example: Dairy Free-stall Summer Cooling

A dairyman wants to add cooling fans to his 6-row free-stall with four 100-cow groups. The barn is 320 feet long and 110 feet wide and based on neighboring farms fan use, the fans would be used about 1500 hours per year. His neighbors use high-speed circulating fans but he's interested in looking at High-Volume, Low-Speed fans (HVLS). He has quotes for using HVLS fans down the center of the barn and 4 rows of 36-inch high speed fans. It would require six HVLS fans, spaced 55 feet apart to cover the barn length as per the spacing generally recommended by the HVLS manufacturer. The 36-inch high speed fans would be spaced 30 feet apart for a total of 10 per row or 40 fans total. The high-speed fans require 500 watts-hour per hour of use per fan while the HVLS fans use 1900 watts-hr per hour per fan. The total electrical use would be:

HS fans: 40 fans × 500 watt-hr/hr × 1500 hrs/yr × kWh/1000 watt-hr = 30,000 kWh/yr

HVLS fans: 6 fans × 1900 watt-hr/hr × 1500 hrs/yr × kWh/1000 watt-hr = 17,100 kWh/yrElectrical Savings of HVLS fans over High Speed fans:

(30,000 – 17,100)/ 30,000 = 43% savings

6.9 Status in the Region

In the Northeast and Midwest, barn age and design tends to vary widely, and opportunities exist to upgrade older systems with improved heating systems, insulation, lighting, ventilation and watering systems. The magnitude of the savings and the economic desirability of these measures will tend to vary depending on each farm's situation and circumstances.

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Chapter 7
Fruit and Vegetable Storage Energy

Scott Sanford and Aluel Go

7.1 Introduction

When stored under optimal conditions, the quality and marketable lifespan of many fresh crops can be dramatically increased, resulting in greater farm income over a longer period of time. Traditionally this took the form of a "root cellar", whose temperature and relative humidity helped extend the period during which the produce can be sold. In the current era, farms in the region tend to utilize more sophisticated systems that employ active cooling, controls, and sometimes atmospheric modification as well. Once fruits and vegetables are harvested, they need to be stored at the proper temperature and humidity to maintain quality and shelf life. Some crops such as Irish potatoes, onions and sweet potatoes need to go through a curing period before the temperature is reduced for long-term storage.

Maintaining ideal conditions for a stored crop can be an energy intensive activity. Thus, care and attention to detail is important to ensure energy efficient and profitable operations for the farmer. It is important to keep in mind that the crop in storage is still alive, and hence emits heat, carbon dioxide and water vapor as it respires. The amount of heat released is equal to 10.67 kJ per g of CO_2 mg (4.59 million BTU per lb. CO_2), with CO_2 and water vapor production varying with the product in storage and storage conditions (Table 7.1).

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Table 7.1 Typical respiration rates and associated heat production of some fruits and vegetables

Crop	Storage temperature	CO_2 production (milligrams CO_2 per second, per tonne of crop)	Heat production (W per tonne of crop)
Apples	0 °C (32 °F)	0.3–1.1	3–11
Apricots	9 °C (32 °F)	2.8–5.5	30–59
Broccoli	0 °C (32 °F)	5.3–5.8	56–62
Cabbage	0 °C (32 °F)	1.1–1.6	12–17
Cherry	0 °C (32 °F)	1.1–1.4	12–15
Corn, sweet	0 °C (32 °F)	8.3–14.1	89–150
Grapes	0 °C (32 °F)	0.3	3
Onions, dry storage	5 °C (41 °F)	0.8	9
Peaches	0 °C (32 °F)	1.1–1.6	12–17
Potatoes, mature	5 °C (41 °F)	0.8–2.5	9–27
Strawberries	0 °C (32 °F)	3.3–5.0	35–54

Adapted from Thompson et al. (2008)

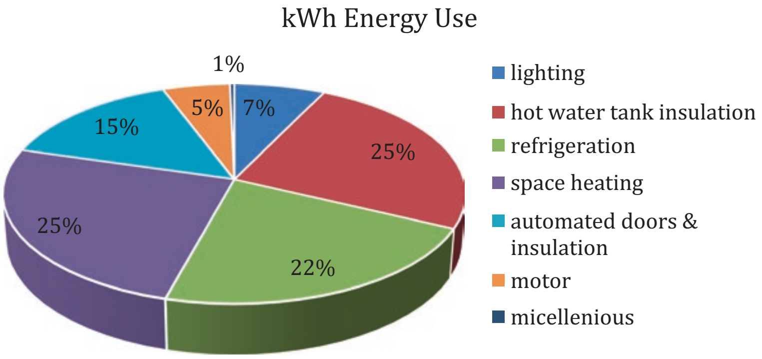

Fig. 7.1 Typical breakdown of fruit packing and storage energy use

7.2 Energy Use

Energy use in tree fruit farms (apart from field operations) is primarily centered on thermal needs – refrigeration, space heat, and water heating (Fig. 7.1). Energy use among operations analyzed in Michigan averaged 3.2 kWh per bushel of fruit (Go 2018).

As in other sectors, the breakdown of energy use can vary widely from farm to farm, due to a diversity of operations and equipment. Some farms utilize minimal hot water or heating, leaving refrigeration as the major load. Some farms will provide refrigeration space for neighboring farms, resulting in even higher refrigeration energy use than would be expected for that farm alone. Refrigeration energy use is highest during the July–Oct harvest, and drops steadily as inventories diminish throughout the winter and spring. Most long-term storage units are commonly shut down from May to July. Some lighting and motor loads may also be found at these facilities, with the magnitude depending on the amount of sorting or processing carried out on the farm.

7.3 Fan Energy Efficiency

During the curing period and the cool-down period, high airflows are needed but once the crops are cool, the air circulation requirements are about half. Traditionally growers run the fans 50% of the time, typically running the fans 4– 6 h and then turning them off for 4–6 h. This saves kWh but doesn't reduce the KW demand charge on the electric bill. Variable speed controllers can be installed so the storage manager can reduce the fan speed during the storage period to maintain a 1°F temperature difference across the produce pile or containers continuously. If the fan speed is reduced by 50%, the energy consumption is reduced by 85% compared to full speed (as noted in Sect. 3.4), which saves both kWh and demand load (KW) during the storage months. As an added benefit, studies by Ashby (1992), Oberg (2003), and Sanford (2006) show 0.7–0.8% reduced water loss (shrinkage) in potatoes when variable speed drives were used.

7.4 Insulation and Energy Efficiency

Insulation is critical for reducing energy use in controlled environment storage. As a rule of thumb, the R-value recommendation for walls and ceiling for refrigerated storage in the region is R-30 (ft2 °F h/BTU) of a foam insulation, although the economic optimum can vary depending on the prevailing climate and operating conditions of the storage system (Sanford 2015). Fiberglass insulation is not recommended because in can become wet in the cooler walls due to condensing of water vapor that will migrate into the insulation. While newer storage facilities in the region are typically well insulated, it is not unusual to find older systems on farms that have less insulation than recommended, or in which the insulation has degraded over time. Older insulation can also crack or shift, leaving regions of uninsulated wall or ceiling. Damaged caulking or door gaskets are also a common source of air infiltration in refrigerated storage, and should be kept in good working order.

7.5 Refrigeration and Energy Efficiency

Refrigerated storage facilities can also benefit from cleaning condensers twice annual as discussed in the Dairy section to keep the refrigeration working as efficiently as possible. One notable aspect of fruit and vegetable storage refrigeration is the high transpiration rate of many crops, and the importance of high humidity conditions for prolonging crop quality. As a result ice-up of coils is usually more common than in most refrigeration systems, and the proper operation of the defrost system is thus more critical.

In the region, refrigeration systems for fruit and vegetable storage tend to vary widely in size and age. Recently, some small farms in the region have adapted room air conditioners and modified controllers to create small, homemade refrigeration systems (Saran et al. 2014). While these systems have potential to provide a low cost refrigeration option for some farms, their long-term viability and efficiency has not yet been demonstrated.

7.6 Status and Outlook in Region

The diverse nature of fruit and vegetable storage in the region makes it difficult to predict future trends. Entry level and small-scale farmers are likely to continue relying on legacy equipment or self-built systems as a way of minimizing first costs. This, in turn, suggests that there will be an ongoing need for energy efficiency education and support. When farms are located in close proximity, the economies of scale may allow for large purpose-built refrigeration facilities that operate very efficiently and provide a cost-effective and trouble-free refrigeration service.

This move towards cooperative efforts among multiple fruit farms to establish centralized storage and packing facilities has started in the northwestern region of Michigan. These newer and large-scale storage and packing operations have modified the air composition of their airtight long-term cold storage by replacing oxygen with nitrogen to reduce the onset of oxidation in fruits and vegetables. They have also started to adopt automated control and data monitoring systems with variable speed drives (VSD) on water-cooled compressors and fans that determine the optimum operational combination of these compressors and fans given the refrigeration load required in each storage or processing section. In the packing and receiving area, high-speed doors, optical grading scanners and sorting systems are being used. Robotic packing and shipping systems are also being installed for direct marketing to major retailers.

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Chapter 8
Grain Drying Energy

Scott Sanford and Aluel Go

8.1 Introduction

When practical, grain crops in the region are typically left to dry as much as possible in the field. However, the highly variable and often wet weather of the region often requires the use of grain drying equipment. Also, some crops cannot be fully dried in the field without incurring unacceptable field losses. The most common grain crops in the Northeastern Quadrant of the United States are corn, soybean, and wheat, with smaller amounts of other grains also in production.

Practically speaking, grain drying is accomplished by forcing air (usually heated) through the harvested grain. In theory, the amount of energy needed to dry a crop is equal to the heat of vaporization of water (2453 kJ/kg at 20 °C), but in practice, the amount of energy used is usually much higher. Energy use when drying grain is used for blowers that move air through the grain, fuel to heat the air, and grain handling equipment for loading, unloading and stirring the grain (Maier et al., 2017). Total energy use can vary dramatically from year to year, depending on the amount of in-field drying that is made possible by weather conditions. Annual energy use indices for on-farm grain drying facilities vary from 1.5 to 5.5 kWh of energy per bushel of grain stored (Table 8.1). Audits of grain drying facilities in Wisconsin, Minnesota, Illinois and Michigan show that an average of 92% of the energy was gas for drying and 8% electricity for blowers and grain handling (Reinholtz 2020).

It comes as a surprise to many that the energy used for drying corn can exceed the energy used for all field work and harvesting of a corn crop. In fact, the energy

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Table 8.1 Representative grain dryer energy utilization index values by state (kwh per bushel)

State	Low	Average	High
Pennsylvania	1.53	2.69	3.97
Michigan		3.2	
Upper Midwest	2.22	3.91	5.48

References: Go (2018), Ciolkosz (2020) and Reinholtz (2020)

input for drying grain is second only to the embodied energy in fertilizer in the production of a corn crop. This chapter explores some options to reduce grain drying costs. Primary opportunities for reducing the cost of drying grain include:

- Only drying salable product.
- Reducing over drying.
- Using heat recovery where possible.
- Using an energy efficient process.
- Purchasing high efficiency dryers.
- Keeping up with dryer maintenance.

All grain should be screened before it enters the dryer to remove fines, beeswings, weed seeds and any other non-marketable content to reduce the amount of drying required. Controls or frequent monitoring should be used to reduce over drying. Corn is traded based on 56 pounds per bushel at 15.5% moisture. If a farmer is storing grain, they will likely want to dry it to 14% or 15% as a margin against heating and spoilage depending on how long it will be stored. If storing for longer than the following June, corn should be dried to 14% and beyond a year, it should be stored at 13%. Soybeans and small grains are stored at 13%. If grain moisture is less than the market rate, you might not be paid for the weight difference so not over drying saves energy and loss of sale weight.

8.2 Strategic Crop Selection and Management

Traditional, full season crops sometimes mature so late in the year that they do not have much opportunity to dry on the stalk prior to harvest. One possible option for farmers is to plant slightly shorter relative maturity varieties so that, when the crop matures, the weather is warmer and has better conditions for drying in the field, thus reducing the amount of artificial drying. For example – a farmer could plant a 100-day corn versus 110-day corn. Yes – there may be a slight reduction in yields but profits should be the guide not yields, and in this case, lower energy use could improve overall return.

Table 8.2 illustrates this for grain corn grown in southern Wisconsin in 2020. Yields and moisture content values are based averages from university hybrid trials and the estimated cost of production for the region. In this example the 100-day corn had $62 higher profit even though it yielded six bushels less per acre. Note:

Table 8.2 Example comparison of costs for 110 day corn vs. 100 day corn grown in Southern Wisconsin

Crop	Ave % moisture	Yield (bu/Ac)	Income ($/Ac)	Non-land production cost w/o drying ($/Ac)	Drying cost ($/Ac)	Total expenses ($/Ac)	Profit ($/Ac)
110 day corn	31.4	244	890	685	155	840	50
100 day corn	23.4	238	869	685	72	757	112

These numbers are illustrative only – actual results will vary depending on climate, planting date, management approach, and other factors.

This strategy is especially effective if cold or wet spring conditions necessitate a later planting date. In the case of corn production in Southern Wisconsin, short season corn tends to be more economical if planted later than ~May 5th for corn that is dried on the farm (Lauer 1996). In warmer climates, such as those found in Pennsylvania, the crossover point occurs later – towards the end of May (Anonymous 2018). Contact your local cooperative extension agent for relative maturity and planting date recommendations.

Another possibility is to leave the crop on the stalk through the winter, in the hopes of obtaining more thorough air drying and reduce overall storage requirements for the farm. This has the risks of higher losses due to lodging, animal predation and kernel drop. A 2-year study looking at the risk of leaving corn standing thru the winter showed an average of 24% yield loss with a range of 10–38% (Schneider and Lauer 2009). This approach has shown to increase returns in some situations, but decrease returns in others (Lauer 1999).

8.3 High Moisture Storage

Another option is to store the grain using a method that doesn't require drying. If feeding cattle, the amount of corn that will be fed during the colder months could be stored in a silage bag as high moisture corn. If corn can be cooled to under 40 F, it can be stored for 90 days at up to 18–20% moisture in a grain bin while being fed out. What isn't used up by spring can then be dried. The corn will need to be aerated continuously when stored at higher moisture contents to keep it from heating.

Stirring devices are used to agitate and mix grain during drying and/or storage. Farms that are using a Low-temperature or Ambient-air dryer can save energy by using a stirring device to reduce over drying and improving air flow. The grain will be stirred two or three times as it dries to mix the dry grain at the bottom of the bin with the higher moisture grain at the top. These devices can save about 20% in energy costs. For ambient air dryers, using a small heater to increase the drying air temperature up to 10 °F (6 °C), reduces the relative humidity of the air and promotes faster drying. Some growers only use the heater during periods of high humidity such as nights and rainy days. This reduces the number of days required for drying and thus saves energy.

Farms with a high temperature bin dryer can also use a stirring device to reduce over-drying and save energy. The stirring device will be run continuously when the grain is being dried. They can save 20–25% in drying costs.

8.4 Drying Strategies

The manner in which a drying system is operated can have a significant impact on energy use. For example, operating a high temperature dryer at the highest possible temperature for the grain type and intended end-use will reduce the energy required. Figure 8.1 shows the energy required to remove water using a cross-flow dryer without heat recovery. The vertical axis is the energy required to remove water in Btu per pound of water evaporated and the drying temperature on the horizontal axis. The curved lines on the graph represent the air flow per bushel in cubic feet per minute or CFM, which is a design parameter of dryers. The graph shows that as the drying air temperature increases the energy to evaporate water decreases but as the air flow increases the energy required also increases.

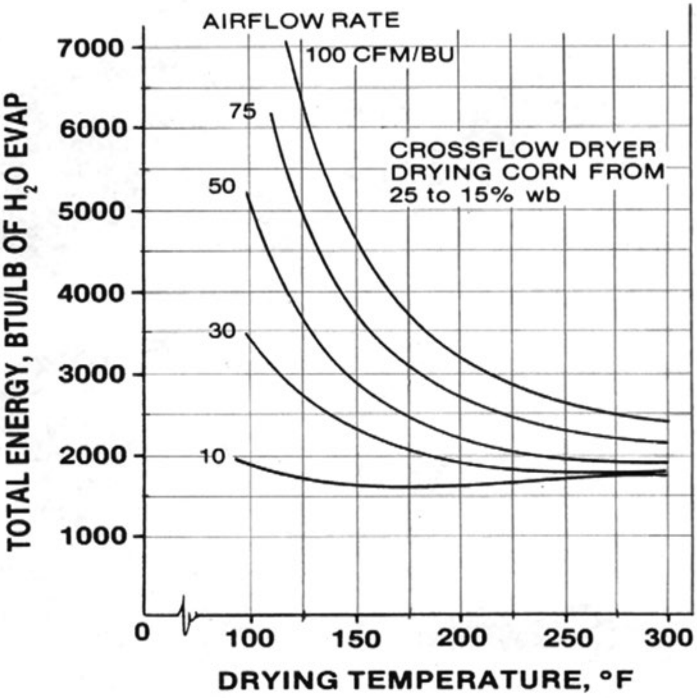

Fig. 8.1 Crossflow grain dryer energy use. (Adapted from Thompson et al. 1968)

It is important to note that the last few points of moisture removed from a crop generally require the most energy and time to remove. Therefore, strategies that improve efficiency during the final stages of drying can result in disproportionately higher energy savings.

One option, if possible, is to operate the dryer in full heat mode, drying the corn to within 1–1.5% points of the storage moisture target point and then transferring the hot grain to a storage bin and remove the remaining moisture with aeration as the grain cools. This is called in-bin cooling. About 0.1 percentage points of moisture can be removed for each 10 °F (6 °C) reduction in grain temperature. The fan in the cooling bin needs to be sized so the grain is cooled at the same rate as the dryer capacity and doesn't become a bottleneck. The cooling bin fan is run continuously until the grain is cooled. In-bin cooling can reduce energy costs by 10–15% and also increase dryer capacity by 30%.

A second cooling+drying option is called "dryeration". In this case corn is transferred hot from the dryer to a cooling bin at 2–2.5% points above the storage moisture target and allowed to steep for 4–12 h before turning on the cooling fans. This steeping period allows the moisture in the kernel to equalize. When the cooling fan is turned on, the moisture in the kernel is more easily removed.

Example: Grain Dryer Upgrade

A farm in south central Wisconsin is looking at updating their grain dryer because the fuel cost has been escalating. The farm hasn't kept very good records on harvested amounts and storage moisture of corn but using the assumption of eight points of moisture removed in an average year and a summary of the average energy usage and bushels sold, it appears that the dryer efficiency was about 5000 Btu per pound (11,600 kJ per litre) of water removed, about twice what it would be expected to be. The farm has been drying 300,000 bushels of corn per year and wants a Heat/Cool mode dryer with a capacity of 900 bushels per hour at 10 points of moisture reduction. The options the farmer was looking at include (1) rebuilding the existing cross flow dryer and updating the controls at a cost of $50,000, (2) purchasing a new cross-flow dryer with heat recovery for $90,000 or (3) purchasing a new mixed flow dryer for $100,000. Based on university research, the mixed flow dryer is known to be more efficient than a cross-flow dryer but is the increase in efficiency enough to justify the additional capital cost?

The existing cross-flow dryer doesn't have heat recovery and based on a dryer plenum temperature of 195 °F (95 °C), it would be expected to have an efficiency of 2800 Btu/lb. (6500 kJ per litre) water removed. The new cross-flow dryer will have heat recovery and would expected to have an efficiency of 2240 Btu/lb. (5200 kJ per litre) water removed, a 20% savings. The mixed-flow dryer has an estimated efficiency of 2000 Btu/lb. (4640 kJ per litre) water removed. Table 8.3 uses the rebuilt dryer as the baseline case since it is the least expensive and compares purchasing new dryers compared to rebuilding the current dryer and compares the new cross-flow dryer to the mixed-flow

Table 8.3 Grain dryer option comparison

Dryer	Capital cost	Incremental cost	Fuel cost per year	Fuel cost savings	Simple payback (year)
Rebuilt cross-flow	$50,000	N/A	$80,990	N/A	N/A
Cross-flow w/ heat recovery	$90,000	$40,000	$64,792	$16,198	2.5
Mixed flow	$100,000	$50,000	$57,850	$23,140	2.2
Mixed-flow vs. cross-flow		$10,000		$6942	1.4

dryer. A cost of $1.50 per gallon ($0.39 per litre) for propane and $0.12 per kWh for electricity was used for the analysis.

In all cases the mixed-flow dryer, despite costing $10,000 more than the new cross-flow dryer and $50,000 more than rebuilding the current dryer, had a faster payback, when compared to keeping the existing system. The payback was 2.2 years which is equal to a 45% return on investment.

With dryeration about 0.2% of moisture can be removed for each 10° F reduction of grain temperature. Once the grain is cooled it needs to be transferred to another bin as there will be condensation on the bin walls and some wet corn. Transferring the grain will mix the moisture so it won't cause mold. Dryeration reduces energy use by 15–25% while increasing dryer capacity by up to 70%.

8.5 Summary and Regional Outlook

In summary, when possible store corn to be used during the winter month for cattle feed at a higher moisture to avoid drying. Grain should be cleaned before drying to remove fines. Operate high-temperature driers at the highest possible temperature and consider using in-bin cooling or dryeration to reduce energy use and increase dryer capacity. If using a bin dryer, use a stirring device to reduce over-drying. When shopping for a new grain dryer system, make energy efficiency part of the buying decision.

