REVIEW: DAIRY FARM ELECTRICITY USE, CONSERVATION, AND RENEWABLE PRODUCTION—A GLOBAL PERSPECTIVE

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HIGHLIGHTS

- Studies of electricity use were reviewed, representing five continents.
- Considering all farm types, electricity use averaged 7.7 kWh 100 kg⁻¹ milk and 612 kWh cow⁻¹ y⁻¹.
- Pasture-based dairy systems used less electricity than barn-based systems (475 vs. 769 kWh cow⁻¹ y⁻¹).
- By combining several conservation technologies there is potential to reduce electricity demand by one-third.
- Dairy farms can reach net zero electricity by combining renewable energy production with conservation.

ABSTRACT. This review summarizes electricity use on dairy farms, with a focus on how energy is used, energy use indices (EUI), conservation strategies, and generation of renewable energy to reach net zero. EUI of electricity consumption varied between the identified studies primarily based on farm management system (confined, pasture-based), housing type (tie-stall, free-stall), and region (North America, Europe, Asia, Africa, Oceania). The highest electricity usage was associated with milking and milk cooling systems, which, on average, accounted for 23% and 22% of total electricity use, respectively. Energy use scaled per cow (EUI_c) was lower, on average, for pasture-based dairy systems than for confined systems (475 vs. 769 kWh cow⁻¹ y⁻¹). Considering milk production, the average EUI scaled to milk (EUI_m) was lower for pasture-based systems (6.6 kWh 100 kg⁻¹) than for confined systems 9.2 kWh 100 kg⁻¹. Considering all non-irrigated farm types, EUI_m averaged 7.7 kWh 100 kg⁻¹ and EUI_c averaged 612 kWh cow⁻¹ y⁻¹. There was a large range of EUI, with higher values associated with automated milking systems and irrigation. Electricity consumption by the global dairy sector (excluding irrigation) was estimated using the average EUI_m at approximately 64.2 TWh y⁻¹. The main conservation technologies include variable speed drives (milk vacuum pumps, milking systems, fans), pre-cool heat exchangers, refrigeration heat recovery systems, energy-efficient light fixtures (compact fluorescents, light emitting diodes), and efficient ventilation (high-volume low-speed fans). Theoretical savings of up to 32% overall could be achieved by combining several technologies. Feedback from electricity monitoring can inform dairy farmers of their energy use pattern to guide decisions to reduce consumption. Tools for predicting energy use and related costs on dairy farms, which can indicate potential energy savings from operational changes, were reviewed. By combining conservation methods with renewable energy from biogas or solar, many dairy farms can produce enough electricity to reach net zero electricity. For example, a hypothetical barn-based 250 milking-cow dairy farm consumed 1021 kWh cow⁻¹ y⁻¹, on average, and could produce approximately 1095 kWh cow⁻¹ y⁻¹ using a biodigester or 960 kWh cow⁻¹ y⁻¹ using rooftop photovoltaic solar panels.

Keywords. Conservation, Dairy footprint, Electricity use, Electricity partitioning, Energy utilization index, Renewable energy.

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The world's population is expected to reach roughly 9.8 billion by 2050 (UN, 2017). As a result, the demand for food production will increase. Global dairy production was more than 850 million tonnes of fluid milk in 2019 (FAO, 2020), and it is expected to increase in the coming decades. Projections from 2006 predict a roughly 55% increase in the consumption of dairy

products by 2050 (FAO, 2006, 2011). Energy on dairy operations is used both directly (fuel, electricity) and indirectly (fertilizer, chemicals) (Schnepf, 2004). Indirect energy use typically makes up 55% to 70% of the total energy requirements of dairy farms (Upton et al., 2013; Houston et al., 2014; Podstolski, 2016). On-farm direct energy use has been estimated to make up 12% to 16% of total energy in rain-fed systems (Bailey et al., 2008; Upton et al., 2013; Shine et al., 2018a, 2018b) and up to roughly 30% on farms with intensive irrigation (Podstolski, 2016). Electricity use in agriculture has been estimated to be roughly 3% of total energy use in the United States and 2.7% in the European Union (Slocombe et al., 1992; Eurostat, 2018). In Canada, the dairy industry is responsible for an estimated 10% of total agricultural electricity use (Khakbazan, 2000). These aggregate figures, although useful, are often based on a number of generalizations and assumptions. In many cases, there have not been systematic assessments of electricity use from different farm components—or of changes in energy use as a result of management or technology—and there is a need to present a summary of current knowledge.