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Chapter 9
Irrigation Energy

Scott Sanford and Aluel Go

9.1 Introduction

Irrigation can aid growers in reducing risk due to uneven distribution of rain during the growing season and growing crops on coarser soils with lower water holding capacities. In the Northeast Quadrant of the United States, Irrigation is used on an average of 2.6% of farmland (Table 9.1). The most intensive use (on a percent basis) is Delaware at 38.3%, where droughty soils benefit dramatically from irrigation. The states with the highest total amount of land area irrigated are Illinois, Indiana, Michigan and Wisconsin, which combined have over three quarters of all irrigated land in the region. In many of the states, irrigation is primarily used for high value products such as fruit, vegetables, nursery crops. For some high value products, irrigation provides an additional protection from crop damage due to excessive sun and heat exposure.

The energy required for irrigation will depend on the type of irrigation system, the amount of water being pumped and height the water is lifted. There are three main ways to reduce irrigation energy use: only pump the amount of water needed to maintain plant production, use efficient pumps and reduce the irrigation system pressure.

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Table 9.1 Irrigation use in the Northeast United States

State	Total acres farmland[a]	Total acres irrigated[b]	Percent Irrigated
Connecticut	381,539	6104	1.6
Delaware	525,324	201,305	38.3
Illinois	27,006,288	566,024	2.1
Indiana	14,969,996	582,611	3.9
Kentucky	12,961,784	58,234	0.4
Maine	1,307,613	35,695	2.7
Maryland	1,990,122	125,024	6.3
Massachusetts	491,653	19,311	3.9
Michigan	9,764,090	827,010	8.5
New Hampshire	425,393	3218	0.8
New Jersey	734,084	89,941	12.3
New York	6,866,171	47,974	0.7
Ohio	13,965,295	39,258	0.3
Pennsylvania	7,278,668	40,586	0.6
Rhode Island	56,864	3231	5.7
Vermont	1,193,437	3022	0.3
Virginia	7,797,979	48,248	0.6
Wisconsin	14,318,630	454,362	3.2
Total	122,034,930	3,151,158	2.6

[a] NASS (2019)
[b] NASS (2018)

9.2 Only Pump the Amount of Water Needed

Excess irrigation is a common energy waster in irrigation systems, as extra water requires extra pumping energy, but typically drains off the site without providing benefit to the crop. To avoid excess irrigation, the evapotranspiration (ET) of the crop needs to be estimated or soil moisture measured. The typical objective is to keep the soil moisture above 50% available water by volume but leave room for potential rainfall to minimize leaching of water below the root zone of the crop being grown. Occasionally, such as when growing wine grapes, crops may be intentionally deprived of irrigation in order to cause stress-induced changes to the quality of the fruit. ET can be estimated using climatic conditions and is published daily during the growing season by universities, irrigation districts and state governments. It can also be measured on farms with ET gages or lysimeters. Knowing the soil water holding capacity, the current soil water content, the predicted ET of the crop for the next few days, rain predictions and the irrigation system capacity (acre/inch-hour), an irrigation manager can determine the amount of irrigation water to apply so the crop is not under stress but doesn't apply excess water that would run off or drain beyond the root zone of the crop (Scherer, 1999).

Related to this, improving the uniformity of an irrigation system can reduce energy use, since the farmer needs to irrigate until the entire field is well watered. As a result, improved uniformity reduces the need to over-water some portions of the field just to ensure that all portions of the field receive enough water.

Maintenance of irrigation systems, by finding and eliminating leaks, is another important strategy for reducing the amount of water needed.

Lastly, drip or micro irrigation has the potential to reduce water use by 35–50% (Sanford and Panuska, 2018). It is accomplished by using drip tape to apply water very slowly just in the area of the plant's root zone. This saves water, energy, reduces fungal diseases because the leaves stay dry and reduces weeds because the area in between the rows stays dry. Water is saved because it only wets the area where the plant's roots are but also reduces evaporation and wind loss that happens when water is distributed through the air. Material cost and labor are higher depending on the crop and whether the drip tape can be used multiple years before being removed from the field. One disadvantage of drip tape is that it must be removed in order to till the ground for subsequent crops. This can be overcome by using subsurface drip irrigation where rigid tubing is buried below the tillage level to supply crops with water. It has the advantage of supplying water with no evaporation or wind losses but is higher in cost to install and harder to monitor application rates or leaks. In very arid climates, it might be necessary to have some type of surface irrigation to establish the crops until the plant roots reach the wetted area of the sub-surface irrigation.

9.3 Variable Speed Well Pumps

Variable speed drives for irrigation pumps can reduce energy use and improve the uniformity of water application.

One use for a variable speed motor drive is on a center pivot irrigation system that has an intermittent end gun or a corner system. When an end gun or corner system turns on and off, it affects the system water pressure and the uniformity of water distribution. Some manufacturers have designed their systems to compensate for the pressure changes by changing the system ground speed or turning on/off extra sprinklers to help maintain the system pressure. Using a pressure transducer to measure the irrigation system pressure and a variable speed drive to regulate the well pump speed in order to maintain a set pressure, will reduce pressure changes which result in uneven water distribution. This application may not save substantial amounts of energy but ensure the proper distribution and utilization of the irrigation water that is applied.

The second use of a variable speed drive is for the situation where one well is supplying water to two or more center pivot systems. In this case the center pivot closest to the well will be operated at a higher lateral pressure than the one farthest away because the pump runs at a constant speed. The center pivot system further away from the well will have a lower lateral pressure due to the pressure losses in the pipeline between the well and the pivot. If a variable speed drive is used on the pump, center pivot closest to the well can be operated at a lower pressure, thus saving energy.

Utilizing a variable speed drive on a pump can negatively impact pump efficiency. As a result, careful analysis is needed to ascertain the potential for savings relative to the cost of implementation.

9.4 Reduce the Irrigation System Pressure

Reduced operating pressure allows pumps to run at a lower pressure, which usually means that energy use is reduced. Drip or micro irrigation, with low pressure emitters, can be used instead of higher pressure overhead spray systems to dramatically reduce system operating pressure. However, drip irrigation is not suitable for all applications.

The water source for irrigation can affect the water pumping energy input. Irrigation systems that use surface water might flow by gravity to the field and run down furrows to the opposite end of the field requiring no energy but typically with poor uniformity of distribution. For sprinkler irrigation, water needs to be raised to the level of the field and be pressurized to distribute it. The amount of head required (in feet or meters of water column, or expressed as pressure at the pump) will equal the head needed to lift the water to the field plus the pressure drop due to pipe friction and the head pressure needed for distributing the water. Growers can't control the height the water needs to be lifted from the water table to the field, but they can reduce friction losses by sizing pipes for a maximum of 5 ft per second (1.5 m/s) water velocity and using low pressure sprinkler technology to reduce pressure head requirements. Converting a system from high pressure (> 60 psi or 415 kPa) to a lower pressure will reduce the horsepower requirement and save energy. A typical irrigation system in Wisconsin would have a 7–8 HP reduction for every 10 psi (70 kPa) of system pressure drop at the pump. The disadvantage of reducing system pressure on an existing sprinkler irrigation system is the water won't be "thrown" as far which increases the water application rate in the vicinity of each sprinkler head and can lead to runoff and erosion on sloping ground or soils with lower percolation rates. When reducing pressure, the sprinkler package will need to be changed and sometimes the pump may need to be pulled from the well and modified. If the sprinkler package is worn out, this is an opportune time to consider modifying the system to a lower pressure.

In some cases, one well pump may provide water for multiple irrigation systems. In this case the irrigation systems often operate at different pressures. The system closest to the pump will operate at a higher pressure than the irrigation system further away. This is necessary when a constant speed pump is used. If a variable speed drive is used to control the pump, the closer irrigation system can operate at the same pressure as the far system. The amount of energy that can be saved will depend on the amount of irrigation system pressure reduction that is possible.

9.5 Use Efficient Pumps

The type of irrigation pump selected for an irrigation system can affect the energy use for irrigation. Deep well turbine and submersible pumps are the most efficient with an average efficiency of 80–85% and are typically used for pumping ground water but can also be used for surface water pumping applications. Centrifugal pumps are used for surface water pumping and come in self-priming or non-self-priming configurations. Non-self-priming pumps are about 5–9% more efficient than self-priming pumps. When sizing a pump to a system, the pump should operate in the highest efficiency range of the pump's capacity. If the system pressure is modified, it may reduce the pump's efficiency. A pump test can help determine the

Example: Irrigation Re-nozzling to Lower Pressure

A grower in southern Illinois has received an EQIP grant to test and improve the distribution uniformity of his quarter section center pivot irrigation system. A uniformity test shows the nozzles are worn out and need to be replaced, Fig. 9.1. The irrigation dealer proposes that he re-nozzle with a low pressure sprinkler package. This would include the sprinkler package, a booster pump for the end gun and pulling the well pump to modify it to work at the same pumping capacity at the lower pressure. The total cost is $11,500 for the upgrades. It would reduce fuel costs by about $2500 per year and have a simple payback of 4.6 years.

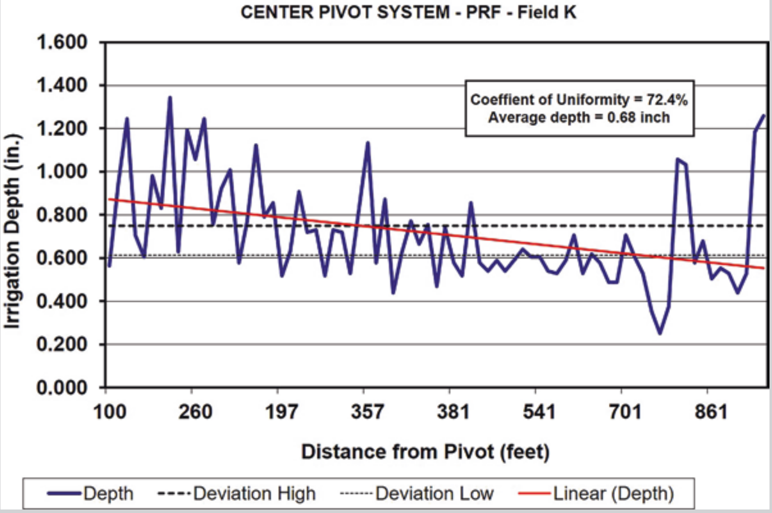

Fig. 9.1 Irrigation depth decreases with distance, indicating nozzle wear

well pump efficiency and determine if it needs maintenance to keep it running efficiently. A well test can also determine the rate water is flowing into the well so the pump is properly matched to the well's capacity.

9.6 Variable Rate Irrigation

Computers and Global Position Sensing (GPS) technology have given us the ability to irrigate fields almost by the square foot. These systems are useful if the water holding capacity of the soil under a center pivot varies widely. The systems can apply more water on the coarse soils and less on the soils with more water holding capacity. This saves water and energy.

There are three different options for accomplishing Variable Rate Irrigation (VRI). The first is to simply change the speed of the center pivot to vary the amount of water applied to a pie-shaped sliver of the area covered by the center pivot, Fig. 9.2. One zone might be five degrees of rotation. The irrigation rate will be the same in the sector-shaped zone. The second type of VRI is Zone Control. Groups of nozzles can be pulsed (rapidly turned on and off) to change the water application rate. This allows the cropland under the pivot to be divided up into circular ring sectors, Fig. 9.3. The area in the circular sectors is larger as the distance from the pivot increases. The number of sectors will depend on the number of nozzles per group. A typical system might have 8 or 9 groups or zones of sprinkler nozzles along the

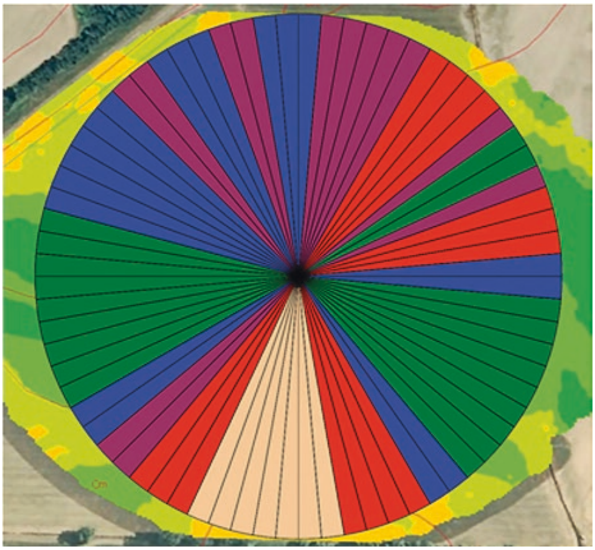

Fig. 9.2 Polar plot of center pivot irrigation coverage using VRI speed control

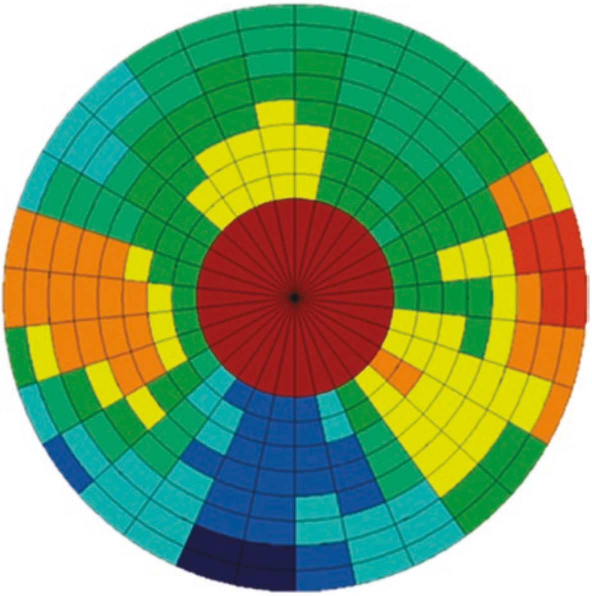

Fig. 9.3 Polar plot of center pivot irrigation coverage using VRI zone control

pivot length, each being 5–10 degrees of rotation for a total of 324–648 management zones under a quarter section center pivot. The first group of nozzles from the center pivot out may have more sprinklers mainly because of the smaller area in the zones. The most variable system has individual nozzle control. In this case, the management zone is the width of a coverage area of a single nozzle by the degrees of rotation used. This could provide upwards of 5000 management zones for a quarter section center pivot.

9.7 Reduce Water Wind Drift

Applying irrigated water as close to the crop as possible increases the likelihood of getting the water where it is needed the most rather than it drifting off the field. This not only improves irrigation application effectivity but can also reduce the amount of water used. For center-pivot irrigation systems this means lowering the nozzles as close above the crop without hindering water distribution and coverage.

Refrain from irrigating during windy days to avoid water wind drift loss and uneven water application.

9.8 Grants

The USDA – National Resource Conservation Service (NRCS) has programs in most states to improve irrigation efficiency, reduce the amount of water require to grow a crop and educate growers on how to use the latest technology. Contact your local Farm Service Agency for assistance.

9.9 Summary and Regional Outlook

Energy can be reduced in irrigation by only applying water when needed, reducing the irrigation distribution pressure, using efficient pumps and using variable speed pumps. In the Northeast United States, irrigation is not universal or widespread in its use. In many areas, it is reserved for use with higher value specialty crops such as fruit or vegetables or in areas with sandy soils. The use of irrigation in the region is fairly stable and is not expected to exhibit dramatic growth or changes in the coming years.

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Chapter 10
Maple Syrup Production Energy

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10.1 Introduction

Maple syrup production is a distinctive Ag enterprise in the Northeast United States, and can be found in the cooler portions of the region where Sugar Maple (Acer sacchrum) trees readily grow. It consists of growing and caring for the trees, collecting the sap during late winter or early spring of each year, and concentrating that sap to create the syrup. The majority of the energy used for maple syrup production is used to evaporate water to concentrate the sugar content of the sap from about 2% to 67%. This requires the evaporation of about 40 gallons of water to get 1 gallon of maple syrup (Heiligmann et al., 2006). Maple syrup production is energy intensive if using conventional methods and equipment requiring 3 to 4 gallons of heating oil (or the equivalent energy) to produce 1 gallon of finished maple syrup.

A recent review of maple syrup producers in Michigan found that, on average, 91% of energy use was for sap processing, with 7% for lighting, and 2% for water pumping. The energy use index for the facilities averaged 33.6 kWh or 0.83 gallons of heating oil equivalent per gallon of syrup produced (Go 2018). A 2003 survey of Wisconsin Maple Syrup producers using fuel oil, natural gas or L.P. gas had an average use of 69 kWh or 1.7 gallons of heating oil equivalent per gallon of maple syrup produced with a range of 39.1–133 kWh or 0.97–3.29 gallons of heating oil equivalent (Sanford 2003).

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10.2 Energy Efficiency for Sap Boiling

Traditional flat bottom evaporation pans using firewood in a naturally aspirated arch (firebox structure on which boiling pans are placed) will have inefficient combustion and is a relatively ineffective heat transfer method for boiling sap. The firebox requires turbulent air flow to completely combust the pyrolysis gases from burning wood and time and surface area to transfer heat through the evaporator pan material into the sap. Switching to a forced-air arch with a higher combustion efficiency (percent of fuel energy transformed to heat) and a higher thermal efficiency (percent of heat transferred to sap) can be an effective way to reduce fuel use and improve efficiency of operation. Having air turbulence in the combustion chamber is important for complete combustion of the fuel; wood, oil, or gas. Air injection under and over the fuel can provide enough oxygen for complete combustion. Wood fired evaporator arches can benefit from forced air for better combustion. Insulating the fueling door will also reduce the heat loss from the firebox (Fig. 10.1). The door can be insulated with 1 or 2 inches of ceramic fiber insulation sheets.

Some producers have switched from cordwood to wood pellets as their fuel. Even though the pellets are more expensive, the improved efficiency more than compensates for the fuel price, resulting in a lower operating cost.

Energy use for boiling down the sap can be reduced by using high surface area pans and recovering the heat from the steam to preheat or evaporate sap. The key for efficient boiling pans is a large surface area to transfer heat efficiently. This is typically done by adding a “flued” bottom to the primary boiling pan. The flues either hang down from the bottom of the pan (drop flues, Fig. 10.2) or protrude up into the

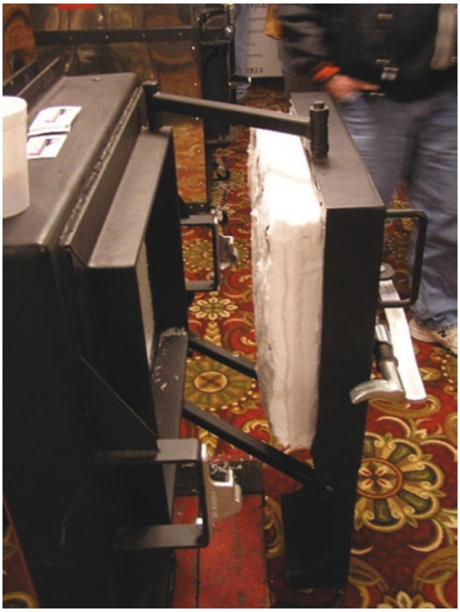

Fig. 10.1 Insulated arch fueling door

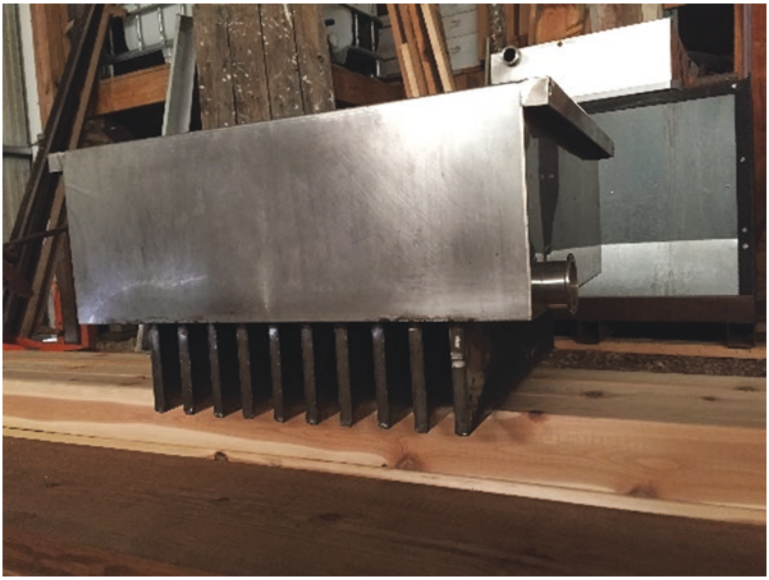

Fig. 10.2 Drop flue evaporator pan

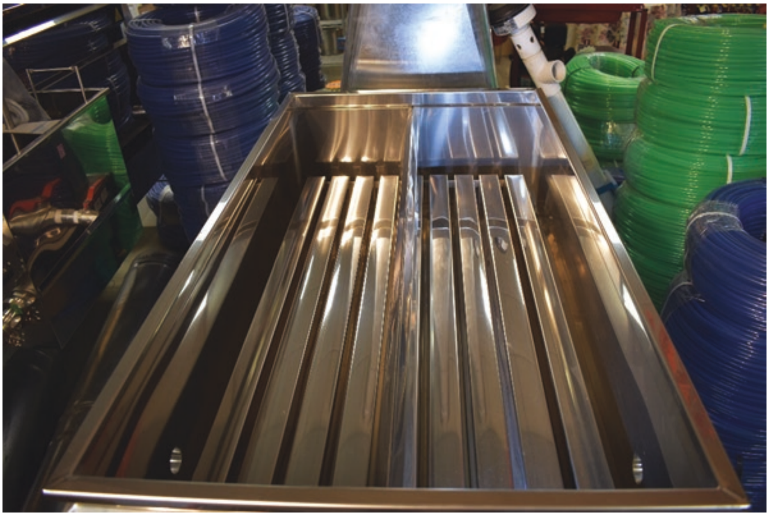

Fig. 10.3 Raised flue evaporator pan

pan (raised flues, Fig. 10.3) to increase the amount of heat transfer area. A 2′ × 4′ (0.6 × 1.2 m) flat pan will have 1152 square inches (0.74 m^2) of heat transfer area while the same size pan set with drop flues will have 3277 square inches (2.1 m^2) or 184% more heat transfer area. More recently, some companies have designed hybrid pans that have flues that both drop below the top of the arch and extend up into the pan. This results in an evaporator with a small footprint and higher evaporation capacities.

10.3 Heat Recovery

The steam evaporating from the pans contains substantial heat that can be used to preheat the sap before entering the boiling pan. There are two methods to recover heat. First a preheater can be used. A preheater is piping that the cold sap is pumped through before the sap enters the boiling pan. The preheater and drip tray are mounted above the flue pan (Fig. 10.4). As the steam from the boiling pan surrounds the preheater, heat is transferred to the sap as the steam condenses. The drip tray routes the condensate out of the evaporator so it doesn't go back into the boiling pans. A preheater can be used with or without a hood but a hood helps to concentrate the heat. If boiling in a building, a hood allows the steam to be routed out of the building without deteriorating the structure. A preheater can reduce energy use by about 15%. A second method of heat recovery is an additional pan that is placed on top of the primary boiling pan to capture the latent energy from the steam to heat the incoming sap. This is referred to as a "Steam Pan". The bottom of this pan either has triangular ribs or flues to increase the heat transfer area, and has air lines submersed in the sap. Low pressure air is injected into the sap, creating some evaporation. Pans or channels collect condensate from the condensing steam and route it out of the

Fig. 10.4 Evaporator preheater

evaporator. The heat transferred from the steam can increase the temperature of the sap to about 200 °F (94 °C). These units are called by various brand names, such as "Piggy-back", "Steam-Away", Sap-Raider, and "Economizer". They can reduce the energy used to produce maple syrup by approximately 50–65%.

10.4 Reverse Osmosis Systems for Energy Efficiency

Reverse Osmosis (RO) technology can be used to dewater the sap, removing up to two-thirds of the water before boiling to concentrate it to maple syrup. It functions by using pressure to separate water from the sap across a membrane, leaving the remaining sap in a more concentrated state. Reverse Osmosis uses only a fraction of the energy that would be required to boil the sap, primarily consisting of electricity to run pumps. However, RO cannot be used for the entire process of concentrating the sap. It is necessary to do some boiling to caramelize the sugar to impart the maple favor.

Example: Maple Syrup Reverse Osmosis

A maple syrup producer is looking for a way to reduce the amount of boiling time. They are tapping 1000 trees and making about 400 gallons (1500 l) of maple syrup per year. They have a 4 ft x 10 ft (1.2 m × 3 m) propane-fired evaporator with a preheater and can boil about 150 gallons per hour. They are looking at purchasing a reverse osmosis unit that can process 600 gallons per hour for $11,000. The sap will be concentrated to 12 brix (12% sugar). Their current propane fuel usage is 1836 gallons (7000 l) at a cost of $1.50 per gallon for an annual cost of $2755. The reverse osmosis unit would be expected to save $2160 annually and reduce boiling time by 75%. The simple payback is 5.1 years.

10.5 Regional Outlook and Summary

Maple Syrup producers in the region are steadily upgrading the efficiency of their operations. High efficiency wood pellet boilers have been popular upgrades for many producers, while Reverse Osmosis systems are becoming standard equipment for larger operations. While the "romance" of boiling sap over an open fire often attracts people who are new to maple syrup production, it usually does not take long before the benefits of energy efficient systems attain a romance all their own.

With the use of reverse osmosis, drop or raised flue boiling pans, steam pans or preheaters, and insulation, the energy required to produce a gallon of pure maple syrup can be reduced to 1 gallon of fuel oil (or equivalent), a 65–75% reduction in energy input.

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Chapter 11
Greenhouse Energy Efficiency and Management

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11.1 Introduction

After labor costs, energy costs are the largest expense for most greenhouse growers with operations located in the northern tier of the United States. These energy costs include fuel for the heating systems and electricity for cooling (ventilation and/or cold storage) systems, supplemental lighting systems, pumps, and other miscellaneous electrical equipment (Aldrich and Bartok, 1994).

The relative size of the energy costs for each of these equipment categories depends on equipment electricity consumption, operating times, electrical conversion efficiencies, local weather conditions, crop requirements, and growing strategies. In other words, the energy costs for a particular greenhouse operation are closely related to local conditions and decisions, and are therefore highly variable from greenhouse to greenhouse operation. For greenhouses located in colder climates, the energy cost for operating a heating system is likely the dominant cost component (Fig. 11.1). However, if that greenhouse is also equipped with a supplemental lighting system, its energy costs can exceed the energy cost for the heating system depending on the operating strategy that is used for the lamps (Runkle and Both, 2011).

The energy consumption of greenhouse ventilation systems is typically much smaller than that of the heating or supplemental lighting system (Fig. 11.2). For greenhouses outfitted with natural ventilation (without electric fans, just strategically placed windows that open and close), the energy cost for ventilation is typically small (Sanford, 2010a). For greenhouses outfitted with electric fans (mechanical ventilation), the associated energy costs are higher since those fans will be running for many hours during the summer months. The choice between natural

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Fig. 11.1 Examples of a hot air (left; unit heater) and a hot water (right; boiler) heating system used in greenhouse operations. (Photographs by A.J. Both)

Fig. 11.2 Examples of supplemental lighting (left; using light emitting diodes) and mechanical ventilation (right; using electric-driven exhaust fans) used in greenhouse operations. (Photographs by A.J. Both)

or mechanical ventilation depends on local weather conditions and crop requirements, so greenhouse growers may feel compelled to pick one system over another.

The energy consumption associated with most greenhouse equipment shows distinct seasonal patterns, with heating and supplemental lighting occurring predominantly during the colder and darker season (winter), and ventilation during the warmer season (summer). Nevertheless, substantial energy consumption can also occur during the transition periods (spring and fall).

Energy prices generally fluctuate by season and have also experienced several substantial swings over the last two decades (mainly as a result of political and economic forces). These trends make energy management more challenging and have resulted in some growers going out-of-business, while others have made large investments in alternative energy systems that later proved less profitable than initially expected. In addition, most energy consumption results in emissions of so-called greenhouse gasses when fuels are combusted to produce either heat or electricity. Consumers are increasingly aware of the negative impacts of emissions and their contribution to global warming and climate change. It is likely that the volatility in energy prices will persist for years to come, making it critically important that greenhouse growers implement sustainable energy management plans.

Energy management plans consist of multiple components. The first component is an energy inventory of how and what type of energy is currently used in different processes (heating, cooling, lighting, transportation), combined with some benchmarking against similar operations. Using this information, an energy conservation plan can be developed that includes operating strategies, an evaluation of various conservation measures that could be implemented (e.g., insulating distribution heating pipes, sealing unintended crack and openings), and a selection of those measures that provide the biggest return on investment (e.g., the installation of a movable energy curtain, a reduction in the nighttime temperature set point). Conducting an energy inventory is the recommended first step for growers interested in reducing their energy costs. After that, additional energy management options should be investigated (e.g., upgrading to more energy efficient equipment) to determine how much energy saving is feasible. This step can involve taking a bigger view of the situation (e.g., what are the future plans for the greenhouse operation, what are the trends in fuel prices and availability, current or future environmental regulations, desire to reduce overall emissions). Finally, it is important to assess the before-and-after situations so that the improvements can be evaluated. This last component is important in order to learn from mistakes and to adjust expectations (when necessary) for future phases of an energy management plan.

In addition to conventional energy sources (such as natural gas, propane, fuel oil; i.e., fossil fuels), alternative energy sources (e.g., solar, wind, ground source or geothermal, hydro) can be used to operate a greenhouse (Fig. 11.3). Prices for alternative energy sources have steadily come down, and in many locations they have become competitive with conventional energy prices. However, the most widely used alternative energy sources (solar and wind) are intermittent (not reliably available during any given 24-h period), requiring a storage system and/or a connection to the utility grid. Nevertheless, alternative energy sources are an attractive option to many greenhouse growers and their use is expected to increase significantly in the near future.

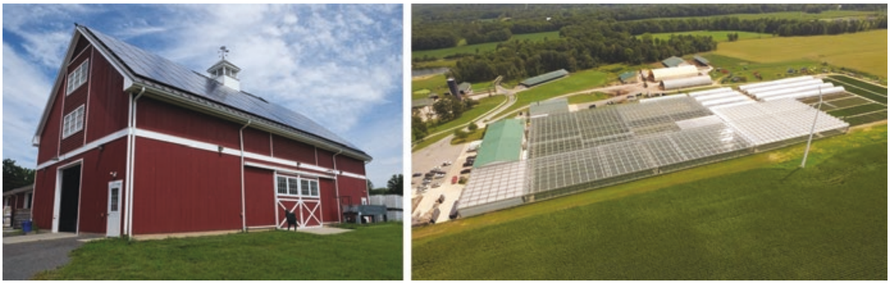

Fig. 11.3 Solar panels (left; installed on the roof of a barn) and a wind turbine (right; delivering electricity to a greenhouse operation). (Photograph on the left by A.J. Both. Photograph on the right from the website of Eagle Creek Wholesale Growers, Mantua, OH)

Fluctuations in heating fuel prices can be circumvented to a certain extent by forward contracting or bulk purchases during off-peak time periods with typically lower prices. Bulk purchases may require sufficient capacity for on-site storage to overcome a period of higher prices. Fluctuations in electricity prices are more difficult to deal with because most often storage is not an option. In addition, larger electricity consumers (such as a greenhouse operation) may be subject to on- and off-peak pricing schemes and/or demand charges. Therefore, growers that use substantial amounts of electricity should implement a well-designed electricity management plan in order to keep overall electricity costs down as much as possible. A comprehensive energy audit is a good starting point for the development of a realistic energy management plan. A discussion with the local electric utility can reveal the availability of alternative rate structures that could result in lower costs.

11.2 Current Status Across the Region

The scale and scope of greenhouse operations varies widely, ranging from simple unheated high tunnels that are used to extend the growing season to computer controlled multi-span greenhouses that are used to grow plants year round. Because of this, energy efficiency improvements span a wide range of possible strategies and associated costs. Applying a “one size fits all” approach is typically not feasible, and each facility should be considered separately. Nevertheless, since heating costs are usually a substantial portion of overall production costs, strategies to reduce heating costs such as movable energy curtains, zone heating, high efficiency heating systems, and computer control are common in many greenhouse operations that grow plants throughout the winter season.

There has been recent interest in fully enclosed production systems (sometimes called plant factories), in which plants are grown inside a building with 100% electric lighting and air conditioning for temperature and humidity control. Because these systems operate in an enclosed and insulated structure and because of the amount of heat generation associated with the high rate of electricity consumption, heating is usually not an issue. Instead, lighting and air conditioning become the main energy consumers. These energy-intensive plant production systems are only feasible for higher value crops, including crops that are grown for specific phytochemicals (e.g., crops grown for medicinal purposes).

The volatility in energy prices over the last couple of decades has many growers more focused on their energy consumption. A useful starting point for an assessment of energy consumption patterns is an energy audit (Pedersen et al. 2018). These audits are conducted by trained professionals who make an inventory of equipment used, energy use patterns, and energy costs based on utility bills. These audits typically result in recommendations for how best to reduce energy consumption and are often well worth their cost. Energy audits are usually required in order to participate in power company or government incentive programs. Therefore, it is recommended that all growers consider an energy audit as a starting point for a comprehensive energy management plan.

In addition to an energy audit, it can be helpful to contemplate various improvements (e.g., a different glazing material, a different fuel type, or switching to more energy efficient equipment). The USDA has developed a software tool (Virtual Grower) that can be used to estimate energy consumption and cost under various crop production and greenhouse design scenarios. Virtual Grower can be downloaded for free and has proven to be a useful tool for assessing the impact of different alternative approaches to energy conservation. It uses a database with historical weather data for a large number of locations across the contiguous US to calculate energy consumption and cost based on crop selection and timing, greenhouse design, and equipment choices.

After the spike in oil prices in 2008, several growers decided to switch from fossil fuels to alternative fuel systems. Biomass was a common choice and included systems for combusting wood, corn, grasses, and crop residue (Sanford, 2010d). Wood chips or wood pellets can be a good choice for a biomass source if they are readily available within approximately 100 km (60 miles) from the greenhouse operation. A few growers installed solar panels or a wind turbine. Solar panels have become cheaper and more efficient, but they require a large area to produce sufficient output. While building roofs are typically used for residential and commercial installations, installing panels on greenhouse roofs is often not feasible due to the resulting reduction in light transmission. Ideally, solar energy collection could be integrated into greenhouse covering materials without reducing the transmission of wavelengths use by plants, but such materials are currently too expensive. There are a few examples of greenhouse operations with floating solar arrays that are installed in rainwater collection ponds. Wind turbines require sustained wind speeds high enough to generate sufficient electricity. This is not always the case for some greenhouse locations. There may be zoning setback requirements for wind turbines, especially in urban and suburban locations. The variability and intermittency of solar and wind energy make them less attractive as replacements for grid provided energy. If a farm's electric utility allows net metering, any excess energy produced during a low usage period can be banked (exported to the grid) for use at a later time when the solar panels produce too little electricity, allowing farmers to use the electric grid as a battery.

Another energy topic of considerable interest to growers is switching from high intensity discharge (HID) lamps (e.g., high-pressure sodium or metal halide lamps) to light emitting diode (LED) lamps as the supplemental lighting source for crop production. Supplemental lighting to increase photosynthesis (also called assimilation lighting) requires relatively high intensities, and thus uses a lot of electricity. Photoperiod lighting (used to induce flowering responses in certain plant species) requires very low intensities, and is therefore not a major electricity user. LED lamps typically consume less electricity compared to HID lamps for the same amount of light output. However, both lamp types still waste a lot of electricity that is converted into heat (more than 50%). This "waste" heat can be helpful (e.g., during a cold night) or not (when it raises the indoor temperature above the set point) and should be considered in any energy assessment of the greenhouse.

Ventilation fans and irrigation pumps can also use substantial amounts of electricity (especially when operated over long time periods). Older greenhouses typically used single settings (on/off), or a staged system (a few steps between 0% and 100% output). Such installations rarely provide the correct amount of output, resulting in more frequent cycling of equipment. Newer installations often include variable-speed motors and pumps that can be throttled to deliver the exact amount of output needed. While their initial cost is higher, these systems reduce equipment cycling and are better able to maintain the desired environmental conditions or deliver the correct pressure and volume in an irrigation system. And they save energy.

Energy management plans can be implemented in both new and existing greenhouse operations. While overall better results may be obtainable when designing and constructing a new greenhouse, substantial improvement is also feasible in existing operations. In addition, many growers and their crews are capable of retrofitting most greenhouse components themselves, which can help reduce installation costs. Devising and implementing an energy management plan is worthwhile exercise for any greenhouse operation.

11.3 Practical Tips

Recommended case studies are described in Sanford (2010e) and Callahan (2014). While both discuss heating greenhouses with biomass, the thought process involved can be applied to other energy systems as well. Some practical tips learned from the case studies include:

- Energy conservation methods should be considered first before considering switching to alternative energy sources and/or new equipment
- Regular equipment maintenance will help maintain optimum system performance
- Collecting adequate system and environmental data before and after any energy use changes will greatly help with the assessment of those changes
- Changing to a different heating fuel source typically involves equipment changes and may result in additional waste products (e.g., combustion ashes) and labor requirements
- When the cost of fossil fuel energy sources is (relatively) low, it is often challenging to financially justify the switch to alternative energy sources
- When considering a fuel source switch, always check the regulatory implications (e.g., air emissions regulations for biomass combustion) and consider the long(er) term availability of the fuel
- Different states have different regulations, and the regulations can change over time
- Always investigate the availability of incentive programs, grants, loans and tax breaks when considering changes in energy consumption

- Evaluating greenhouse energy use choices on a regular basis (e.g., once every 5 years) can help ensure that the cheapest energy source is used (energy prices fluctuate)

The following ballpark numbers can be used as a starting point for different energy savings considerations (note that the percentages are not cumulative; e.g., switching to double-layer glazing material and installing an energy curtain will result in overall energy savings of less than 60%):

- Switching from a single layer to a double-layer glazing material: 30% energy savings
- Installing an energy curtain: 30% energy savings (Sanford, 2010c)
- Installing a condensing heating system: 15–25% energy savings (Sanford, 2010b)
- Incorporating energy storage (e.g., an insulated hot water tank): 15–25% energy savings
- Using computer control and variable speed pumps/motors: 5–15% energy savings
- Lowering the greenhouse temperature set point: 5–15% energy savings
- Preventing air infiltration through unintended cracks and openings: 5–10% energy savings
- Adding insulation where feasible: 5–10% energy savings

11.4 Outlook for the Future

Delivering the right amount of heat at the right location can result in energy savings. For example, switching from a hot-air heating system to a hot-water heating system allows for more uniform and localized heating, especially when root-zone heating (heating tubes placed in the floor or on the bench) is used (Fig. 11.4). Savings are also possible when the temperature set point is allowed to drift over a specific temperature range, reducing the number of times the control system needs to take

Fig. 11.4 Examples of root-zone heating systems: bench heating (left, heating tubes installed between the bench surface and the bottom of the seedling flats) and floor heating (right, heating tubes embedded in the concrete floor). (Photographs by A.J. Both)

corrective action. Equipment advancements will continue to occur and they will certainly impact their overall energy consumption. For example, recent advances in LED technology have resulted in increased control of their spectral output, dimming capabilities, and improved energy conversion efficiencies.

It is challenging to study the impact on a greenhouse operation of different scenarios that are part of an energy management plan. Results from experiments with (small) research greenhouses do not always translate well to (typically much larger) commercial greenhouses. And using commercial greenhouses does not always allow for a proper control treatment (e.g., comparing a new versus the original system). Collecting data over longer time periods (e.g., a growing season, or an entire year) can also be challenging. Growers interested in changing their energy consumption are encouraged to partner with Extension personnel and equipment companies in order to devise and implement the best energy strategy.

It is unlikely that concerns over energy issues and their associated environmental impacts will disappear anytime soon. Fossil fuels are convenient and we have built an entire infrastructure around them, but we have mostly neglected to consider their negative environmental impacts (especially carbon emissions). We are in the middle of a transition to alternative energy sources and this transition will likely involve some challenges along the way. Therefore, energy will continue to be an important issue for the greenhouse industry and growers are advised to stay informed, develop comprehensive energy management plans, and implement changes when they make economic sense and when they contribute to reducing the emissions of greenhouse gasses.

11.5 Conclusions and Summary

At the time of writing (2021), energy prices are manageable, and less of a concern to most growers. But recent history teaches us that this situation can change quickly. A doubling or even tripling of conventional fuel prices is not inconceivable. If that were to happen, many growers would quickly find it difficult to produce a competitive product for the marketplace. Some might go out-of-business, while others would scramble to find alternative energy options. While nobody knows what will happen, history also teaches us that it is better to be prepared than to be caught unprepared. As this chapter outlines, developing an energy management plan requires an appropriate assessment of the current situation and a strategy for implementing a new approach. Any energy management plan requires careful thought, adequate funding, and time for implementation. It is unlikely that a new energy management plan can be implemented overnight, so each grower needs a long-term plan. Members of the Extension community are ready to assist when needed.

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Sanford, S. 2010d. Biomass energy for heating greenhouses. University of Wisconsin Fact Sheet A3907-04.

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Useful Web Sites

Greenhouse Engineering, University of Massachusetts-Amherst - https://ag.umass.edu/greenhouse-floriculture/fact-sheets/greenhouse-engineering

Virtual Grower - https://www.ars.usda.gov/midwest-area/wooster-oh/application-technology-research/docs/virtual-grower-3-model/

National Greenhouse Manufacturers Association - https://ngma.com/

Chapter 12
On-Farm Energy Production: Solar, Wind, Geothermal

Arend-Jan Both

12.1 Introduction

Since the start of the twenty-first century, crude oil prices have been less predictable than during decades prior, and have seen several steep spikes and declines. These fluctuations have reverberated through the entire energy system. In addition, mankind has become more aware of the impact of carbon emissions associated with the combustion of fossil fuels on our environment, making the use of fossil fuels less attractive. As a result, many farmers have become more interested in alternative energy sources, including solar, wind and geothermal energy. Each of these sources can generate energy without the need for a fuel supply, and with little or no carbon emissions. However, some carbon emissions are often associated with the use of raw materials and the construction of energy generating equipment, as well as the disposal of that equipment after it reaches its useful life. Over the last few decades, the equipment used to generate alternative energy has seen rapid technological advances as well as sizable reductions in production costs, further increasing the appeal of alternative energy sources. This chapter addresses several of the key aspects associated with the use of solar, wind and geothermal energy on the farm.