Electricity utilization on dairy farms has been identified as an area where significant savings and optimization can be achieved (Kammel and Patoch, 1993; Peebles et al., 1994; EnSave, 2015). Conserving electricity can reduce potential air pollution, and can reduce the carbon footprint of milk production (Pervanchon et al., 2002; Christie et al., 2012; EnSave, 2015; Wang et al., 2018). In addition, the cost of electricity is a concern for dairy operations, and increased efficiency could lead to financial savings (Upton et al., 2014b). The amount of the savings depends on electricity rates, which vary considerably across regions, e.g., 0.05 to 0.25 USD kWh⁻¹ in North America (HydroQuebec, 2018), roughly 0.12 USD kWh⁻¹ in the European Union (Eurostat, 2019), 0.16 to 0.27 USD kWh⁻¹ in New Zealand (figure.nz, 2019), and approximately 0.10 USD kWh⁻¹ in China (CEIC, 2019).

Beyond energy efficiency, there is growing interest in the concept of net zero energy, whereby a facility produces as much on-site electricity as it uses. This concept comes from the field of building sciences and combines energy conservation with the production of renewables to achieve this goal (Marszal et al., 2011). Within the dairy farming context, renewable technologies that have the potential to enable farms to achieve net zero electricity are discussed, specifically anaerobic digestion and solar. There are tools available to estimate electricity use (or generation potential) of various on-farm activities, some developed for farm managers or policy makers, while others target an academic audience. An overview of these tools and models is also presented in this review.

This review seeks to compile the information from relevant studies to better quantify electricity demand of various dairy farm components across a range of global regions and management scenarios. The objective of this review is to assemble previous research on dairy farm electricity use, conservation (design/technology/management), production of renewable energy, and estimation tools. It also explores theoretical scenarios and the feasibility of net-zero-energy dairy farms, while highlighting areas for further research and information transfer.

REVIEW METHODOLOGY

Data were collected from a variety of publications, including technical reports, factsheets, modeling studies, on-farm energy audits, surveys, and sensor-based energy monitoring studies. Only the electricity component of on-farm activities was considered and, in some cases, differences observed between studies may be due to varying degrees of reliance on other forms of energy (fuel, animal power, etc.). In total, 37 studies were identified: 19 from North America, 9 from Europe, 3 from Asia, 2 from Africa, and 4 from Oceania. Study farms were classified as either “confined” (i.e., housed year-round), or “pasture-based” dairies. The term “pasture-based” can have different implications depending on region. For example, a pasture-based dairy in Canada may have their herd on pasture from May to October (Houston et al., 2014), whereas some pasture-based dairies in New Zealand graze for the entire milking season. There were 15 farms classified as confined dairies, 19 classified as pasture-based, and 13 that did not fit into either of these two broad categories or did not provide enough information. Some of these unclassified farms include open dry-lot corral systems (Bickert and Light, 1982), which are discussed separately from confined and pasture-based dairies. Electricity consumption data from each study were compiled and, when possible, partitioned by electricity use type, including milk cooling, milking system, water heating, lighting, cow comfort (ventilation fans, misting systems), manure handling, and feed handling (table 1). Electricity used for irrigation, where applicable, was also partitioned.

Confined dairy farms were sub-categorized as either free-stall or tie-stall. Many free-stall barns shared the following general attributes: (1) separate feed and bedding areas with cows free to move between areas; (2) separate milking area; (3) open side- and/or end-wall design (i.e., natural ventilation); (4) more than 100 milking cows; and (5) bunker silo feed storage. The general attributes of tie-stall barns included: (1) combined feed and bedding area with the cows tethered to the stall; (2) in-stall milking; (3) mechanical ventilation; (4) over 100 milking cows; and (5) vertical silo feed storage. Overall, the comparison of free-stall and tie-stall operations in this review was done as a convenient way to group farms likely to share similar barn attributes (e.g., ventilation, milking system).

It is useful to employ energy utilization indices (EUI) to standardize electricity usage data. Since milk production per cow can vary significantly across different management and production systems, studies have noted that EUI scaled to milk (EUI_m) can be a better indicator of on-farm efficiency than EUI scaled per cow (EUI_c) (Edens et al., 2003). However, EUI_c can still be useful for comparing dairy energy efficiency in cases where one wishes to isolate milk production as a separate variable. With the exception of specific cases (low input, low production systems), both types of EUI seem capable of serving as benchmarks. This study considers both electricity use per cow (EUI_c, kWh cow⁻¹ y⁻¹) and electricity use scaled to milk production (EUI_m, kWh 100 kg⁻¹). Descriptive statistics (mean, median, standard deviation) were calculated for multiple parameters and grouping variables using Pivot Tables in Microsoft Excel® 2016, and Tabulate

Table 1. Breakdown of electricity consumption by dairy operation (% of the total use).^[a]