12.2 Solar

Figure 12.1 shows how much solar radiation, on average, is received per day on a horizontal surface across the United States. A map like this can be used to determine the best locations for the installation of energy systems that convert solar radiation

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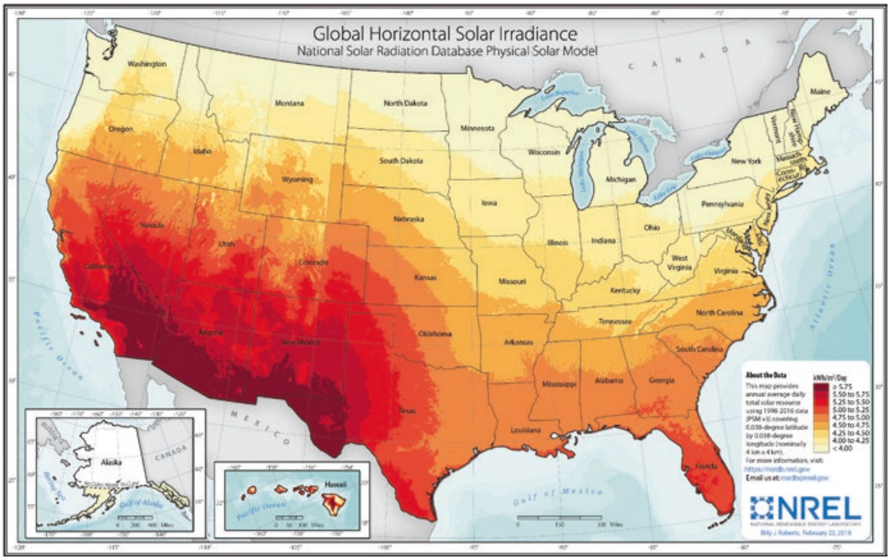

Fig. 12.1 Solar radiation resource map for the United States. Map produced by the National Renewable Energy Laboratory. (Image source: https://www.nrel.gov/gis/solar.html)

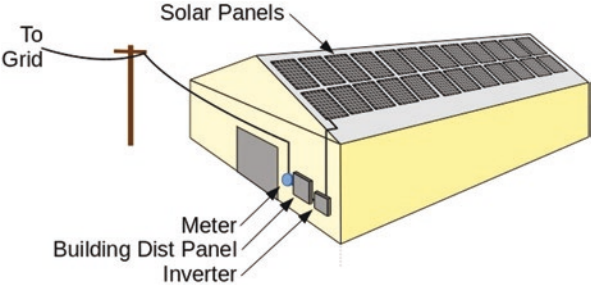

Fig. 12.2 Diagram of a solar PV system installed on a farm building

into useful energy. As the map shows, the Southwestern US and Hawaii are locations with a high availability of solar radiation. But other parts of the country can also be used for solar energy generation, despite the fact that their generation potential is lower.

Solar energy applications primarily consist of two different technologies: (1) Photovoltaic (PV) panels (a.k.a. modules), and (2) Solar Thermal Collectors.

- Photovoltaic (PV) Systems (Fig. 12.2) – convert a portion of the energy contained in light particles (photons) into free-flowing electrons that can be used to power electrical devices. PV systems generate direct current (DC) electricity that can be used in DC systems, or the DC current can be converted into alternating current (AC) that is used to power a variety of equipment or appliances or can be

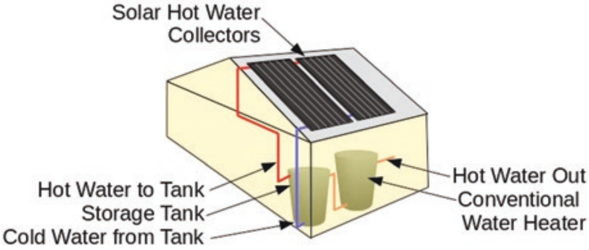

Fig. 12.3 Components of a solar hot water system

delivered to the local grid. Overall conversion efficiencies for PV panels are relatively low at approximately 20%.

- Solar Thermal Collector Systems (Fig. 12.3) – absorb a portion of the heat energy that is part of solar radiation and use it to heat a fluid (e.g., air, water, synthetic oil). The warm/hot fluid is then typically used for heating purposes. Collector efficiencies can range between 30% and 80% depending on operating conditions.

Common challenges with solar energy include the fact that the location of the sun in the sky moves throughout the day (possibly necessitating tracking devices for optimum interception, or the installation of additional panels to make up for lost energy generation), the amount of solar radiation received depends on local climate, season, latitude, and may not sync with the highest energy demand for a particular application. In addition, the availability of solar radiation is intermittent (day and night time intervals, cloud cover).

Elements of a solar photovoltaic system installed on a farm building are shown in Fig. 12.2. In this case, the system is connected to the local utility grid that allows export of excess electricity to the grid, or import from the grid when the panels are not able to deliver sufficient amounts of electricity. A system like this can also be outfitted with batteries as a back-up source, with an option of becoming independent of the local grid.

12.3 Wind

Figure 12.4 shows the average wind speed across the U.S. at a height of 100 m above the ground. The higher the average wind speed, the better a particular location is suited for wind energy. The average wind speed varies depending on the height above the ground and similar maps are available for other reference heights. Lower capacity wind turbines will operate at lower heights above the surface, while higher capacity wind turbines may have a hub height that exceeds 100 m. Note that at a height of 100 m above the ground, the best wind resources can be found across the Midwestern states and offshore.

Wind energy is converted via turbines with typical efficiencies of approximately 50% (typically, the larger the turbine, the higher the maximum efficiency, but the theoretical maximum efficiency is 59%). These turbines convert a portion of the

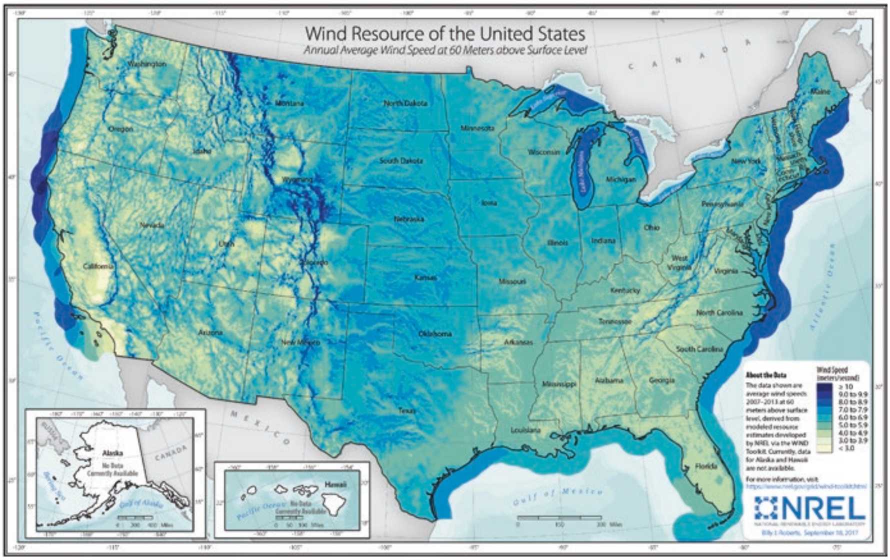

Fig. 12.4 Average wind speed at a height of 100 m above the ground. Map produced by the National Renewable Energy Laboratory. (Image source: https://www.nrel.gov/gis/wind.html)

kinetic energy contained in the airflow into electricity using a generator. The high cost of turbines can only be recovered when the average wind speed at a particular location exceeds a certain minimum value. As a result, not all locations are suitable for investments in wind energy systems. Additionally, it can be difficult and costly to adequately characterize the wind resource for a specific location, particularly for smaller projects. Lack of wind resource characterization can increase project risk for a site, as the system may not perform as desired. Obstructions that impede wind patterns (trees, buildings, hills, mountain ranges) should be avoided. The average wind speed usually increases with the vertical height above ground level, so the most efficient turbines tend to be the taller (bigger) ones. Wind conditions are highly variable at most locations (in speed and direction), and as a result, the energy output of a turbine varies depending on local wind conditions.

12.4 Geothermal

Geothermal energy systems extract energy from below the ground surface. There are two general systems that sometimes are identified by the same name: (1) Geothermal, and (2) Ground-source energy systems.

- Geothermal energy systems (Fig. 12.5) – extract heat energy from significant depths (sometimes several miles down). Often, these systems are sited at specific locations with unique natural geological features enabling project development.

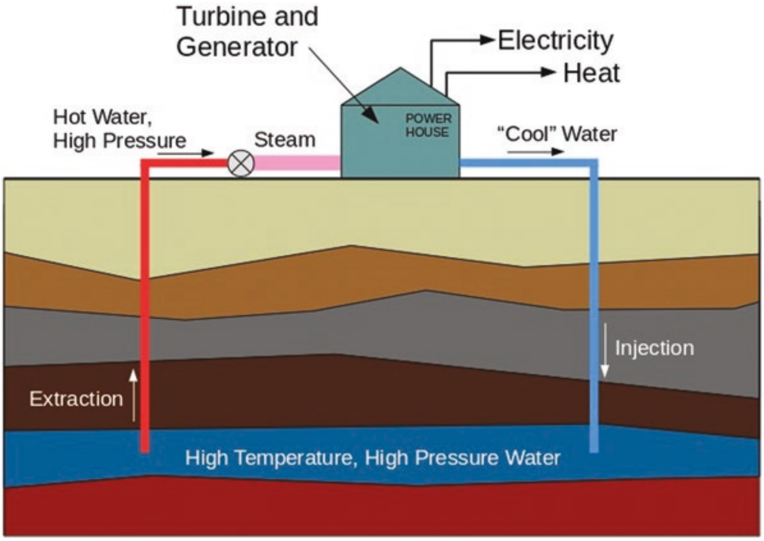

Fig. 12.5 Sketch of a typical geothermal energy system. Note that the underground geology has to be conducive and that deep drill holes (several miles deep) are expensive

At those depths, temperatures can exceed the boiling point of water, allowing the surfacing steam to drive a turbine that generates electricity. Geothermal systems require the right geological conditions and are therefore not feasible in every location.

- Ground-source energy (or heat pump) systems (Fig. 12.6) – circulate heat energy from/into the soil (or a body of water) at a depth of a few feet down (6–10 ft is a common operating depth for horizontal installations), or up to several hundred feet down (in the case of a system with vertical bore holes). Ground-source heat pump systems are attractive across many locations due to the predictable and constant temperatures at (relatively) shallow depths below the ground surface.

One of the advantages of ground-source energy systems is that they can be used for both heating and cooling. This can result in lower installation costs compared to traditional installations that require both a heating and a cooling (air-conditioning) system. During the wintertime, the (shallow) ground temperature is higher than the outdoor temperature, so heat energy can be extracted from the soil and used to heat a structure. During the summertime, the ground temperature is lower than the outdoor temperature, so heat energy can be removed from the structure and transferred to the soil, providing cooling to the structure. The efficiency of ground-source energy systems can be further improved by incorporating an energy storage capability (e.g., in the form of an insulated water tank). Ground-source energy systems are often used to cover baseload heating/cooling requirements, but they may not be an economical option to cover peak loads. Therefore, additional (stand-by) capacity may be needed if it is critical that peak loads can be handled properly when needed.

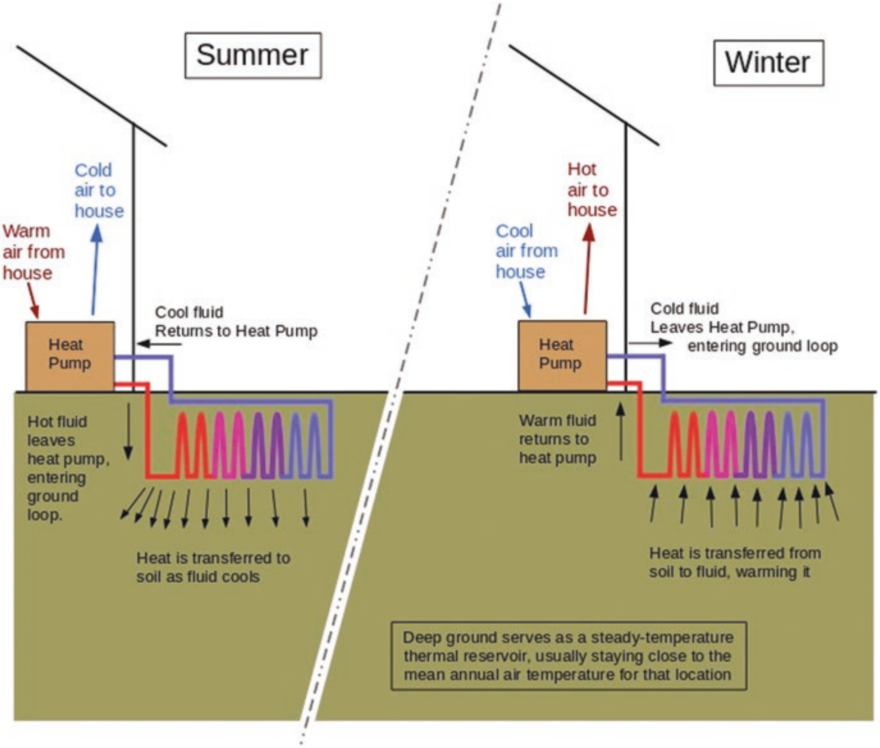

Fig. 12.6 System components of a ground source heat pump system. A single system is used to provide either cooling (during the summertime), or heating (during the wintertime). The ground with its constant temperature serves as heat exchanger: The ground is used to 'dump' heat (summertime), or heat is extracted from it (wintertime)

12.5 Current Status Across the Region

PV systems are becoming very common both for agricultural and commercial/residential applications. The low maintenance aspect of PV systems is seen as a distinctly positive attribute, relative to solar thermal and wind systems. In many cases, the adoption of this technology is aided by a variety of incentive programs such as low interest loans, rebates, or tax breaks. While such systems can be off-grid (and in that case a storage capability is needed for example with a battery backup system), the most common approach is to have them connected to the local power grid via a grid interconnection. That way, any excess electricity can be delivered to the grid (depending on specific arrangements with the local utility) and the grid can be used as a back-up energy source in case on-site energy demand exceeds the generation capacity of the PV system. Often, a key economic ingredient for successful solar PV is the availability of "net metering", whereby excess power production can be fed to the grid and used later at no cost. Not all utility providers allow net metering, despite the fact that some studies show that net metering reduces the overall cost of electricity for all since excess PV production typically occurs on hot summer afternoons, when system-wide electricity demand is often at its greatest. The second key economic ingredient for successful solar PV is the availability of Solar Renewable Energy Credits (SRECs), which provide a payment to producers of solar electricity as an incentive to meet state mandated solar power production targets.

Solar thermal collectors are not very common, but should receive more consideration. Especially in areas with decent solar radiation, solar collectors can lower the cost of water heating. While these systems may not be able to deliver sufficient heat energy for peak demands, they are often capable of delivering a respectable base load. One of the challenges of solar thermal is that, in order to have sufficient hot water on cloudy days, the system must be sized to over-produce heat on clear days. Some studies have suggested that a combination of PV, net metering and an electric water heater can sometimes be more cost effective. However, this should be carefully evaluated for each case.

Large wind turbines as an energy source for farms are not very common, mainly due to the high installation costs and the limited number of suitable sites outside the Midwest region of the U.S. And the output of large turbines is typically not well matched with the electricity needs of a farm. Of course, some farms are excellent sites for so-called wind farms: a grouping of multiple turbines. In those cases, farmers have sold or rented small patches of land (and the right to access those sites) to energy companies that install and operate the turbines. In some cases, arrangements with farmers allow for a financial return to them based on the electricity that is generated. While wind farms create interesting opportunities for some farmers, they are not part of the rest of the discussion in this chapter.

Smaller wind turbines (not to be confused with windmills that harvest wind energy and convert it into mechanical energy typically used to pump water in remote locations) can be an attractive option for farmers as long as the local wind conditions are conducive. Like PV panel systems, on-farm wind systems can benefit from a storage capability in order to overcome the fact that wind energy is an intermittent resource. However, energy storage (e.g., batteries) can be expensive and may not be economical in all situations. Fortunately, battery storage technology is improving and prices are coming down. The magnitude of the wind resource is of critical importance – in a few cases, poorly located wind turbines have actually used more power (from their control circuitry) than they have produced. Sites that are prone to lightning can contribute significant maintenance costs to the system's overall budget.

Geothermal energy systems are not very common, except in locations with suitable geological conditions (e.g., the Pacific Northwest). While these systems may still be feasible in other areas, the very deep drilling needed to access sufficiently high temperature conditions can be prohibitively expensive. But in locations with the right conditions, a virtually unlimited amount of energy can be used to generate electricity (provided the system temperature is high enough) and/or operate a variety of heating processes (e.g., material drying, hot water for processing, building temperature control).

Ground-source energy systems are still more common in residential and commercial applications. Several farmers have also discovered their benefits for providing a baseload for their heating and cooling requirements.

12.6 Practical Tips

Different case studies are discussed in Boyd (2008), Elgin Energy (2019), and Xiarchos and Vick (2011). Some practical tips learned from these case studies include:

Solar PV

- The permitting process can take longer than expected
- Ground based installations are straightforward and quick
- Ground based installations can be combined with simultaneous agricultural uses of the property (e.g., grazing sheep; this dual-use approach is sometimes called agrivoltaics)
- Grid connected systems may require a remote shut-off feature that can be operated by the local power company (in case of maintenance or repairs on the local grid).
- The common life expectancy of PV panels is approximately 25 years.

Solar collectors

- This technology is underutilized at farms across the US
- Dust accumulation on the collectors can reduce the conversion efficiency
- The technology is easy to integrate with existing plumbing and heating systems

Wind

- Not everyone appreciates the aesthetics of wind turbines, making the permitting process sometimes more difficult
- Large (utility-scale) wind turbines are not a good match for most farm operations
- Smaller wind turbines can be used to generate baseload electricity needs
- Not every farm has adequate wind resources

Geothermal heating systems

- Water temperatures as low as 107 °F (42 °C) can be used for greenhouse heating
- Metal corrosion in heating pipes can occur depending on the composition of the well water
- Booster pumps may be required in order to maintain adequate flow rates in heating pipes
- The withdrawal rate from the well should be matched with the system's recharge rate
- When maintained and operated properly, the system's reliability is high

Ground-source heat pump systems

- Horizontal installations are easier, but have a larger footprint compared to vertical systems
- Water-filled ponds (instead of soil) can also be used as the 'rechargeable energy battery'
- Using a single system for both heating (winter) and cooling (summer) reduces equipment costs

12.7 Outlook for the Future

Efficiency improvements and declining system component costs for PV technology will likely continue to further reduce system prices and make this technology even more attractive for agricultural applications. Integrating PV systems into semitransparent glazing materials could be a major boon to the greenhouse industry.

Solar collectors will become more commonplace, especially for locations with higher amounts of solar radiation and/or higher electricity costs. The technology is simple and can be easily integrated into many systems that require water heating.

Interest is growing in renting farmland for utility-scale solar PV installations. This can be a beneficial income source for farmers, but reduces or eliminates the usability of that land for agricultural purposes. Ideally, farm-based utility scale PV would be located on less valuable, agriculturally marginal sites such as south facing slopes that are not suitable for crop production. One variant of utility-scale solar, called "community solar", allows a group of people (a community) to purchase "shares" in a large solar PV facility, and gain individual credit for their portion of the facility's operation, even though their individual homes may be relatively far from the PV facility. Legislation is usually required at the state level to make this business structure possible, but where permitted, it provides an opportunity for farmers to produce renewable energy, gain a new source of income, and connect to their communities in a new way.

Large wind turbines will continue to increase in size as designers look for ways to improve their efficiency. These large turbines will not likely contribute to the energy needs of farms, with the exception of when they are part of a wind farm.

Smaller wind turbines are an attractive energy option for a variety of farm applications if their productivity and maintenance costs fall within acceptable bounds. Some systems are small enough for farmers to install themselves (save for the electrical connections which should always be done by a licensed electrician).

Ground-source energy systems for agricultural applications will receive more consideration as excellent baseload providers, while on-farm installations should include (insulated) energy storage capacity.

Many alternative energy systems are relatively new and have not yet been used on a large scale. Therefore, a variety of challenges will likely emerge, including regulatory issues that have not yet been fully developed. Farmers are encouraged to participate in the regulatory process to ensure that new rules are workable without creating undue burdens.

It is likely that grid-connectivity will remain an important component of many alternative energy solutions so that the grid can provide back-up power when the alternative energy supply is interrupted or temporarily unavailable. But substantial changes in the generation and supply of electricity through the grid are not inconceivable given to volatility of energy prices on the world market.

As more alternative energy systems are installed, additional waste products will (eventually) be generated. Examples include solar panels and wind turbines that have reached the end of their economic life. The recycling and/or disposal of these materials should be considered so as not to create additional environmental problems down the road. For example, the Solar Energy Industries Association has developed a national PV recycling program that helps maintain the sustainability of renewable energy sources. As more renewable energy systems come online, more recycling programs are needed.