Source	Location	FT	No. Cows	MH										EUI		
				MS	MC	H	L	CC	FH	WH	MP	O	Total	kWh 100 kg ⁻¹ cow ⁻¹ y ⁻¹	kWh 100 kg ⁻¹ cow ⁻¹ y ⁻¹	
													kWh y ⁻¹			
Energy Efficiency on Dairy Farms (Alberta Government, 2014) ^[b]	Alberta, Canada	Confined	100		44	6	13	15	-	-	3	19	111,000	-	1,110	
Farm Lighting & Energy Incentives (Clarke, 2016) ^[c]	Ontario, Canada	Confined(FS)	-	38	5	8	42	-	-	-	7	-	-	6.5	837	
		Confined(TS)	-	32	10	21	17	7	2	9	2	-	-	12.4	1,417	
Evaluation of energy efficiency and renewable energy generation opportunities for small scale dairy farms: A case study in Prince Edward Island, Canada (Houston et al., 2014) ^[d]	PEI, Canada	Pasture	95	13	32	5	33	16	-	1	-	-	95,000	12.0	1,000	
Comparing the environmental impacts of pasture-based and confinement-based dairy systems in Nova Scotia (Canada) using life cycle assessment (Arsenault et al., 2009) ^[d]	Nova Scotia, Canada	Confined	70	-	-	-	-	-	-	-	-	-	56,000	8.8	995	
		Pasture	40	-	-	-	-	-	-	-	-	-	33,000	9.2	988	
Energy conservation on Nova Scotia farms: Baseline energy data (Bailey et al., 2008) ^[d]	Nova Scotia, Canada	Various	-	-	-	-	-	-	-	-	-	-	-	9.0	-	
Measuring energy conservation on Nova Scotia (NS) farms: A 2004 to 2011 comparison (Bailey et al., 2016) ^[d]	Nova Scotia, Canada	Various	-	-	-	-	-	-	-	-	-	-	-	5.1	-	
Modelling and benchmark development for electrical energy use and energy efficiency on Nova Scotia dairy farms (Pradhanang, 2015) ^[e]	Nova Scotia, Canada	Confined(FS)	116	11	14	20	29	4	3	3	-	16	102,000	8.6	878	
		Confined(TS)	45	16	18	21	24	7	5	4	-	5	51,000	11.2	1130	
Water and electricity consumption on pasture-based and confined dairies in Georgia (Belflower et al., 2012) ^[d]	Georgia, U.S.	Confined(IR)	700				72			5	21	3	814,000	10.4	1,163	
		Confined	700				79			5	13	3	751,000	9.5	1,073	
		Pasture(IR)	500				53			12	35	-	270,000	10.6	541	
		Pasture	500				43			6	51	-	132,000	5.3	265	
Got pasture? How grazing intensity affects the environmental impacts of dairy systems (Aguirre-Villegas et al., 2017) ^[d]	Wisconsin, U.S.	Confined	286	-	-	-	-	-	-	-	-	-	-	13.4	-	
		Pasture	298	-	-	-	-	-	-	-	-	-	-	13.7	-	
Energy Usage Survey of Dairies in the Southwestern United States (Capareda et al., 2010) ^[d]	Texas, U.S.	Other(OL)	2100			87			1	3	10	-	1,189,000	5.26	566	
		Pasture	180			78			-	22	-	-	50,000	2.58	280	
Net Zero Energy Dairy Production: Powering Minnesota Dairy Farms with Renewable Energy (Dice, 2017) ^[b]	Minnesota, U.S.	Pasture	250	9	26	25	8	15	-	-	1	16	110,000	7.7	440	
Conservation applied research & development (Ebinger, 2015) ^[b]	Minnesota, U.S.	Various	105	15	18	22	13	19	-	-	-	13	-	-	-	
Energy efficiency in New York state agriculture: summary of energy efficiency programs and research opportunities (EnSave, 2015) ^[b]	New York, U.S.	Various	730	26	11	16	19	-	-	14	14	-	556,000	-	762	
Dairy Farm Energy Efficiency (Pressman, 2010) ^[b]	U.S.	Not Specified	-	18	26	5	17	24	-	-	-	10	-	-	-	
Dairy farm energy audit summary (Ludington and Johnson, 2003) ^[a]	New York, U.S.	Confined(FS)	244	17	27	2	26	22	1	4	-	1	198,000	6.0	811	
		Confined(TS)	77	18	23	10	17	21	7	3	-	1	72,000	10.0	934	
Dairy farm energy efficiency guide (Ludington et al., 2004) ^[a] ^[b]	California, U.S.	Not Specified	-	12	27	8	13	10	-	24	4	2	-	-	-	
The Economics and Feasibility of Electricity Generation using Manure Digesters on Small and Mid-size Dairy Farms (Mehta, 2002) ^[a] ^[b]	Wisconsin, U.S.	Not Specified	400	-	-	-	-	-	-	-	-	-	105,000	-	262	
			200	-	-	-	-	-	-	-	-	-	54,000	-	272	
			60	-	-	-	-	-	-	-	-	-	41,000	-	689	
Feasibility of Fuel Cells for Energy Conversion on Dairy Farms (Minott and Scott, 2001) ^[b] ^[c]	New York, U.S.	Confined(FS)	500	27	17	-	14	27	-	5	9	1	414,000	-	828	

^[a] FT = facilities type, MH = average milking herd, MS = milking system (parlor system, vacuum pumps), MC = milk cooling, H = heating (space / water), L = lighting, CC = cow comfort (ventilation / misting), FH = feed handling, WH = waste/manure handling, MP = motors and pumps (excl. milk production), O = other (unspecified), EUI = energy utilization indices. Some studies measured a single farm whereas others are averaged from a group of farms. FS = free-stall, TS = tie-stall, OL = open dry-lot corral, IR = irrigated, MR = milking robots, "-" indicates not measured, whereas a value centered among blank cells indicates that multiple electricity uses were measured together (e.g., MS+MC).

^[b] Technical report/factsheet.

^[c] Conference paper/presentation.

^[d] Peer reviewed publication.

^[e] Thesis.

Table 1 (continued). Breakdown of electricity consumption by dairy operation (% of the total use).^[a]

Source	Location	FT	MH											Total	EUI	
			No. Cows	MS	MC	H	L	CC	FH	WH	MP	O	kWh y ⁻¹	kWh 100 kg ⁻¹	kWh cow ⁻¹ y ⁻¹	
				%												
Environmental implications of anaerobic digestion for manure management in dairy farms in Mexico: a life cycle perspective (Rivas-Garcia, 2015) ^[d]	Mexico	Not Specified	592	-	-	-	-	-	-	-	-	-	271,000	5.0	458	
Energy use and management in dairy farms (Murgia et al., 2008) ^[c]	Italy	Not Specified	186 69	15 22	21 24	-	5 5	-	-	7 4	-	52 45	93,000 31,000	4.8 5.1	501 455	
A partial life cycle assessment approach to evaluate the energy intensity and related greenhouse gas emission in dairy farms (Murgia et al., 2013) ^[d]	Italy	Not Specified	141	21	26	9	4	10	-	13	12	5	56,000	-	400	
Consommation d'énergie en élevage bovin—Des repères pour se situer et progresser (Galan et al., 2007) ^[d]	France	Not Specified	-	51	16	19	-	-	-	-	-	14	-	6.0	-	
		Not Specified(MR)	-										-	11.5	-	
Life cycle inventory of 23 dairy farms in South-Western Sweden (Cederberg and Flysjö, 2004) ^[b]	Sweden	Pasture	54	-	-	-	-	-	-	-	-	-	76,000	-	1,400	
Electric energy consumption of milking process on some Finnish dairy farms (Rajaniemi et al. 2017) ^[b]	Finland	Pasture	82	34	14	22	-	-	-	-	-	30	-	5.14	-	
Electricity & direct water consumption on Irish pasture based dairy farms: A statistical analysis (Shine et al., 2018b) ^[d]	Ireland	Pasture	116	18	29	20	3	-	-	-	5	24	25,000	4.0	214	
Daily and seasonal trends of electricity and water use on pasture-based automatic milking dairy farms (Shortall et al., 2018) ^[d]	Ireland	Pasture(MR)	114	59	18	12	-	-	-	-	4	11	38,000	6.3	336	
Energy demand on dairy farms in Ireland (Upton et al., 2013) ^[d]	Ireland	Pasture	118	20	31	23	3	-	-	-	5	18	24,000	4.2	200	
Investment appraisal of technology innovations on dairy farm electricity consumption (Upton et al., 2015) ^[d]	Ireland	Pasture	45 88 195	20 14 19	50 39 48	23 29 24	2 4 2	- - -	- - -	4 6 0	0 7 8	-	10,000 25,000 33,000	4.0 4.9 4.1	231 287 168	
Greenhouse gas emissions and land use from confinement dairy farms in the Guanzhong plain of China—using a life cycle assessment approach (Wang et al., 2016) ^[d]	China	Confined	342	-	-	-	-	-	-	-	-	-	126,000	6.2	367	
Environmental impacts and resource use of milk production on the North China Plain, based on life cycle assessment (Wang et al., 2018) ^[d]	China	Confined	531	-	-	-	-	-	-	-	-	-	156,000	4.1	294	
Economic assessment of photovoltaic water pumping integration with dairy milk production (Zhang et al., 2018) ^[d]	China	Pasture(IR)	352	-	-	-	-	-	-	-	-	-	312,000	14.3	886	
A comprehensive method to assess the feasibility of renewable energy on Algerian dairy farms (Nacer et al., 2016) ^[c]	Algeria	Confined	26 12 14 10 17 13	60 - - - - -	- - - - - -	21 - - - - -	- - - - - -	15 - - - - -	- - - - - -	- - - - - -	- - - - - -	-	8,600 5,600 6,300 5,660 6,375 6,200	6.6 9.4 8.9 9.4 7.5 10.6	330 470 450 566 375 480	
Modeling and Assessment of Dairy Farm-Based Biogas Plants in South Africa (Boadzo, 2011) ^[d]	South Africa	Confined	150	-	-	-	-	-	-	-	-	-	200,000	16.1	1,333	
Whole-farm systems analysis of Australian dairy farm greenhouse gas emissions (Christie et al., 2012) ^[d]	Australia	Pasture	355	-	-	-	-	-	-	-	-	-	146,000	6.5	411	
Dairy farmers milk free energy (EECA, 2009) ^[b]	New Zealand	Pasture	-	26	21	32	-	-	-	-	10	11	-	-	-	
Environmental input-output analysis of the New Zealand dairy industry (Flemmer, 2012) ^[d]	New Zealand	Pasture	-	-	-	-	-	-	-	-	-	-	-	6.3	-	
The Evolution of Total Energy Inputs in the New Zealand Dairy Industry (Podstolski, 2016) ^[c]	New Zealand	Pasture	433	-	-	-	-	-	-	-	-	-	185,000	9.1	428	
		Pasture(IR)	630	-	-	-	-	-	-	-	-	-	736,000	23.4	1,169	