12.8 Summary

Alternative energy systems such as solar, wind, and geothermal (ground-source) are here to stay and will experience more widespread adoption across agriculture. While they have their own limitations and constraints, solutions to address these issues (e.g., battery storage) are being developed and are becoming less expensive. Solar and wind energy have reached grid parity (meaning their generating costs equal the costs of generating electricity with fossil fuels) in some markets and this trend is expected to continue. Alternative energy sources are poised to substantially reduce harmful emissions (such as carbon dioxide, nitrogen oxides, particulates), which is particularly beneficial to the agriculture community which has been especially targeted as a large contributor to world-wide greenhouse gas emissions.

There are a variety of alternative energy options available to farmers. Framers are encouraged to remain aware of new developments and, from time-to-time, reevaluate their own energy consumption patterns. Enlisting the help of energy experts can help farmers decide whether a change is warranted to better meet their objectives. Several alternative energy systems have matured enough to the point where risk assessments and return-on-investment calculations can be performed with a high degree of accuracy. This makes the decision process a lot easier and will also help to develop a detailed budget and to investigate financing options.

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http://www.earth-policy.org/books/wote/wotech9
http://farmenergy.org/success-stories/reap

Chapter 13
On Farm Energy Production: Biomass Heating

Edward V. Johnstonbaugh

13.1 Introduction

The production of biomass on farms and ranches provides, in many cases, the primary source of income as a primary product for sale or as feed for animals that are subsequently taken to market. Converting sunlight, nutrients, carbon dioxide and water by way of the process of photosynthesis, energy can stored for long periods of time. Storage of the sun's energy, following conversion in this manner, allows forage crops like hay, or grains such as oats or barley, to be kept through periods of low sun for months or even years. In the same manner conversion of sunlight, using the same process, into biomass such as trees, warm season grasses, or conventional crops like corn converted to ethanol allows for the storage of the sun's energy for release at will rather than under the limitations of conditions that allow or inhibit the arrival of sunlight to the earth's surface. In this way, biomass is truly a form of "stored solar energy".

Nurturing the development of specialized crops such as warm season grasses (i.e. switchgrass) or short rotation woody crops like shrub willow species permit agricultural producers to maximize the conversion, collection and storage of the sun's energy. By selecting attributes that leverage the nature of the growing season, the quality of the land being cultivated, limits on the availability of water or supplemental nutrients, growth can be maximized. In many cases energy crops can be grown on land not suited for traditional higher value crops. However, the potential does exist for biomass heating to incentivize poor land management in the form of deforestation or other ecological degradation. While this has been an issue in some parts of the world, biomass heat seems to have much the opposite impact in the Northeast United States, providing markets for ecologically undesirable woody

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materials or incentivizing the growing of perennial crops that have beneficial sustainability attributes. One potential negative impact that does deserve attention is the effect of biomass combustion on air quality. Low efficiency biomass combustion equipment has been implicated in air quality problems in some communities, and while a well-designed well-operated system will minimize emissions, even the best biomass combustion equipment tends to emit fine particulate materials into the atmosphere, which may be a concern depending on the specifics of the location such as the pre-existing amount of particulates in the area, the atmospheric conditions, and the number of people living near the combustion equipment. Larger combustion systems tend to include increasingly sophisticated emissions control equipment, such as multiclone separators or baghouses, so that emissions are minimized (Fig. 13.1).

Energy crops for heat are generally considered attractive for their attribute of providing energy independence to the farmer – when the energy source is grown on the farm, the farmer is no longer subject to the volatility of fossil fuel energy prices that can swing unexpectedly and dramatically impact a farmer’s bottom line. It is also attractive due to its “local energy” characteristics, providing an immediate connection between the energy needs of the farm and the resources of the farm itself. At present, biomass for energy remains a niche market in the Northeastern United States. This is due in part to a combination of social, technical, and governmental constraints. Breaking down barriers to gain acceptance of biofuel energy sources requires overcoming numerous obstacles before a plant can be designed, financed and built that will operate on the sun’s energy in short term storage in the form of biofuel (Fig. 13.2).

Processing these stored energy crops, or Biofuels and transporting them to points of use is a cost issue when competing with traditional fossil fuels such as propane, natural gas, or fuel oil. Selecting processes that lower the cost and preparing the biofuel so it is “burner ready”, and purchasing combustion equipment capable of handling biofuels are important factors in developing a functional marketplace. Among the many potential positive environmental attributes are:

- Renewability (i.e. circular economy contribution),

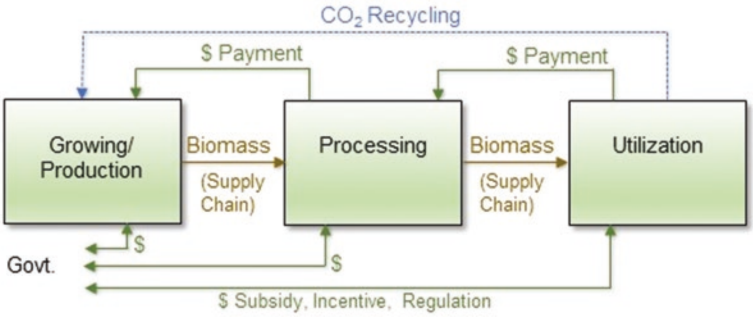

Fig. 13.1 Generalized diagram of material, cash and CO_2 flows in biomass heating

Fig. 13.2 Ground switch grass loaded into a fuel bunker. (Photo by EV Johnstonbaugh)

- Habitat restoration,
- Water quality improvement,
- Atmospheric carbon offset and/or sequestration, and
- Soil quality improvement.

Public recognition of the value of these attributes is emerging in the region, and new opportunities are arising to sell “credits” to public or private entities that wish to subsidize the development of these attributes for the general good of the populace.

Public policy decisions are another important factor in growing the biomass heating sector. When well implemented, they properly weight the numerous environmental benefits that biofuels provide as a replacement for carbon emitting fossil fuel sources. This feature adds another dimension to proper support for the market for biofuel conversion efforts. For example, abandoned or reclaimed mine land is a common feature of many Northeast US states, and significant public expense is used to improve those sites (Table 13.1). While traditional row crops are often very difficult to grow in these locations, biomass crops often are more amenable to the conditions in these disturbed sites.

Highly developed and long subsidized supply chains for conventional fossil fuel resources sit atop the market for flexible distributed energy utilization infrastructure. For example, boiler plants in health care facilities large and small around the world rely on conventional fossil fuel sources. Decreasing the amount of carbon released into the atmosphere is one of the benefits that the marketplace has yet to properly value. Adding combined heat and power to biofuel combustion facilities adds the dimension of electricity production to the equation and can improve overall

Table 13.1 Abandoned mineland in Northeast US

Rank	State	Acres unfunded	Acres funded	Acres completed	Total acres
1	Ohio	5,447,935	387	21,644	5,469,966
2	West Virginia	132,631	28,552	353,365	514,548
3	Pennsylvania	276,863	19,131	68,687	364,681
4	Kentucky	32,654	12,223	103,003	147,880
6	Virginia	57,140	4287	22,385	83,812
12	Maryland	25,066	344	7313	32,723
14	Illinois	5720	5836	16,863	28,419
17	Indiana	2161	36	14,634	16,831
27	Michigan	28	0	1090	1118
31	Rhode Island	0	0	6	6

From Dixon and Bilbrey (2015)

facility efficiency while reducing the consumption of electricity from fossil fueled generation resources. Each beneficial aspect of biofuel utilization must be in play for biofuel systems to earn a place in the thermal energy marketplace.

13.2 Types of Biomass Fuel

Fuel types for use in Biofuel combustion systems are numerous, as are the forms in which they are stored prior to combustion. Woody biomass, for example, can be harvested, transported, and stored in tree form ready to be chipped in time to be fed into a combustion system. An alternative would be to chip the tree at the job site landing in the forest prior to transport. In the case of wood pellets, the woody chip material, once at a pellet plant, is finely ground, heated to remove moisture, and then processed under high heat and pressure to form pellets that can be delivered in bulk to combustion unit locations. The goal of the secondary process of pelleting is to raise the value of the fuel by lowering the cost of transport and handling, and raise the energy density by compacting the woody material with significantly less moisture present (Fig. 13.3).

Warm season grasses and crops like switchgrass or miscanthus can be used as biomass fuels with the advantage that they can be grown on marginal farmland with low nutrient and water inputs while thriving in the warmest season of the year when sunshine is most available for conversion to plant matter based energy stored for later use. Typical yields for a well established switchgrass planting can be in excess of 5 tons of plant material per acre in a growing season. Switchgrass can also be harvested using conventional equipment used on farms for cutting, raking and baling hay. Miscanthus, though similar to switchgrass in its preference for warm season, can achieve harvest weights in excess of 10 tons per acre but can be more challenging to produce.

Fig. 13.3 Low value woody biomass ready for further processing, or a wood stove. (Photo by EV Johnstonbaugh)

Miscanthus, which is not native to North America, includes many cultivars, some of which can be invasive. Thus, only sterile hybrids such as Miscanthus giganteus (developed at the University of Illinois) are recommended for biomass production. Planted as a rhizome miscanthus requires specialized equipment to establish, harvest and bale. Fibrous in nature, miscanthus can grow in excess of 10 ft in height in a single growing season. With its high yields and heat content comparable to switchgrass, miscanthus is a viable option for pelletizing as is switchgrass. When processed in the manner similar to that described for wood, switchgrass and miscanthus can be formed into fuel pellets with favorable characteristics for transportation and storage.

Conventional crops such as corn stover and wheat and rye straws can also be harvested for use in biofuel combustion applications. Combustion system designs that have the capacity to handle baled forms such as square, round and large bales have made the use of these materials an option for heating supply needs. Harvested using conventional baling equipment the bales can be exposed to inclement weather for a limited time prior to use although increased water content always results in a reduced useful heat content of the stored fuel. While stover and straw have markets in the Northeast US for animal bedding, combustion can be a secondary market for those customary farm commodities when there is an abundance. In many areas of the Northeast United States, farms often have a woodlot on a portion of their land, providing an opportunity for woody biomass production and use from mixed hardwood forest in addition to field-grown crops.

Liquid and gaseous biofuels present another option for Ag producers considering renewable fuels for heating needs. Biodiesel, for example, can be used in the operation of diesel equipped farm machinery and also for use in oil burning heating systems. Likewise gases such as methane or hydrogen can be used to replace conventional bulk fossil fuels such as propane or natural gas or even gasoline in conventional engines equipped to run on natural gas.

13.3 Types of Combustion Equipment

The types of combustion systems available for burning biomass are numerous. In their simplest form pellet stoves come in a range of heating capacities sized for a range of room sizes and for a range of heating goals. If the goal is to keep an office space warm through the heating season a unit to do the job can be purchased at a local farm supply store. Residential scale biomass heat from a woodstove or pellet stove continues to be popular for providing space heat in the Northeast US, and outdoor wood boilers are a preferred method to provide hot water heat to the farmstead (Fig. 13.4).

On the other end of the spectrum if you want to keep a poultry shed or large greenhouse warm there is a biomass heating system sized and equipped to do the job. Commercial scale equipment typically consists of a large combustor with automated fuel feed, computer controls, pollutions controls and a hot water or steam boiler to deliver thermal energy to its end use (Ciolkosz and Babcock, 2013; Van Loo and Koppejean, 2008). Even larger Industrial and Utility scale facilities are also possible, although they are not common in the region (Table 13.2).

Fig. 13.4 Pellet stoves (left) provide a reliable, low maintenance source of heat, relying on densified biomass. Commercial wood boilers (right) are an efficient option for farms with larger heating loads. (Photos by EV Johnstonbaugh, D Ciolkosz)

Table 13.2 Common scales of biomass combustion equipment

Scale	Typical size	Typical fuel
Residential	25,000–50,000 Btuh	Cordwood, pellets
Farm	30–150 kWth (~100,000–500,000 Btuh)	Wood chips, baled grasses
Commercial	900–3000 kWth (~3000,000–10,000,000 Btuh)	Wood chips, pellets
Industrial	6000–15,000 kWth (~20,000,000 Btuh–50,000,000 Btuh)	Wood chips, pellets
Utility	30,000 kWth and up (~100,000,000 Btuh and up)	Wood chips

With the exception of wood stoves, these systems come with automated feed, variable heat level outputs and several safety features built in that prevent unit operation if hazardous or unsafe conditions are present. An important owner responsibility is to become familiar with safe operation and to make sure that they are using the equipment in "as designed" conditions.

Maintenance is another aspect of biomass heating equipment operation that cannot be overlooked. Clean operation of all combustion equipment requires an unobstructed supply of combustion air as well as a means of properly exhausting the spent combustion gases. This is certainly true of Biofuels because there is also a component of ash in most cases that must be properly managed. While not notably toxic, biofuel ash is typically very fine, and known for becoming airborne in a light breeze. Proper maintenance and clean up are important chores that go with the use of biomass derived biofuels. Providing adequate primary and secondary combustion air to facilitate release of the stored energy is important to overall efficiency. Keeping heat exchangers free of ash and debris also helps maximize the efficient transfer of heat energy between heat transfer fluids (Fig. 13.5).

Processing of biomass fuels from plant material requires equipment designed for its special properties. Materials harvested on farms and from forests typically come with an amount of dirt and the plant matter itself can include an amount of silica. These materials can create excessive wear conditions for processing equipment. Whether chopping or grinding biomass, excessive wear can increase the amount of energy needed to complete the treatment and shorten the life of the equipment installed to do the job. Steps should be taken to minimize the amount of dirt that becomes mingled in the harvest and collection process, Scheduling harvest for periods of the year when the crop is dormant can also reduce the amount of abrasive material present in plants when time the time comes to pretreat the material prior to combustion.

In the Northeast United States, residential heat is the most common use of biomass on farms, but several larger farms are using biomass for space or process heat. Greenhouses, with their large heating load in the winter months, are probably the most common application for larger biomass heating systems on the farm. In addition to that, Maple Syrup producers are a niche where biomass has traditionally been a source for on-farm process heat (via fires with low efficiency evaporator trays), but high efficiency pellet-based systems are increasingly popular.

Fig. 13.5 Ground switch grass awaits co-firing with waste coal at a fluidized bed combustion plant. (Photo by EV Johnstonbaugh)

It is worthwhile to note that it is possible to use biomass as a non-combustion heating source, by collecting heat from a biomass composting facility. The exothermic breakdown of biomass in a compost pile can provide a considerable amount of low grade heat that, depending on a farm's setup and needs, may be worth considering. This concept has yet to see widespread acceptance, however.

13.4 Economics and Efficiencies

The price at which a renewable biofuel becomes cost effective directly correlates to the price per thermal unit provided by the competing fossil fuel being replaced.

The actual energy comprising a biofuel is captured sunlight from the sun. That energy is free. Thus, biomass fuel cost consists of the land costs, and the costs of growing, harvesting, temporarily storing and transporting the biofuel to its point of use. By comparison, fossil fuels consist of similarly captured sunlight, but it is the conversion and storage process over millions of years that create the fossil fuel, while simultaneously impacting the extraction cost and environmental costs that drive the pricing of these fuels. Substituting biomass crops shortens the cycle by millions of years while avoiding the slow, high pressure conversion process and forgoes the long term storage requirement. This eliminates the extraction cost, and

Table 13.3 Equivalent price of heat from different fuels

Natural gas /Mcf	Propane / gallon	Green wood chips /ton	Wood pellets /ton	Oven dried switchgrass /ton	Hay, round bale (750 lbs.)	Electricity (kWh)
$3.28	$0.29	$29.40	$54.44	$49.60	$19.70	$0.013
$5.33	$0.47	$47.75	$88.48	$80.60	$32.00	$0.022
$13.94	$1.22	$125.00	$231.00	$211.00	$83.65	$0.057

Source: USDA Forest Service & Pellet Fuel Institute Fifth Edition, 2004

in many cases the cost to refine. All of this helps avoid environmental management and restoration costs that are usually associated with fossil fuels.

Comparing fossil fuels with Biofuels requires the selection of a common denominator. In English units the most common unit of measure for comparison is Millions of British Thermal Units, or MMBTU. In metric units the Joule is the common unit for measure of heat capacity or MegaJoules (MJ) for large volumes. One MMBTU is equivalent to 1055.06 MJ.

When comparing the cost of natural gas at the burner tip with an alternative biofuel, converting the price to "per equivalent units of heat delivered" allows the consumer to make a choice of the most economical fuel from the pocket book perspective. As the "all in" price of fossil fuel increases, alternative biofuel options in many cases lower the cost for the same amount of heat. Table 13.3 compares the commodity price (not including transportation) with other commodity biofuel options.

Biomass fuels utilized in a well designed, properly operating and well managed facility achieve efficiencies equivalent to those of typical fossil fuel plants of comparable capacities.

13.5 Conclusions

As the search for solutions that reduce the release of anthropogenic carbon into the atmosphere intensifies, increasing the reliance on biomass as a fuel for heat and electricity is a logical path to follow. Capturing the solar energy and storing it for the short term by means of photosynthesis is a natural extension of the direct conversion of sunlight to electricity by means of photovoltaics.

Expanding the use of marginal, under utilized, farmland for growing biomass crops along with improved forest management practices aimed at biomass fuel production can create economic opportunities while reducing the negative impacts of fossil fuels. The establishment of networks of growers, processors, transporters and users of biomass fuels has the potential to stimulate local economies while improving the conservation and quality of natural resources.

The establishment and stimulation of a bioenergy economy that includes biomass production as part of the foundation is a necessity to weaning the economy from reliance on fossil fuels.

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Chapter 14
On-Farm Energy Production: Biogas

Amro Hassanein, Stephanie Lansing, and Emily Keller

14.1 Introduction

14.1.1 Anaerobic Digestion (AD) Process

Anaerobic digestion (AD) is a series of microbial processes that break down biodegradable material in the absence of oxygen producing biogas. Biogas can be produced from a wide-ranging of organic material, such as animal manure, food waste, crop waste, or sewage sludge (Fig. 14.1). Biogas is mainly composed of methane (CH_4) (50–75%), carbon dioxide (CO_2) (25–50%), and water vapor (3–4%), with trace quantities of hydrogen (H_2), ammonia (NH_3), hydrogen sulfide (H_2S), and carbon monoxide (CO).

The AD process involves three main steps: (1) hydrolysis, where hydrolytic bacteria use extracellular enzymes to convert complex organic material into soluble carbohydrates, fats, and proteins; (2) acidogenesis, where acid-forming bacteria convert soluble compounds into short-chained organic acids, known as volatile fatty acids (VFAs); and (3) methanogenesis, where methanogenic bacteria utilize the VFAs to produce biogas (Fig. 14.2) (Eryildiz et al. 2020; Wainaina et al. 2019). Methanogens are sensitive to pH (pH range of 6.5–8), digester temperature fluctuations, and oxygen concentrations (Eryildiz et al. 2020). When using anaerobic digestion to process animal manure (a typical application on the farm), the digester temperature, livestock feed ration changes, influent feed rate, and non-manure substances introduced into the digester affect the productivity of microorganisms to produce biogas.

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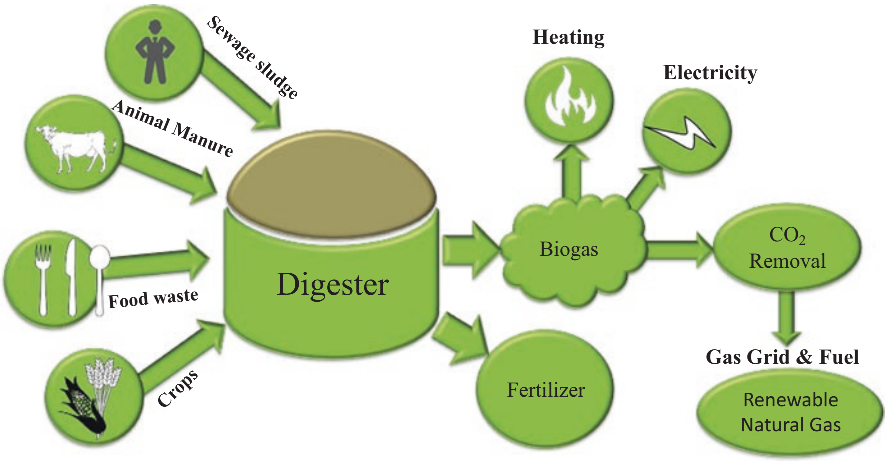

Fig. 14.1 Anaerobic digestion basics

Operating temperature is one of the critical factors affecting overall digester performance. The AD process is generally operated in the mesophilic (35–40 °C) or thermophilic temperature range (50–60 °C) (Gerardi 2003; Hassanein et al. 2015), which have been shown to be optimal for two different categories of methane-forming bacteria. Thermophilic bacteria have been shown to be more sensitive to environmental changes, such as high organic loading rates, temperature fluctuations, and feeding irregularities (Kim et al. 2002).

14.1.2 Biogas Energy Content

The lower heating value of CH_4 is 33,384 kJ/m^3(896 BTU/ft^3) at standard conditions (20 °C and 1 atm). Correcting for non-energetic gases (CO_2 and water vapor) and impurities present in biogas, the lower heating value of wet biogas (at 60% CH_4) is approximately 20,343 kJ/m^3 (546 BTU/ft^3), which can vary based on process conditions and CH_4 content (Hassanein et al. 2017, 2020). Biogas has a lower energy density (energy per unit volume) than other common fuels, as shown in Table 14.1.