^[a] FT = facilities type, MH = average milking herd, MS = milking system (parlor system, vacuum pumps), MC = milk cooling, H = heating (space / water), L = lighting, CC = cow comfort (ventilation / misting), FH = feed handling, WH = waste/manure handling, MP = motors and pumps (excl. milk production), O = other (unspecified), EUI = energy utilization indices. Some studies measured a single farm whereas others are averaged from a group of farms. FS = free-stall, TS = tie-stall, OL = open dry-lot corral, IR = irrigated, MR = milking robots, “-” indicates not measured, whereas a value centered among blank cells indicates that multiple electricity uses were measured together (e.g., MS+MC).

^[b] Technical report/factsheet.

^[c] Conference paper/presentation.

^[d] Peer reviewed publication.

^[e] Thesis.

in JMP® 15 (SAS Institute, Inc., Cary, N.C.). Since studies reported different parameters, the number of observations varied depending on the parameter (e.g., if a study reported number of cows but not milk production it was included in EUI_c but not EUI_m calculations). Comparisons between groups were conducted with a two sample t-test in Excel®.

RESULTS AND DISCUSSION

DAIRY ELECTRICITY CONSUMPTION

Farms from the surveyed literature varied in size from 40 to 2100 milking cows, with an average of 307 milking cows. Milk production ranged from 11.3 to 37.1 kg cow⁻¹ d⁻¹, with an average of 21.2 kg cow⁻¹ d⁻¹ (median: 22.2 kg cow⁻¹ d⁻¹). Total annual electricity usage was between 10,000 and 1,189,000 kWh y⁻¹, with an average of 203,868 kWh y⁻¹ (median: 103,500 kWh y⁻¹). Electricity partitioning was available to varying degrees in some studies. Overall, the highest consuming components were the milking (23%±12% s.d.), milk cooling (22%±9%), water and space heating (16%±8%), lighting (14%±11%), and cow comfort (fans and misting) (15%±7%) systems. The balance (10%) was related to feed handling, waste handling, motors and pumps (non-milking related), or unspecified uses. The partitioning of electricity for confined and pasture-based dairies is provided in figure 1. The main difference in electricity use between confined and pasture-based systems is that confined systems used more electricity for cow comfort and lighting.

The EUI_c and EUI_m calculated from all non-irrigated studies averaged 7.7 kWh 100 kg⁻¹ and 612 kWh cow⁻¹ y⁻¹, respectively (median: 6.6 kWh 100 kg⁻¹ and 464 kWh cow⁻¹ y⁻¹; table 1 and 2). There was a wide range in the individual values, EUI_m ranged from 2.6 to 23.4 kWh 100 kg⁻¹, and

Figure 1. Representative milk-scaled electrical consumption (kWh 100 kg⁻¹) breakdown by dairy operation components for confined and pasture-based dairies. Data were calculated using 4 to 8 studies from table 1 in which electricity use was partitioned into milking system, milk cooking, cow comfort (fans, misters), heating, and lighting. The balance of these components was classified as other, which includes feed handling, waste handling, other motors and pumps. Most data was from North America and Europe; irrigated studies were not included.

EUI_c ranged from 168 to 1,417 kWh cow⁻¹ y⁻¹. Part of this variability can be explained by irrigation and farm size. For ‘small’ non-irrigated dairies (≤100 cows) the average EUI_c 699 kWh cow⁻¹ y⁻¹ (median: 566 kWh cow⁻¹ y⁻¹) was significantly higher than for ‘medium’ dairies (101-500 cows; excluding irrigation) where it was 466 kWh cow⁻¹ y⁻¹ ($p = 0.025$, two sample t-test; median: 384 kWh cow⁻¹ y⁻¹). ‘Large’ dairies (>500 cows; excluding irrigation) were between ‘medium’ and ‘small’ dairies, yielding an average EUI_c of 631 kWh cow⁻¹ y⁻¹ (median: 566 kWh cow⁻¹ y⁻¹). Irrigation greatly increased the EUI_c to 714 kWh cow⁻¹ y⁻¹ for medium, and 1166 kWh cow⁻¹ y⁻¹ for large dairies ($n=2$ for each size class). The farm size to efficiency relationship is consistent with the findings of Ebinger (2015) estimated an EUI_c of roughly 1,200 kWh cow⁻¹ for small farms (1-49 cows), and roughly 650 kWh cow⁻¹ for medium farms (100-499 cows). Some of these differences may be attributed to economies of scale as farm size increases, but also to a shift in the prevailing management type (confined, pasture-based) or barn design (free-stall, tie-stall) between each farm size category. Specific differences among these management types are discussed in later sections.

Average EUI_c and EUI_m categorized by region (North America, Europe, Asia, Africa, Oceania) and by farm system type (confined, pasture-based) are provided in table 2. On a EUI_c basis, the region with highest EUI_c was North America (762 kWh cow⁻¹ y⁻¹), followed by Oceania, Africa, Asia, and Europe (419 kWh cow⁻¹ y⁻¹). The pattern was different on a EUI_m basis due to differences in milk production, ranging from 9.8 kWh 100 kg⁻¹ in Africa to 5.2 kWh 100 kg⁻¹ in Asia. In general, pasture-based European dairies were most successful at achieving high milk yields with low electricity use. Pasture-based dairies in Oceania were similarly efficient when there was no irrigation. In contrast, North American confined systems had high milk yields but also the highest electricity demand. In general, pasture-based systems were more efficient than confined systems on a per-cow basis (EUI_c), but the difference was less pronounced when scaled to milk production (EUI_m) (table 2). Irrigation increased the average EUI_c by over 50% and the average EUI_m by over 90%.

Using EUI_m , the national electricity usage for milk production can be estimated from national milk production data. In Canada, for example, the dairy sector produced approximately 9.9 million tonnes of milk in 2017 (CDIC, 2018). Using the average EUI_m of North American confined dairy systems (9.6 kWh 100 kg⁻¹), it is estimated that Canadian dairies use roughly 950 GWh y⁻¹, or roughly 842 GWh y⁻¹ if using the North American EUI_m considering all dairy systems (8.5 kWh 100 kg⁻¹). If this estimate is compared to national agriculture electricity use estimates (NRCan, 2019), the dairy industry would account for roughly 5% to 6% of total agricultural electricity use, less than has been estimated by Khakbazan (2000) using federal statistics (roughly 10%). According to the United States Department of Agriculture, total milk production in the United States was 95.3 million tonnes in 2016 (USDA, 2017). Using the same calculation gives an estimate for on-farm direct electricity consumption of 9.15 TWh y⁻¹ when using the confined EUI_m and 8.10 TWh y⁻¹ considering the EUI_m calculated from all systems.

Table 2. Average EUI scaled per cow (EUI_c) and by milk production (EUI_m) for different general management systems (confined, pasture-based, or other/unspecified).^[a]

	kWh cow ⁻¹ y ⁻¹				kWh 100 kg ⁻¹			
	Confined	Pasture	Other	All	Confined	Pasture	Other	All
Without Irrigation (N=42)								
Africa	572	-	-	572	9.8	-	-	9.8
Asia	331	-	-	331	5.2	-	-	5.2
Europe	-	405	452	419	-	4.7	6.9	5.5
North America	1,021	595	548	762	9.6	8.4	6.1	8.5
Oceania	-	420	-	-	-	7.3	-	7.3
Average	769	475	519	612	9.2	6.6	6.6	7.7
Median	824	312	480	464	9.2	5.8	5.2	6.6
With Irrigation (N=4)								
Average	1,163	865	-	940	10.4	16.1	-	14.7
Median	1,163	886	-	1,025	10.4	14.3	-	12.5

^[a] Data from non-irrigated systems are partitioned by region, whereas data from irrigated systems are aggregated. Average and median values are shown for each management type (column) within each irrigation group. Data in this table were generated using components of the data presented in table 1.

Global dairy production was estimated at 852 million tonnes (FAO, 2020), with most milk being produced in Asia, Europe, and North America (table 3). A range of electricity estimates were calculated for each region depending on the EUI used. The actual value would depend on the distribution of farming systems within each region. Overall, the total electricity use estimates range from 55 to 77 TWh y⁻¹, excluding irrigation. Using the average EUI_m would give a global value of 64.2 TWh y⁻¹.

Whether scaled per cow or per unit of production, the annual dairy electricity consumption varied substantially among the studies surveyed. Ludington et al. (2004) pointed to three main factors that contribute to this variability: total milk production, milk production efficiency, and electricity conservation technology. The next sections examine variability stemming from two broad, sometimes overlapping areas: (i) farm design and management, and (ii) technology and equipment.