14.1.3 Anaerobic Digestion (AD) System Designs

An anaerobic digester is simply a large, sealed vessel in which feedstock can be kept in a moist, oxygen-free environment until the bacteria breaks down its digestible components into biogas. Digester designs include plug flow digesters, complete mix digesters, covered lagoon digesters, and fixed film digesters. In the US, plug

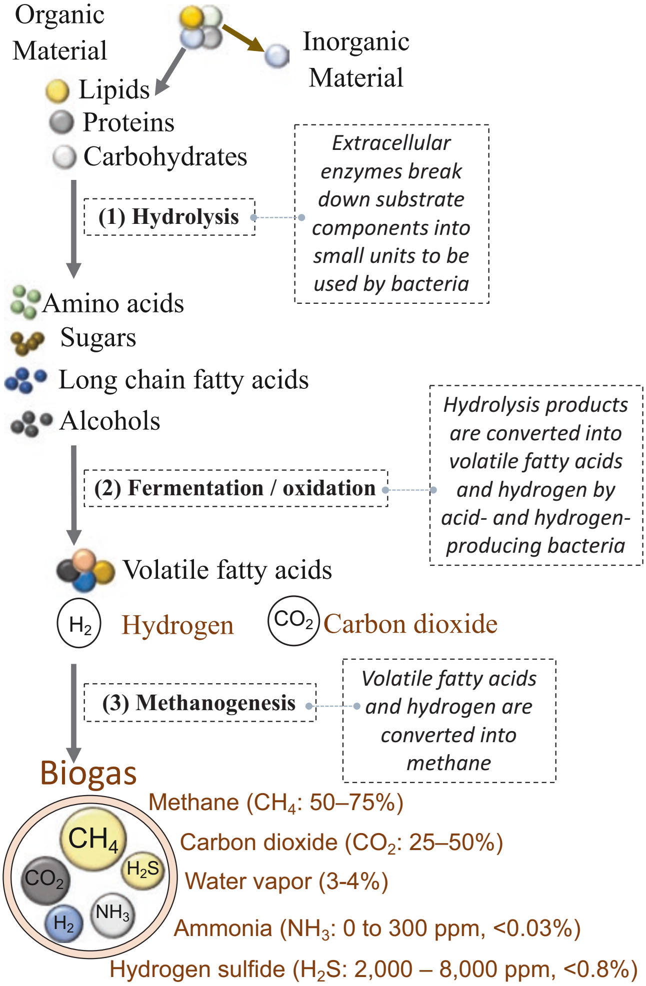

Fig. 14.2 Fundamental steps in the anaerobic digestion of complex organic substrates

Table 14.1 Combustion properties of gaseous fuels

Fuel	Energy density (kJ/m^3 of fuel)[a]	Octane rating
Propane[b]	85,062	104
Natural Gas[c]	33,384	120
Biogas[d]	20,343	--

[a] Lower heating value at atmospheric pressure

[b] Primary component of liquid propane gas

[c] 20°C and 1 atm of 100% CH_4 in natural gas

[d] Assuming 60% methane at 15.5 °C (60 °F)

flow digesters are generally below-grade vessels in which a "plug" of high solids waste moves from the digester inlet to the outlet. An advantage of plug-flow digesters is that they are mechanically simpler than mixed digesters, but a high total solids (TS) content (8–14% TS) should be used to reduce settling within the digester. Complete mix digesters are periodically or continuously mixed by mechanical means. One advantage of a mixed digester is the ability to handle wastes with higher moisture content (compared to plug-flow units), including non-farm feedstocks, such as food waste. The mixing components add mechanical complexity and electrical parasitic load, which can increase operational costs. Covered lagoon digesters are covered manure storage structures that capture the produced biogas and are usually operated under ambient conditions. The benefits of covered lagoons include lower capital and operational costs. However, a major disadvantage of covered lagoon digesters is the higher likelihood for inconsistent production of biogas due to seasonal changes in ambient temperature. Fixed film digesters are packed with media that support the attachment and growth of essential microorganisms required for biogas production using low solids waste, such as food processing waste (5–15% TS), flushed dairy manure (4–10% TS), or manure with solids separated prior to digestion (EPA 2020a; Lorimor et al. 2000; Yi et al. 2014). For food waste co-digested with manure, a mixed digester system is recommended. Table 14.2 shows the recommended digester types based on the manure collection systems used on the farm and the solid concentration of the substrate.

The hydraulic retention time (HRT) is the total time that a volume of organic substrate resides inside the digester vessel. For manure-based AD, the minimum recommended HRT is 15–21 days (Shelford et al. 2019), with longer HRTs increasing the overall biogas production but requiring a larger AD vessel. The loading rate is the quantity of organic material, often measured by the volatile solids (VS) content, added to the digester per unit volume of digester per day. Changes in the VS loading rate should be implemented over time to allow the bacteria to acclimate. Mixing enhances the digestion process by distributing bacteria, substrate, and

Table 14.2 Recommended digester types based on dairy manure collection system, bedding, and influent total solid (TS) concentration (EPA 2020a; Lorimor et al. 2000; Wilkie 2005; Yi et al. 2014)

Manure system	% Total solids (TS)	Recommended digester type
Flushed dairy manure	4–10	Covered lagoon or fixed film digester
Scraped dairy manure + milking center wastewater	3–11	Complete mixed digester
Scraped dairy manure + soiled organic bedding	>11	Plug flow digester
Food waste co-digestion	5–15	Mixed system: complete mixed or plug-flow digester with mixing
Sand-laden dairy manure	3–5	Complete mix, with pre-treatment to remove sand bedding

nutrients throughout the digester. Mixing can also help reduce foam buildup, create a more uniform temperature profile and reduce sedimentation of inert/non-digestible solids.

Biogas piping and handling is a crucial part of the digester operation due to the properties of biogas (water saturated, corrosive, and presence of toxic gases). The biogas handling system should include a biogas meter that can withstand corrosive and saturated conditions, a gas delivery system, a pressure relief mechanism to avoid excess pressure in the system, and a condensate trap. It is recommended that non-ferric pipe be used, with PVC for biogas piping below-grade and black iron pipe for biogas piping above-grade (Shelford et al. 2019). Because biogas is explosive, toxic, and hazardous to human health, extreme care must be taken when working with and around biogas equipment. Personal safety monitors are highly recommended (and may be required) for workers. In addition to posing a hazard to human and animal health, biogas containing H_2S is highly corrosive and negatively affects equipment and equipment components.

Biogas clean-up can be performed using a variety of complexities, from simply removing moisture to more advanced clean-up strategies to produce renewable natural gas (RNG) for injection to a natural gas pipeline or use as a transportation fuel (>99% CH_4). To produce RNG, the H_2S, moisture, CO_2, and trace gases in the biogas must be removed or significantly reduced, as illustrated in Fig. 14.3.

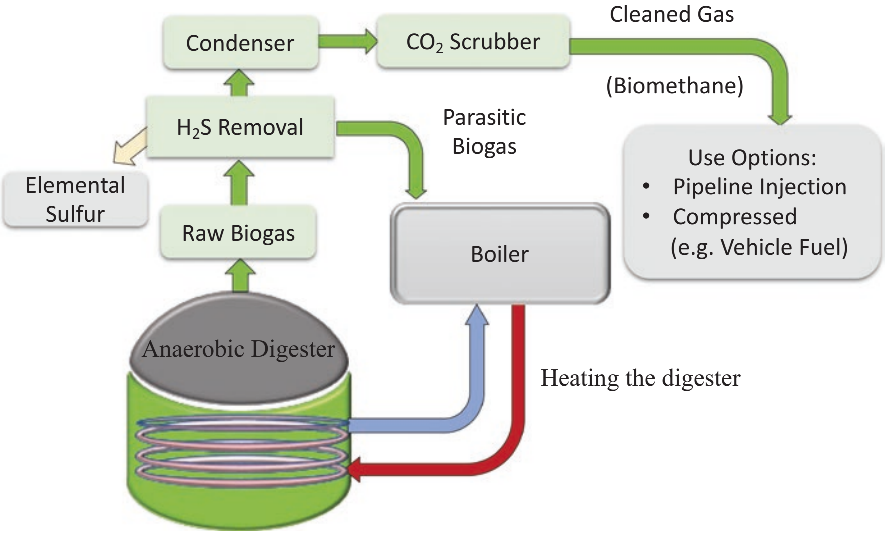

Fig. 14.3 An anaerobic digestion system with processes shown to produce renewable natural gas (RNG), or ‘biomethane’

Table 14.3 Recommended maximum concentration of H_2S for various biogas end uses (Shelford et al. 2019)

Biogas end-use	Maximum recommended H_2S concentration (ppm)
Boiler	1000
Engine-generator set	500
Vehicle fuel	23
Pipeline injection	4
Fuel cell	1

14.1.4 Hydrogen Sulfide (H_2S) Removal

Hydrogen sulfide removal is necessary for most farm-based digesters due to the high levels of H_2S that naturally occur in the biogas when the feedstock contains sulfur, such as animal manure. The maximum concentration of H_2S in biogas recommended for various uses is shown in Table 14.3 (Electrigaz Technologies Inc 2008). There are three main strategies for removing H_2S from biogas: physical/chemical methods, microbial fixation, and influent addition.

Physical/Chemical Removal of Hydrogen Sulfide (H_2S)

Physical or chemical treatment systems rely on media that reacts with the H_2S in the biogas by converting or binding the H_2S, such as an iron sponge. An iron sponge system consists of iron oxide impregnated media contained within an above-ground tank located between the digester and the biogas utilization system. The chemical reaction that occurs within an iron sponge system at ambient temperature is a bond between sulfur and iron oxide (Fig. 14.4). For each 0.45 kg (1 lb) of iron oxide (Fe_2O_3) present in the system, 0.25 kg (0.56 lbs) of H_2S can be removed from the biogas (Choudhury et al. 2019). Iron sponges are a common approach to H_2S removal in the Northeast US.

Microbial Fixation for Removing Hydrogen Sulfide (H_2S)

Sulfur oxidizing bacteria (SOB) that naturally develop on surfaces in certain low-oxygen environments, such as a digester vessel biogas headspace, can be used to reduce H_2S concentration in the biogas (Fig. 14.5). Formation of SOB inside the digester can be enhanced by using air injection (micro-aeration), with a regulated amount of O_2 (between 0.3% and 3% of the produced biogas), injected into the headspace of a digester to create a micro-aerobic environment, often injected through use of regulated air pumps (Huertas et al. 2020; Muñoz et al. 2015; Shelford et al. 2019). A properly controlled micro-aerobic environment allows SOB to remove H_2S without large reductions in biogas production and quality, with the O_2

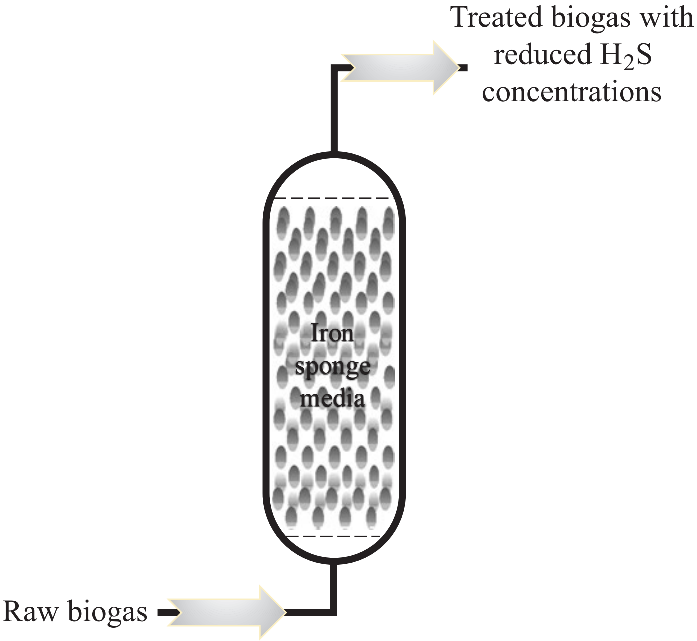

Fig. 14.4 Iron sponge treatment to remove hydrogen sulfide (H_2S) from biogas

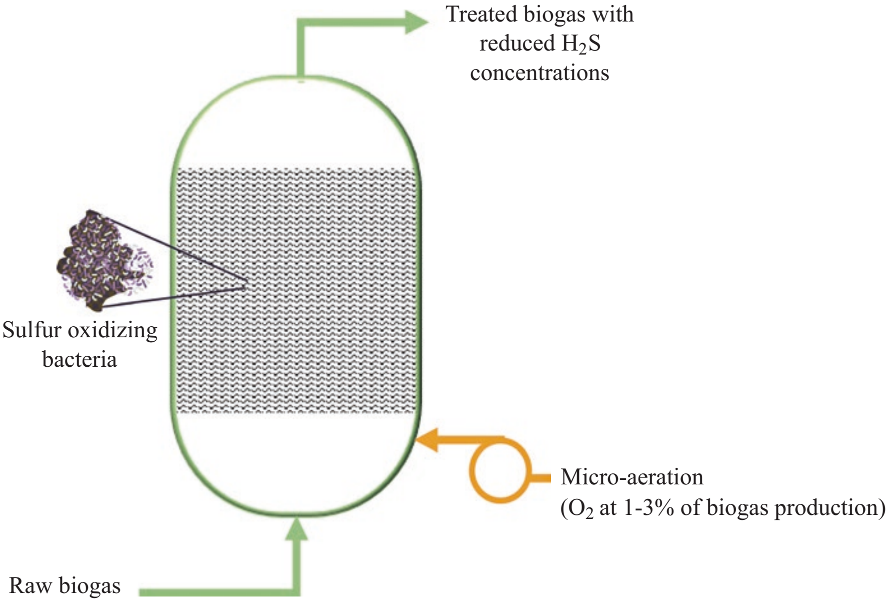

Fig. 14.5 Biological treatment to remove hydrogen sulfide (H_2S) from biogas using a separate biological tricking filter vessel located between the digester and biogas utilization equipment

(or air) flow controlled to match changing sulfur feedstock concentrations (Muñoz et al. 2015). Biological trickling filters (BTF) are separate reactors that use a packed bed colonized by SOB, where nutrient water 'trickles' through the packed media from the top. As the biogas from the digester is blown through the media, H_2S is removed from the biogas and metabolized by SOB. A BTF must be large enough to handle the maximum biogas flow rate and H_2S concentrations.

Influent Addition to Remove Hydrogen Sulfide (H_2S)

Compounds, such as ferric chloride (liquid) and ferric hydroxide (powder), can be added into the digester influent to directly react with the sulfur in the organic material before it has an opportunity to produce H_2S (Hassanein et al. 2019; Shelford et al. 2019). Iron chloride reacts with sulfur to form an insoluble iron sulfide salt particle, which can settle within the digester tank or leave in the effluent. Ferric hydroxide can also remove sulfur, preventing H_2S production from aqueous systems through oxidation and precipitation reactions within the operating pH range of most digesters (6.5–8.5). Ferric hydroxide has been used primarily in the wastewater treatment industry, with a constant daily dose necessary to maintain low H_2S emissions (Lin et al. 2013). The amount of iron compounds needed can be determined based on measuring the biogas volume and influent sulfur concentration (Feng et al. 2010; Hassanein et al. 2019, 2021). An advantage of using digester influent additives is reduced capital and maintenance costs compared to separate H_2S scrubbing systems, while a disadvantage is the ongoing cost of chemical additions necessary throughout the lifetime of the system. However, an extremely high concentration of iron (>6000 mg Fe/L) in the digester could negatively affect biogas production and be toxic for the microorganisms responsible for CH_4 production (Jackson-Moss and Duncan 1990).

14.1.5 Carbon Dioxide Removal for Enhanced Biogas Quality

Carbon dioxide must be removed from biogas if the biogas is injected into a natural gas pipeline or used as a vehicle fuel. The resulting RNG has a higher CH_4 content than raw biogas and can be utilized in any equipment or pipeline designed for conventional natural gas. Four commonly employed processes for removing CO_2 include:

1. **Regenerative water wash**. This approach is based on the principle that CO_2 dissolves better in pressurized water than CH_4. Counter flow technology uses an adsorption scrubber, which contains media to increase the surface area between the biogas and water. Cleaned biogas is harvested from the top of the pressure vessel, and dissolved CO_2 (and any dissolved CH_4) is removed from the wash water in a flash tank when the water pressure is reduced.

2. **Regenerative amine wash**. This process is similar to the regenerative water wash system but uses alkylamines, such as diethanolamine (DEA), monoethanolamine (MEA), and methyldiethanolamine (MDEA) (referred to together as amine), to adsorb CO_2. Amine chemicals are effective at CO_2 removal, resulting in almost pure biomethane and little loss in the tail gas. The biogas after regenerative amine wash will not require any further processing (Abdeen et al. 2016). However, moisture in biogas can dilute the amine chemicals, thereby reducing efficiency (Shelford et al. 2019).
3. **Pressure swing adsorption (PSA)**. Contaminant gases, such as CO_2 and H_2S, are absorbed by a porous adsorption material (i.e., a molecular sieve with uniform small pores), usually composed of activated carbon. The adsorption material preferentially adsorbs the contaminant gases (CO_2, H_2O, N_2, O_2, H_2S, hydrocarbons, volatile organic compounds (VOC), and silicon compounds) while allowing CH_4 to pass through the column. PSA typically requires a refrigeration system and is operated at high pressure (approximately 100 psi) (Shelford et al. 2019).
4. **Membrane separation**. In this process, CO_2 passes through a membrane, while most of the CH_4 is retained. Current applications require the use of a two-stage system so that any CH_4 that is not captured in the first stage can be captured in the second stage.

14.1.6 Moisture Removal from Biogas

Moisture can negatively affect biogas quality and may require removal, depending on the end use requirements and/or the distance the biogas is piped between the digester and the end use equipment. Removal of moisture can improve combustion and biogas equipment longevity (Shelford et al. 2019). The simplest method to remove moisture from biogas is a passive strategy that uses the temperature differential of the biogas leaving the digester and the biogas being piped underground. The ground cools the biogas piping material, which, in turn, results in moisture contained in the saturated biogas to condense to liquid (Chin et al. 2020). A refrigeration system can also be used to remove condensate by cooling ethylene glycol, which is circulated through a heat exchanger to cool the biogas below the dew point (~11 °C, depending on the moisture content of the biogas). Though highly effective at removing moisture from biogas, there is a cost and energy load associated with the refrigeration process.

14.1.7 *Biogas Utilization*

The options for biogas end use vary significantly based on the needs of the digester operator, accessibility to the electric grid, pipeline availability for RNG, and the biogas treatment system.

Engine-Generator Set (EGS) and Combined Heat and Power Generators (CHP)

Combined heat and power (CHP), considered one of the most efficient methods to turn biogas into electricity and heat, is a type of engine-generator set (EGS) that combines heat recovery with electricity generation (Zeng et al. 2017). It is highly recommended to reduce the moisture content in the biogas before using CHP, as biogas with a low moisture content can generate more power than biogas with a high moisture content. It has been reported that decreasing the fuel moisture content from 30% to 0% increases thermal efficiency by approximately 6% (Wickwire 2007). Moreover, it is recommended that the H_2S concentration in the biogas be reduced to <500 ppm to mitigate corrosion of the CHP engine.

In the CHP system, the compressor or pump moves the biogas from the biogas holder to the generator to generate electricity, while the heat produced during electricity generation is absorbed by the heat recovery system. The heated media (water or glycol) is then used to heat the digester, as shown in Fig. 14.6 (Shelford et al. 2019). The recommended size of the engine will depend on the expected biogas

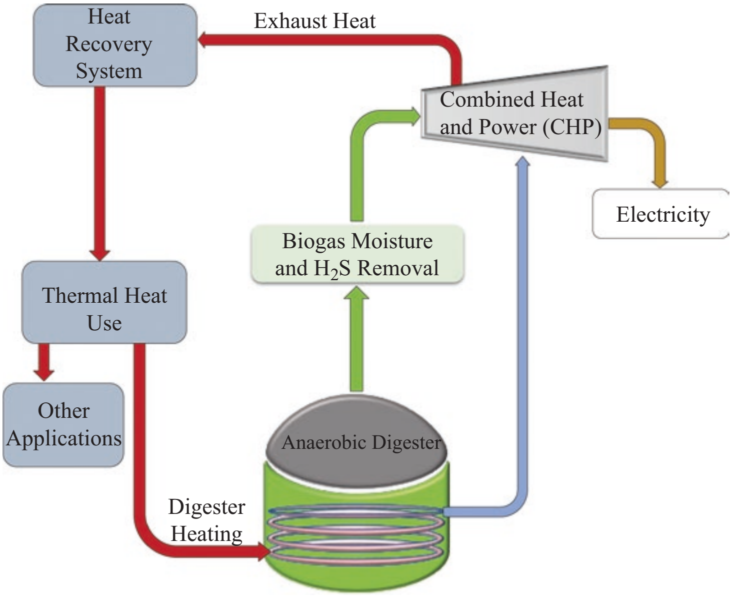

Fig. 14.6 Components of a combined heat and power system (CHP) using biogas

production rate. Most digestion systems in the Northeast connect the generator output to the electricity grid. It is recommended that the EGS output should not exceed the expected biogas supply to operate the EGS at full capacity for a high percentage of the runtime (Shelford et al. 2019).