Farm Design and Management

The choice of farm design is a product of multiple interacting factors including the regional climate, landscape, availability of labor, access to capital, market factors, and preference. Climate enables year-round pasturing in warm regions with adequate rainfall and land. Regions with freezing winters require barns with appropriate ventilation to manage temperature, humidity, feed delivery, cow cleanliness, milking, bedding, and manure management (Bickert and Light,

1982). Barn design and milking system affect the labor requirements, with free-stall barns requiring less labor and tie-stall barns generally needing more labor but may be preferred for smaller or registered herds. Warm, dry, regions are more suitable for open dry-lot corral systems where cows are fed outdoors and provided with shade (Bickert and Light, 1982). This lowers the cost of construction and ventilation compared to barn-based housing. Market factors such as the cost and availability of concentrates, the ability to sell milk seasonally (e.g., pasture with seasonal calving) versus the requirement for consistent milk production throughout the year are also important factors affecting how farms are managed.

In terms of electricity use, the average EUI_m and EUI_c of confined dairies were 9.2 kWh 100 kg⁻¹ and 769 kWh cow⁻¹ y⁻¹, respectively, compared to 6.6 kWh 100 kg⁻¹ and 475 kWh cow⁻¹ y⁻¹ for pasture-based dairies (excluding irrigation). Pasture-based dairies were generally more energy-efficient on a per cow basis (EUI_c) due to fewer electricity consuming activities (e.g., lights, fans, pumps, etc.). However, pasture-based operations generally exhibited lower milk yields per cow than confined dairies. Cases where there was a large difference in per cow milk production between these two systems may be related to seasonal milking in the pasture-based dairies, but this information could not be confirmed in the studies that directly compare the two. In a North American study, Belflower et al. (2012) reported that a confined dairy had more than twice the per cow milk production of a pasture-based dairy (roughly 11,000 kg cow⁻¹ y⁻¹ vs. roughly 5,000 kg cow⁻¹ y⁻¹). As described by Delaby et al. (2020), the high genetic potential for milk production of Holstein cows are unable to meet their potential in a grazing system without feed supplementation. This lower production rate is also observed in African and New Zealand dairies, many of which adopt a lower-input, lower-production farming strategy (Nacer et al., 2016; Podstolski, 2016).

The electricity consumption of fans (cow comfort) and lighting has been noted as a data gap (Dyer and Desjardins, 2006). In addition, the electricity needed to handle feed and manure is often not reported or is combined with other components. Fans and misting systems (i.e., cow comfort) are major contributors to the overall electricity budget on confined dairies, representing 140 kWh cow⁻¹ y⁻¹, on average (roughly 15% of the total budget). As expected, cow comfort-related electricity demand is less significant for pasture-based systems, where it is estimated at 21 kWh cow⁻¹ y⁻¹ (4%

Table 3. Global milk production and estimated electricity usage (2019 data from FAO, 2020).^[a]

Region	Milk (million t y ⁻¹)	Total Electricity Estimate		
		Regional EUI _m (TWh y ⁻¹)	Confined EUI _m (TWh y ⁻¹)	Pasture EUI _m (TWh/y)
Africa	46.8	4.6	4.3	3.1
Asia	360	18.7	33.1	23.8
Europe	226	12.4	20.8	14.9
North America	108.6	9.2	10.0	7.2
South America	61.8	-	5.7	4.1
Central America	18.2	-	1.7	1.2
Oceania	30.7	2.2	2.8	2.0
Global	852	-	76.7	55.0

^[a] Electricity demand is estimated using the EUI_m data from table 2 for each region (where available) and the overall average EUI_m for Confined and Pasture systems (9.2 and 6.6 kWh 100 kg⁻¹, respectively).

of the total budget). Lighting is important on confined dairies, where it accounts for 23% of electricity use (218 kWh cow⁻¹ y⁻¹), compared to 4% on pasture-based dairies (21.0 kWh cow⁻¹ y⁻¹), when it was reported at all (roughly half of the time). Feed handling (3.6%, 34 kWh cow⁻¹ y⁻¹) and manure handling (4.8%, 45 kWh cow⁻¹ y⁻¹) made contributions to the confined dairy electricity budget, but were mostly absent for pasture-based dairies. Taken together, the lower electricity use for lighting and cow comfort were the main drivers of lower EU_I in pasture-based dairies (fig. 1). Open dry-lot corral systems are expected to have lighting requirements more akin to those of pasture-based dairies. For example, Capareda et al. (2010) calculated that lighting accounted for 3% of the electricity demand on an open dry-lot corral system.