In the Northeast US, on-farm digester use varies widely from state to state, but CHP systems are most prevalent in Wisconsin, New York, and Pennsylvania. Dairy farms are the most common location for farm digesters in this area, and they typically use CHP to produce electricity and heat. The electricity is used on-site or fed to the grid, and the heat is used to heat the digester, meet hot water requirements in the milking center, and/or other heating needs on the farm.

Maintenance can be a significant source of downtime in EGS systems and should be minimized when possible. The primary goal of EGS maintenance is to sustain operation 92% of the time or more (Shelford et al. 2019). It has been noted that successful operations should have a person whose primary responsibility includes maintenance of the EGS, scrubber, and digester system (Shelford et al. 2019). Table 14.4 lists many typical EGS maintenance procedures and their recommended frequencies. The relatively short time interval for changing the EGS oil is due to the accumulation of sulfur compounds that can occur in the oil due to H_2S present in the biogas.

Microturbines

Biogas can also be used in a gas microturbine for electricity production (Fig. 14.7). The advantages of microturbine generators include mechanical simplicity, quiet operation, remote operability, and small size. Disadvantages include the

Table 14.4 Engine-generator set (EGS) maintenance items (Shelford et al. 2019)

EGS recommended maintenance and service	Yearly hours required	Frequency (time between service)
Oil and filter change, with shorter intervals recommended initially	300	12 days
Spark plug replacement and ignition timing	500	21 days
Air filter replacement	500	21 days
Generator lubrication	500	21 days
Check/adjust valve lash	2000	3 months
Gas meter service	2000–4000	3–6 months
Carburetor mixture setting	4000	6 months
Water pump bearing replacement	4000–8000	6–12 months
Engine head/valve train overhaul	4000–8000	6–12 months
Removal and cleaning of gas handling components	8000	1 year
Coolant system flushed	8000	1 year
Safety controls check	8000	1 year
Major engine overhaul	8000–16,000	1–2 years

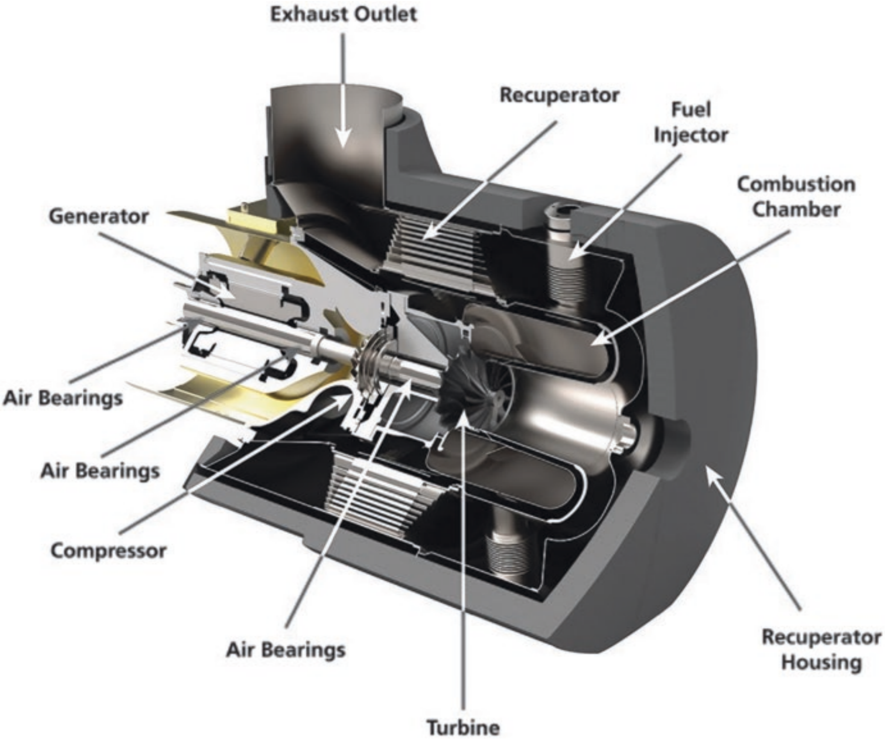

Fig. 14.7 Cross-section of a gas microturbine (Commons 2014)

requirement to compress the biogas and scrubbing H_2S to trace levels or using corrosion resistant compressors. For farm biogas applications, the microturbine generator requires a compressor and a gas scrubber/conditioner (Wellinger et al. 2013).

Boilers

On-farm biogas utilization by a boiler is the second most popular use of the produced biogas in the Northeast (Shelford et al. 2019). Natural gas boilers can be slightly modified to run on biogas (Shelford et al. 2019). The main modification involves increasing the pipe delivery size and orifices in the burners to accommodate the lower fuel density. Boilers are mainly used to provide primary or secondary heating of the digester and in some cases also to provide domestic heating of farm offices, farm housing, or on-site processing.

14.2 Current State of Anaerobic Digestion (AD) in the US

The US currently has more than 2000 operating AD sites. The US ‘Roadmap for Biogas’ found that with the proper support, more than 11,000 additional biogas systems could be deployed in the US (US White House 2015). If these additional AD systems were built, the expected biogas output would generate enough electricity to power >3 million homes and reduce greenhouse gas emissions by 54 million metric tons CO_{2e}, which is equivalent to the annual CO_2 emissions from 11 million passenger vehicles (US White House 2015).

It is estimated that US swine and dairy operations could generate nearly 16 million megawatt-hours (MWh) of electricity each year, which is equivalent to more than 2000 MW of electrical grid capacity or displacing approximately 5.4 million MMBtu of fossil fuels. According to the US Department of Energy, the average price of electricity in 2019 was $0.11/kWh. Using this rate, swine and dairy operations in the US could generate $1.7 billion annually in electricity sales and/or avoided electricity purchases. Alternatively, the AgSTAR database maintained by the US Environmental Protection Agency (EPA) (EPA 2020b) estimated that if captured biogas was directed to RNG or compressed natural gas (CNG) applications, instead of electricity generation, there would be enough CH_4 produced from swine and dairy farms to heat over 2.7 million homes or produce over 8 billion pounds of CNG annually, which has the energy equivalence of 1.3 billion gallons of diesel or the fuel needed to drive 150,000 refuse trucks (EPA 2018).

The US EPA has stated that the profitability of AD systems depends on the size of the operation, the method of manure management, and local energy costs. Available data from the US EPA indicate that the unit costs for construction, operation, and maintenance decrease significantly as the AD system size increases (EPA 2020b). A positive financial return appears most likely at dairy operations with >500 milking cows and swine operations with >2000 head (EPA 2018). Using these criteria, biogas recovery systems are potentially profitable for more than 8100 dairy and swine facilities in the US (Table 14.5).

In the US, AD systems are often owned and run by the farm’s owner, with some systems operated by third-parties due to the multitude of operational maintenance procedures that could require more specialized experience. Creative business strategies have been deployed to distribute project risk and benefits, diversify project income streams, and build more effective AD processing. There are numerous business models for AD ownership and operational control, with individual, cooperative, or municipality ownership of the AD system, as shown below:

Table 14.5 Potential for biogas recovery systems at U.S. swine and dairy operations (EPA 2018)

		Energy generating potential		
Animal sector	Candidate farms	MW	MWh/year	Thousands of MM BTU/year
Swine	5409	837	6,597,520	71,484
Dairy	2704	1172	9,240,893	100,124
Total	8113	2009	15,838,413	171,608

- **Farmer-owned and operated AD systems:** A farmer maintains and runs the AD system on-site using farm manure, at a minimum, as the AD substrate. In certain cases, the farmer will add other organic substrates from off-site, usually for a tipping fee.
- **Third-party owned and operated AD systems**: The farmer or landowner of the site may receive a rental fee or a share of the net profits, but a third-party owns, operates, and manages the AD system. Third-parties can be venture capitalists or fund companies specializing in renewable energy ventures. The manure feedstock may be handled by a third party or the farmer.
- **Third-party operated AD systems**: A third-party operates the digester, controls the feedstock, and may manage other aspects, such as the sale of produced energy, but does not own the AD system. The AD system may be owned by the farmer or other individuals.
- **Hub and spoke models**: Feedstocks from various sites are gathered and transferred to a centralized digester, with the biogas often used on-site and the digester effluent distributed back to the farms. Another hub and spoke model consists of AD systems at multiple farms, with the biogas and/or digester effluent sent to a centralized processing location for more sophisticated processing to reduce the financial burden for each entity (Fig. 14.8).

A variety of revenue sources can be generated from AD systems, such as electricity sales, RNG sales, heating energy, tax credits, tipping fees, nutrient enhancement products, carbon offset credits, organic products, Renewable Fuel Standard (RFS) credit, and tradable Renewable Energy Certificates (REC), as shown in Fig. 14.9 (EPA 2020a). Utilizing a wide range of saleable co-products could generate extra income to increase the capital return on the AD investment costs.

- **Heat, electricity, and RNG sales**: The price of the sales will depend on the final product being sold, such as raw biogas for heat, upgraded biogas (RNG), or electricity after operating an EGS and/or heat from a CHP system. With the price being negotiated between the owner and the energy recipient, with government incentives differing based on AD location.

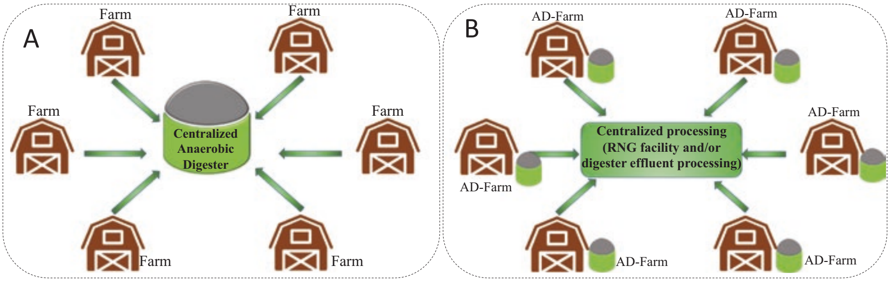

Fig. 14.8 Two hub and spoke models showing in (**a**) a centralized digester and in (**b**) centralized processing

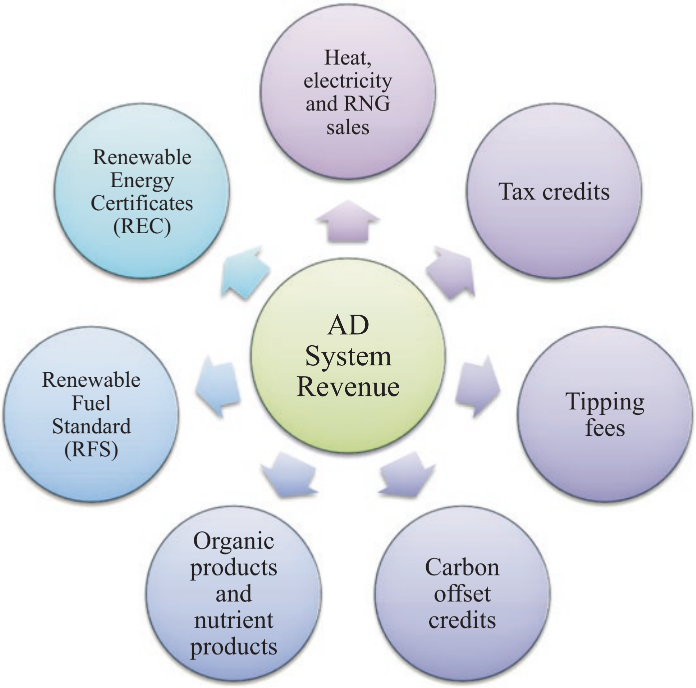

Fig. 14.9 Possible anaerobic digestion (AD) revenue sources

- **AD effluent (fertilizer) sales**: Due to the dilute nature of digester effluent (high water content), the cost of shipping the AD effluent is often prohibitive, and the AD effluent is often used as a fertilizer on surrounding fields. Nutrient recovery systems can be used to concentrate the nutrients (nitrogen and phosphorus), which would decrease the shipping costs and increase the fertilizer value. However, nutrient recovery systems operate within a few newly emerging markets with many undefined variables.
- **Tax credits**: Federal Electricity Production Tax Credit (PTC) is a credit adjusted to the kWh produced to reflect the inflation in the renewable electricity generated by qualified projects. The PTC could be sold to an unrelated individual. The term of the credit is 10 years from the date in which the facility is operational. The 2020 PTC is $0.023/kWh (EPA 2020a).
- **RFS and REC programs**: These programs were approved by the US Congress to reduce greenhouse gas emissions, expand renewable fuels, and reduce reliance on imported oil. Biogas can receive renewable identification numbers (RINs) for use in energy trading (Greene 2017). Every equivalent gallon of renewable fuels or electricity is assigned a RIN at its point of generation or origination. RINs, which have a minimum price of $0.01 and maximum price of $2.00, can be traded between parties, bought as attached RINs to fuel purchased, and/or bought

unattached on the open market (Greene 2017). Furthermore, multiple states have established renewable energy portfolio standard programs. Electric utilities can buy the tradable RECs to achieve credit for each MWh of electricity generated from a qualified renewable energy resource, such as an AD project (EPA 2020a).

- **Carbon offset credits**: Carbon offset credits may be received by decreasing greenhouse gas emissions, such as CH_4 and CO_2. AD systems can decrease CH_4 emissions from the storage of manure or food waste and reduce CO_2 emissions through renewable energy production. The credits can be bought or sold through private transactions or through credit aggregators (EPA 2020a).
- **Tipping fees**: Manufactures, businesses, or entities that generate large quantities of organic waste can partner with an AD to receive their organic waste. This type of partnership could generate revenue through regular tipping fees determined based on the composition of waste and is usually measured based on $/ton or per gallon basis (EPA 2020a).

14.3 Case Studies

This section provides three case study examples of farm biogas systems for three distinct scenarios: dairy manure digestion to produce Compressed Natural Gas, Co-digestion of dairy manure and food waste, and Poultry manure digestion.

14.3.1 Dairy Manure Digestion to Compressed Natural Gas (CNG)

Prairie's Edge Dairy Farm in Indiana uses two mixed, plug flow, on-farm AD systems to treat dairy manure from 16,300 milk cows. The digesters produce 33,980 m^3 biogas/day, with part of the refined to RNG and piped to one of two CNG filling stations in the area and a portion used for on-site electricity generation (7,818,300 kWh/year) (EPA 2020b). The farm and its associated trucking company partnered with the Indiana "Clean Cities" coalition to secure funding from the Federal Recovery and Reinvestment Act (2009) to convert the entire 42-truck fleet of semi-tractors from diesel to CNG, creating one of the largest fleets of Class 8 trucks that run on CNG (US DOE 2013). By converting to CNG, the trucking company reduced fuel costs and CO_2 emissions. The dairy products produced by the farm are distributed to various points-of-sale across the country with the CNG-powered trucking fleet.

14.3.2 Anaerobic Co-digestion of Dairy Manure and Food Waste

In Maryland, dairy manure is co-digested with pre-consumer food waste in a 2600 m^3 covered lagoon digester. The food waste is sourced from food manufacturing facilities and provides added organic material to the digester feedstock (Achi et al. 2020). The food waste input (15 m^3/day; 2415 kg VS/day) consisted of 6% of the daily digester loading rate and combined with flushed dairy manure (227 m^3/day; 3927 kg VS/day) in a short-term, open storage lagoon (<1 day) prior to entering the AD system (Lansing et al. 2019). Although the volumetric input of the food waste was low, 87% of the VS in the digester was attributed to the pre-consumer food waste, and thus, the food had a higher contribution to CH_4 production relative to the manure substrate.

The covered lagoon digester was unheated and unmixed, with a temperature ranging from 15 to 30 °C and a HRT of 10.7 days. The effluent from the digester was diluted with parlor wash water and used as barn flushing water. The biogas powered a 110 kW generator used for on-site power. For H_2S removal, the biogas passed through a 210 L plastic drum filled with rusted iron and steel scrapings, providing H_2S reduction similar to the aforementioned iron sponge method (Choudhury et al. 2019). The digester system produced biogas energy equivalent to 47,158 kWh of over 4 months, resulting in a daily average rate of 380 kWh/day. In the unheated lagoon digester, the percent CH_4 (66.2%) in the biogas was stable, but the H_2S concentration in the biogas prior to scrubbing varied from 3 to 1722 ppm, likely due to temperature fluctuation affecting microbial activity from sulfate reducers in the digester.

14.3.3 Anaerobic Digestion (AD) of Poultry Litter

The AD of poultry litter is far less common than other manure substrates, with approximately ten operational AD systems utilizing poultry litter in the US (EPA 2020a). The primary barriers for poultry litter AD are its low moisture content and high total ammonia-nitrogen (TAN) levels. Therefore, successful AD often requires the addition of water to the relatively dry (~20% moisture content) manure prior to AD processing (Hassanein et al. 2021). A demonstration site in Maryland (Fig. 14.10) consists of the mixing tank, two digesters, a biogas scrubber system, biogas boiler for system heating, EGS, solid separator, triplicate prototype ammonia scrubber of the AD effluent for nutrient recovery, and a filter press. After the AD process, the liquid portion from the solid separator continues to an acid tank and filter press system to capture the nutrients from the water and enable the reuse of the water to dilute the incoming poultry litter waste.

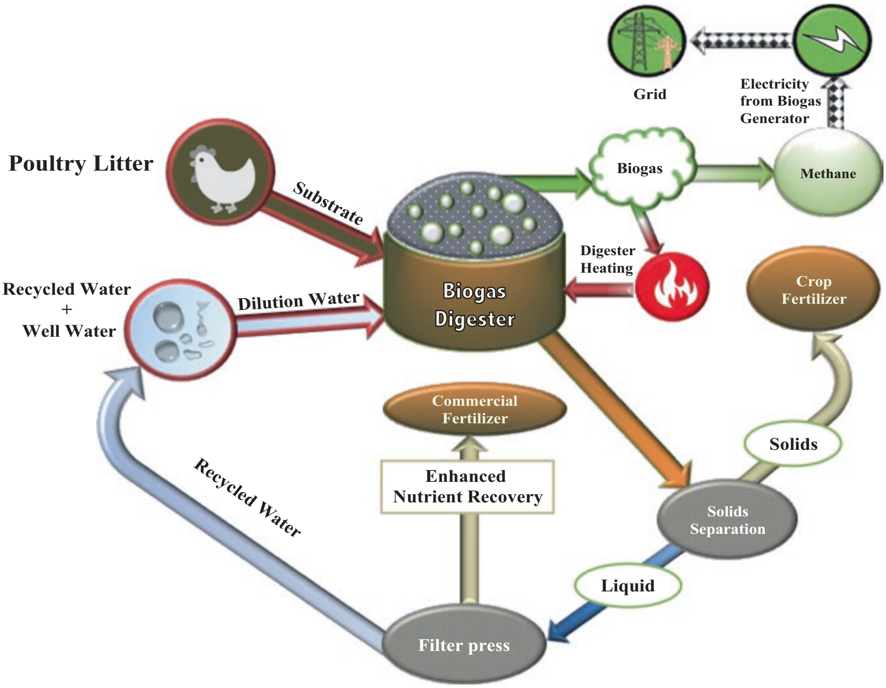

Fig. 14.10 Poultry litter anaerobic digestion with nutrient capture system (Hassanein and Lansing 2020)

The system processed 122 tons of poultry litter per year, with the highest energy production averaging 1490 m^3 biogas/month (949 m^3 CH_4/month; 222 L CH_4/kg VS), and a yearly average of 677 m^3 biogas/month (430 m^3 CH_4/month). While biogas can be used in a broiler or generator, there were challenges with the biogas usage due to the high H_2S concentration (>10,000 ppm). In 2019, the cumulative solids produced from 8 runs of the nutrient capture system was 6.2 tons of separated solids, 15.6 tons from the first cycle of the filter press, and 1.1 tons from the second cycle of the filter press (Hassanein and Lansing 2020).

In the digester, the total nitrogen (N) and phosphorus (P) concentrations increased 229% at project inception (849 mg/L) to 2793 mg/L after 2 years of operation, likely due to the use of recycled water. The average N and P in the separated solids (after digestion) was 1.9% and 0.9%, respectively (based on dry weight), with the P increasing in the filter press cake from the first run (1.4% N and 0.9% P) to the second run of the filter press (1.6% N, and 1.8% P) through the addition of the alkaline material between runs (Hassanein and Lansing 2020).

14.4 Outlook for Future

The CH_4 potential from animal manure, wastewater, landfills, industry, and food waste in the US is estimated at about 7.9 million ton/year, which is equal to about 11.9 billion m^3 CH_4/year (NREL 2013). This potential CH_4 production could displace approximately 56% of the natural gas consumption in the transportation sector and about 5% of natural gas consumption in the electric power sector (NREL 2013).

A 2018 EPA report identified the capacity for electricity generation from dairy and swine farms by US state, identifying 2704 dairy farms and 5409 swine farms as candidates for AD installation, which would reduce CH_4 emissions by 2,230,000 metric tons of CH_4/year, while generating 15,838 MWh/year of electricity (EPA 2018). For dairies, the top ten states represented 79% of the total AD potential, with California having 30% of the identified capacity (EPA 2018). Three of the US states in the top 10 states for potential on-farm AD systems (Wisconsin, Michigan, and New York) were located in Northeast US, with 622 candidate farms identified, which could result in reductions of 167,000 tons of CH_4/year and generate 1456 MWh/year of electricity (approximately 17% of the total electricity generation potential from dairy manure in the US) (EPA 2018). North Carolina and Iowa, the largest pork-producing states in the US, accounted for 16 and 31% of the total candidate farms, respectively. In the Eastern US, North Carolina, Illinois, Indiana, and Ohio were in the top ten states for candidate swine farms to produce biogas, with 1634 farms identified, with an energy potential of 2001 MWh/year of electricity generation and reducing emissions by 288,000 tons of CH_4/year. These four states accounted for approximately 30% of the total electricity generation potential from swine manure (EPA 2018).

In the Northeast US, several factors could influence the expansion of on-farm AD. The continued focus on surface water quality in the Chesapeake Bay, Mississippi River watershed, Great Lakes, and other sensitive waterways may be an opportunity for AD systems with nutrient capture technology. Digesters intrinsically function as nutrient collectors, with large quantities of nutrient-rich feedstock broken down during AD processing, with the nutrients released from complex matrices into a dissolved form inside the digester. Once digested, these complex organic materials can be more easily treated to extract excess nutrients in a format that can be transported and used more precisely for agricultural and horticulture production. Additionally, bioenergy crops, cover crops, or algae, grown without nutrient enhancements could be used as supplementary feedstocks to AD systems. While some farms in the region are already receiving food waste as a supplementary feedstock, further opportunities may arise in the Northeast US region as municipalities are implementing or considering implementing mandatory organics recycling. Already, Oregon and California have set a goal to recycle 75% of all wastes, with new legislation introduced that requires businesses to recycle organic wastes (Chesbro et al. 2020; Oregon.gov 2020). This quantity and needed sites for this waste diversion is high, as California generates seven million tons of food waste and landscape waste per year (City of Del Mar California 2014). These could encourage significant growth of the on-farm AD system in the coming years. The success of reaching the region's AD production potential will likely depend on future incentives, regulations, and new technology that will influence the economic feasibility of future AD systems.

14.5 Conclusions and Summary

Biogas can be produced from manure and other organic products (on-farm or imported) using AD systems. Biogas can be used directly for heat and electricity production or upgraded to RNG after removing the CO_2 and H_2S in the biogas. The biogas quality is dependent on CH_4, H_2S, and moisture content. Biogas production depends on the organic loading rates, the type of substrate utilized, the type of digester utilized, the pH of the digester, HRT, agitation, and operating temperature. To develop new AD systems, it is important to estimate raw biogas quantity and quality as accurately as possible to properly size the biogas utilization equipment (i.e., EGS) and biogas scrubbing or upgrading systems. Biogas scrubbing can be performed at various levels, from simply removing moisture to more advanced upgrading strategies to produce RNG for injection to a natural gas pipeline or use as a transportation fuel. Incentives, off-farm tipping fees, and nutrient removal technologies can affect the economics and feasibility of future AD systems.

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Chapter 15
On-Farm Energy Production: Biofuels

Daniel Ciolkosz and Matt Steiman

15.1 Introduction to Topic

Liquid biofuels are a topic of great interest in the farming community. Not only are they a potential fuel for use on the farm, they are also almost always sourced from bio-based feedstocks, which means that the potential exists to grow biofuels on the farm for self use or for resale to others. However, the technology involved in transforming farm crops into biofuels is varied in its complexity and performance, and even when biofuel production is technically feasible, consistently high quality and safe production conditions are not always easy to achieve. Thus, while farmers are encouraged to consider biofuel production, they should thoroughly research the requirements and challenges of the complete processes and proceed with caution.

15.2 Biodiesel

The most common biofuel to be produced on farm is biodiesel. Biodiesel is a clean burning, renewable alternative to petroleum diesel fuel made from vegetable oil or animal fats. Using biologically derived oils for fuel is not new – whale oil was used for lamp lighting until the development of the petroleum industry. Vegetable oil has nearly the same energy content as diesel fuel but is too thick at normal operating temperatures to burn properly in modern diesel engines. For satisfactory engine

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performance, vegetable oil can be thinned through a chemical process called "transesterification", resulting in biodiesel, a product with a viscosity that is more like that of mineral diesel fuel.

Transesterification results from mixing methanol and a caustic soda catalyst (sodium hydroxide or potassium hydroxide) into vegetable oil or animal fat in a heated reactor. The result of the reaction is biodiesel and a crude glycerine byproduct, which settles out of the biodiesel by gravity. For every five gallons of oil reacted into biodiesel, about ½ to 1 gallon of glycerine will result. After separation, impurities are removed from the biodiesel by water washing or filtration, then the fuel is dried before transfer to final product storage. A biodiesel production line typically includes several components, including tanks for raw oil storage and cleaning, the biodiesel reactor, biodiesel wash and dry system, glycerine storage, methanol recovery apparatus, final product storage and chemical storage (Fig. 15.1).

Converting vegetable oil into finished biodiesel is not especially complicated – the technology is within reach of farmers with fabrication skills and a basic chemistry background. However, making high quality fuel in a safe and environmentally responsible manner does require attention to detail, careful record keeping and investment in training or self-education. A well-run biodiesel operation is similar to a successful craft beer brewery – in fact many of the same skills apply to each system. A farm-based biodiesel operation will require at least on person dedicated to learning the technology and able to take responsibility for the nuances of fuel production, quality testing, equipment troubleshooting, safety and environmental compliance. Given the time, skill and equipment requirements most on-farm biodiesel plants do not return an economic profit if the operator's labor cost is included in a project budget.

While the process is fairly straightforward, several points should be noted:

- The flammability and corrosiveness of the reactants calls for extreme care to be taken to prevent property damage, injury, or death.
- Catastrophic fires have resulted from accidental ignition of methanol fumes or spontaneous combustion of biodiesel-soaked rags or absorbent materials.
- Biodiesel producers are encouraged to consult local fire officials for safety tips and to alert them to the quantity of materials stored on site in case of an accident

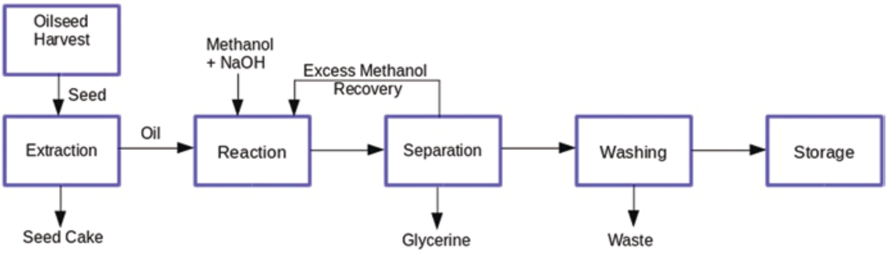

Fig. 15.1 Typical process diagram for biodiesel production

- Complete reaction of oil into biodiesel requires additional efforts such as overfeeding of methanol or multi-stage reaction. Incomplete reaction will result in poor quality fuel.
- “Washing” of the biodiesel is necessary in order to remove contaminants such as soaps that can be created during the reaction.
- Cold weather performance of biodiesel can be a problem for most types of oil, as biodiesel has a tendency to gel more readily than petroleum diesel. Blending biodiesel with petroleum fuel for winter use is a common solution, as is restricting biodiesel use to warmer months.
- Seals and other fuel system parts in tractors and vehicles, if made from natural rubber and some non-resistant elastomers, may not be suitable for biodiesel. Biodiesel compatible fuel lines are available for equipment retrofits. The likelihood of rubber part failure increases with high percentage biodiesel blends and extended time running biodiesel, as well as using equipment produced prior to 1994
- Biodiesel absorbs moisture from the atmosphere and is more quickly biodegraded than regular diesel fuel. Consequently, biodiesel has a limited storage life unless treated with biocide products. To avoid fuel system problems from microbial growth, it is helpful to use fresh fuel and purge equipment of high biodiesel blends when going into storage.

With the above in mind, biodiesel can work very well in tractors and other farm machinery, especially during summer crop production when fuel demand is high. Its energy content is only slightly lower than that of mineral diesel, and it has outstanding lubricity characteristics. Some engines tend to be more compatible with biodiesel than others, which is likely related to differences in robustness of fuel pumps and injectors. Fuel quality control is critical when making biodiesel, and farmers interested in producing biodiesel should plan to learn and carry out a testing plan for their fuel. Farmers are encouraged to consult their equipment service providers regarding biodiesel compatibility and warranty compliance. Biodiesel blends very well with petroleum diesel and even low percentage blends like B5 or B20 (5–20% biodiesel) provide some air quality and lubricity benefits.

15.2.1 Biodiesel Oil Sources

Oil for biodiesel production can be pressed from oilseeds (soybean, canola, sunflower, etc.) grown on the farm. An oilseeds to biodiesel venture has potential benefits to a diversified farming operation, including adding value to commodity crops already grown and market value of small batch edible oils. Co-products such as oilseed press meal are valuable as animal feed. A study of on-farm oilseeds for fuel conducted by the Vermont Bioenergy Initiative documented an average oil yield of 65 gallons per acre from 2009 to 2012 (White and Callahan, 2013). Automated oil presses help reduce the labor required to convert seed crops into feedstock for fuel or edible oil markets White. Many oilseed crops grown in the Northeast are suitable for biodiesel production, including soybeans, sunflowers and rapeseed (Canola).

Biodiesel is also made from used fryer oil collected from restaurants and food concessions. Rendered animal fat from poultry and other meat production industries can be used where affordable. Farmers are advised to investigate the oil resources available locally to determine if their fuel production goals are realistic. Long-term contracts for restaurant oil collection are common but new opportunities may exist within farmers' community contacts. Oil collected from restaurants must be filtered to remove food particles, dewatered, and tested for acidity prior to processing for biodiesel. Collection, transfer, cleaning and storage of used cooking oil is an inherently messy operation that benefits from disciplined housekeeping efforts and prior design for materials flow through the facility.

A safe, responsible and successful biodiesel shop will include the following features (Steiman et al., 2009):

- Ventilation: Lye dust is caustic and methanol vapor is toxic and flammable. Biodiesel shops must be well ventilated and should not be attached to homes or buildings that house livestock. Biodiesel reactors should be vented to the outdoors through dedicated piping.
- No ignition sources: Smoking, open flame, and sparking tools should be kept away from methanol vapors.
- Secondary containment: Shop designers should plan ahead for spills and tank failures and have a recovery and clean-up system in place.
- Personal protective equipment: chemical resistant gloves, safety goggles, dust mask or respirator, coveralls.
- Eyewash station or running water in case of accidents.
- Signage and MSDS to alert visitors and first responders to the potential hazards inside the shop.
- Labeling: Tanks and containers should be labeled to identify liquid contents and date produced or accumulated.
- Record keeping for fuel quality improvement.
- Secure door to keep out children, pets and livestock.

15.2.2 Byproducts and Waste Products

An on-farm biodiesel operation may produce the following waste products:

- Soilds, water and off-spec oil from used fryer oil pre-processing
- Empty oil jugs from restaurants or concessions
- Biodiesel wash water and oil/water interface layer
- Crude biodiesel glycerine
- Failed batches of biodiesel

While these materials (with the exception of jugs) are potentially biodegradable in a large-scale composting pile, farmers should consult with local authorities before releasing these wastes into the environment. Biodiesel byproducts are not allowed in compost used for organic production, and use in home garden compost piles is not recommended. Biodiesel wastes absorbed onto wood chips or sawdust present a spontaneous combustion risk that can result in catastrophic fires.

15.2.3 Glycerine

Crude biodiesel glycerine (CBG), the primary waste product of biodiesel production, is the heavy fraction of vegetable oil that settles out of the fuel after the transesterification reaction. CBG is a mixture of glycerine, fatty acids, residual biodiesel, methanol and other impurities. The quantity and quality of CBG generated will vary with vegetable oil feedstocks and specific production methods. On-farm biodiesel plants will need to find a use or responsible disposal option for their byproduct before it accumulates in problematic quantities. CBG with methanol is classified as a hazardous material due to its ignitability at temperatures below 140 °F – storage, handling, and transport of raw CBG should be approached with caution and attention to applicable regulations. A best practice for biodiesel production is distillation of surplus methanol from CBG for reuse in future batches of biodiesel (Bohon et al., 2010). Uses for CBG of interest to farmers may include:

- Composting: Pilot experiments with addition of glycerine to both machine and hand turned compost piles at the Dickinson College Farm showed no ill effect on the composting process nor the quality of the end product. A published study of CBG composting with laying hen manure from Brazil found improved solids breakdown and retention of nitrogen in the finished product compared to manure alone (Orrico et al., 2017; Parker, 2013).
- Anaerobic digestion: Several studies document increases in biogas production when CBG is added to other feedstocks (manure, crop residues) for microbial breakdown into burnable methane.
- Dust control: Where permitted by local authorities, dilute CBG may prove valuable for reducing nuisance dust on farm roads, horse arenas, piled materials, etc.
- In dust control, composting and anaerobic digestion, dilute additions of CBG were most successful with minimal unwanted effects (please see references for further details).
- Soap production: A soap-like material can be made by adding additional lye catalyst and water to CBG after methanol removal. Marketing this product is challenging but it may prove useful in farm applications.
- Combustion: Burning glycerine byproduct on-farm is not advised due to the potential for toxic emissions and high ash production. However, use in specialized industrial burners has been demonstrated as a potential replacement for fossil fuels.

15.2.4 Non-chemical Option

Another option for vegetable oil-based diesel fuel is reducing viscosity by heating the oil onboard the tractor or vehicle in a second fuel tank. These systems, called "Straight Vegetable Oil" conversions (SVO), start the vehicle on diesel fuel from the original fuel tank, then use engine heat to warm a vegetable oil tank to the proper viscosity for flow though the fuel injection system. SVO systems require extensive fuel system modifications in each piece of equipment that will run on vegetable oil, whereas biodiesel made in a central processing system can run in any diesel engine on the farm. A major benefit of SVO systems is that chemicals are not required for fuel production and fewer waste materials are generated in the process.

15.3 Bioethanol

Bioethanol is another potential biofuel that can be manufactured on the farm. Used in place of gasoline, ethanol has been successfully used in many countries as a blendstock with gasoline and occasionally as a pure ethanol fuel.

The energy content of bioethanol is about 30% less than that of petroleum gasoline, and minor adjustments can make most gasoline engines suitable for use with ethanol.

The process of producing ethanol on the farm generally requires either a sugar crop (i.e. sugar beet or waste fruit) that is fermented then distilled, or else a starch crop (i.e. corn or barley) that is converted to sugar then fermented and distilled. Less common is the use of a lignocellulosic crop (i.e. switchgrass or corn stover) that is chemically transformed into sugar via hydrolysis or other methods. While all of these steps can be carried out on the farm, it is challenging at best from a practical point of view, largely because of regulatory concerns and restrictions (since the ethanol has potential to be used or sold as an intoxicant). Safety is also of paramount concern, owing to the flammability of the product (Fig. 15.2).

15.4 Current Status in the Region

The value of oilseed for the feed and culinary oil market makes it challenging to economically justify growing canola or sunflower only for biodiesel production. However, several enterprising farmers in the Northeast US do make their own biodiesel. It is not unusual for them to seek waste oils from restaurants or other sources to use them in the biodiesel production process rather than using vegetable oil extracted from an oil crop. Soy oil may have potential for some farmers, especially if the separated meal is desirable for use on site as a protein source. USDA Statistics indicate that the largest numbers of biodiesel producers on the farm are in the major corn producing states of Illinois, Indiana, and Ohio. Interestingly enough, the number of farms producing ethanol is nearly as high as for biodiesel (Table 15.1).

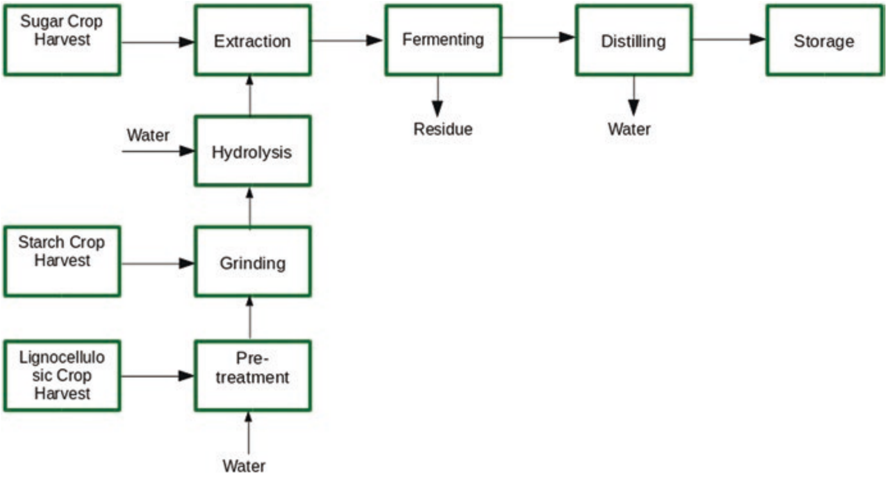

Fig. 15.2 Typical bioethanol production process diagram, showing three possible feedstock types

Table 15.1 Number of farms producing biofuel, northeast United States (USDA 2019)

State	Biodiesel	Ethanol
ME	17	11
DE	8	1
IL	431	385
IN	161	114
MD	16	34
MA	13	16
MI	53	53
NH	7	11
NJ	0	0
NY	61	35
OH	128	142
PA	91	65
RI	0	0
VT	5	3
VA	60	54
WI	1	1
CT	3	10
KY	85	67
WV	29	43
TOTAL	1169	1045

In addition to on-farm production of biofuels, several commercial facilities exist in the region that purchase feedstock from farmers and produce the biofuel for sale on the open market. These facilities provide a steady market for farmers interested in producing biofuel feedstock but who do not wish to take part in biofuel manufacture. Compared to on-farm biofuel facilities, the economy of scale of larger plants facilitates higher standards of industrial safety, integrated management of waste streams and engineering for overall system efficiency (Table 15.2).

Case Study: V.M. Farms

"V.M." is a farmer in Pennsylvania who has been making biodiesel for over 15 years. His main motivation was to make beneficial use of a waste product by utilizing waste oil available in the area. He also likes that his farm is less reliant on fossil fuel, and costs less to operate. In addition to that, it's "just plain fun" to make your own fuel. Approximately 750 gallons of biodiesel are produced per year at his facility, which is used to operate farm tractors, a loader and excavator, and a UTV.

The biodiesel production process at V.M. Farms is a batch process, using Potassium Hydroxide as the catalyst. The system does not employ "methanol recovery" at this time. The steps in the process are as follows:

- Bubble dry/treat oil (helps to clarify the oil and remove impurities)
- pump oil into processor
- mix in processor and titrate
- heat oil in processor
- mix methoxide in a separate "methoxide mix tank" and pump into processor
- react for 2 h while paddle mixing
- settle for several hours
- drain glycerine into a separate "tote" container
- bubble dry/treat biodiesel
- pump through two (in series) wood fiber dry wash towers
- store in large "tote" container

The glycerine byproduct is primarily used as a degreasing/release agent and dust retarder. Wash water is applied to the fields.

The biodiesel has worked very well in the equipment at V.M. Farms, where the only issues occurred when initially switching over from petroleum diesel to biodiesel. "We plugged a couple fuel filters quickly while the system (the engine) was cleaning itself. Also, we determined through trial and error, that our peanut oil biodiesel gels at a very high temperature, ~50 degrees (Fahrenheit)".

The main challenges in making biodiesel at V.M. Farms has been obtaining a consistent used oil supply, and dealing with all the materials handling tasks involved in producing the biodiesel. The biodisel is definitely a money saver – "if you don't consider the value of time spent collecting oil and processing into biodiesel".

Do they recommend that every farmer in their situation produce biodiesel? "Yes and No. Yes because it is a satisfying process to make fuel that your vehicle can run on or that can heat a home. No because it requires a lot of attention to detail and safety precautions that may not be suited for everyone."

Table 15.2 Biodiesel and ethanol producing plants, by state (Anon 2020a, b)

	Biodiesel		Ethanol	
State	# Plants	Capacity (MMGy)	# Plants	Capacity (MMGy)
ME	1	1.5	–	–
DE	–	–	–	–
IL	8	170.1	14	1836
IN	2	96.4	15	1250
MD	–	–	–	–
MA	2	3	–	–
MI	3	15.9	5	377
NH	1	6.5	–	–
NJ	1	25	–	–
NY	–	–	2	140
OH	1	70	4	470
PA	2	95	1	110
RI	2	9.2	–	–
VT	–	–	–	–
VA	2	8.6	–	–
WI	2	25	9	642
CT	1	40	–	–
KY	3	47.1	2	51
WV	–	–	–	–

15.5 Outlook for the Future

Relatively low petroleum prices at present tend to make on-farm biodiesel production a difficult option for most farmers. It is likely to remain a specialty option for those who particularly value having a local, renewable fuel source for their engine-driven farm equipment. Small-scale biodiesel production gained popularity during the 2000–2010 period driven largely by grassroots enthusiasts with some support from academia. This wave has largely crested with many on-farm and community biodiesel plants currently shuttered due to safety concerns, competition for used cooking oil, and the economic realities of competition with subsidized petroleum diesel. Uncertainty of governmental incentives for biofuels is also an impediment to continued growth of biofuels production and use at the industrial scale, since a steady and reliable market is generally needed to justify the cost of building biofuel production facilities.

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