The average EU_I in irrigated systems was >50% higher than non-irrigated systems, and the EU_m was almost twice as high (table 2). Studies that include irrigation in their electricity budgets noted that irrigation can account for up to 50% of the total electricity usage (Belflower et al., 2012; Podstolski, 2016). The electricity used by irrigation is estimated to range from 200 to 275 kWh ML⁻¹ of water, depending on the type of irrigation used (Christie et al., 2012). Most studies that reported irrigation as an important electricity factor were pasture-based dairies. Including irrigation significantly increased the overall electricity usage and EU_m of pasture-based dairies, which in one example rose from 5.3 to 10.6 kWh 100 kg⁻¹ (Belflower et al., 2012). An irrigated low-input, low-production pasture system in New Zealand had the highest EU_m (23.4 kWh 100 kg⁻¹) and a moderately high EU_I (1,169 kWh cow⁻¹ y⁻¹) (Podstolski, 2016). The high electricity usage of this type of farm management makes it more vulnerable to fluctuations in weather and the price of electricity. For example, Wells (2001) found that the New Zealand drought conditions in 1998-1999 resulted in increased irrigation, which in turn increased electricity use by 15% to 20% compared to 1996-1997. Of course, irrigation is not associated only with pasture-based production systems; all dairy feed crops can be irrigated, depending on the production region. However, given the higher overall electricity budget of confined dairies, irrigation, when it occurs, tends to be a lower fraction of the budget. For example, Belflower et al. (2012) noted that irrigation on a confined dairy accounted for 63,000 kWh y⁻¹, or 8.4% of total electricity use.

Combined, the milking and milk-cooling systems are responsible for an average of 370 kWh cow⁻¹ y⁻¹ on confined dairies and an average of 286 kWh cow⁻¹ y⁻¹ on pasture-based dairies. In parlor-based milking systems, milking times are usually marked by surges in electricity demand of 6 to 8 times the base load (Mehta, 2002; Upton et al., 2013). On farms equipped with milking robots, the overall electricity usage consisted of the energy needs for the milking system and air compressors that use electricity consistently throughout the day (Calcante et al., 2016; Shortall et al., 2018). Calcante et al. (2016) reported that the average daily electricity use of five different automated milking systems was 64 kWh d⁻¹ (roughly 34 for the milking unit plus 30 for the air compressor), which equated to 2.1 kWh 100 L⁻¹. Shortall et al. (2018) reported an average of 111 kWh cow⁻¹ y⁻¹ for the milking system and 87 kWh cow⁻¹ y⁻¹ for the air

compressor, which accounted for 59% of the total electricity usage on the pasture-based farms. The number of milkings per day will affect the total electricity demand and EU_I of a dairy operation, although the EU_m will change less due to increased milk production per cow resulting from an extra milking (11 to 19% increase; Allen et al., 1986). Shortall et al. (2018) also showed this to be the case on farms with milking robots, where the number of milking times and electricity usage were positively correlated.

On average, free-stall operations were more energy-efficient than tie-stall operations. In the three reports that compared the two systems, the EU_m and EU_I were 7.0 kWh 100 kg⁻¹ and 842 kWh cow⁻¹ y⁻¹ for free-stalls compared to 11.2 kWh 100 kg⁻¹ and 1,160 kWh cow⁻¹ y⁻¹ on tie-stalls. These differences may reflect the natural ventilation in free-stall barns as well as the economies of scale and the newer, more efficient technologies of the free-stall facilities, which were larger (180 milking cows) and had newer barn designs than the tie-stall facilities (61 milking cows). Feed handling electricity use was lower in free-stall operations (18 kWh cow⁻¹) than in tie-stall operations (51 kWh cow⁻¹). This is likely because free-stall operations use more diesel-powered feed delivery due to the use of bunker silos (more economical for larger dairies; OMAFRA, 2011), whereas tie-stall operations often use electric feed delivery from vertical silos. The same may be true for waste handling equipment, which is typically diesel-powered in free-stall operations compared to electric in tie-stall operations, resulting in electricity demands of 37 and 58 kWh cow⁻¹, respectively.

Technology and Equipment

Technology can have an impact, both positive and negative, on the electricity requirement of dairy farms. This section examines the literature on the electricity usage of various types of equipment and related conservation technologies. The dairy industry in many countries is transitioning from predominantly pasture-based systems to predominantly confined systems (Meul et al., 2012). It has been stated that electricity use on dairy operations had increased in step with the proportion of cows confined and with increases mechanization over many decades (Kraatz, 2012).

Potential energy-efficient technologies identified include variable speed drives (VSD), efficient lighting (Ebinger, 2015), efficient ventilation, pre-cooling heat exchangers, scroll compressors (Pressman, 2010), and refrigeration heat recovery (RHR) systems (Brinker et al., 2013; Alberta Government, 2014). As the name suggests, VSD systems adjust motor speed to match demand and optimize performance (e.g., pumps, compressors, fans). RHR systems function by connecting refrigeration heat exchangers to a water tank and using the discharge heat to partially temper the water before it is heated to the required temperature (FarmEnergy Nova Scotia, 2017). Scroll compressors use two spirals (or scrolls), one fixed and the other not, to create positive pressure more efficiently than a piston (Grace et al., 2002). These and a number of other technologies for reducing electricity consumption (see summary in table 4) can provide energy savings of 20% to 60% for the given component.

Table 4. Dairy electricity conservation strategies and potential savings.^[a]

Reference	Location	MH	Farm Type	Strategy	Energy Saving For Component
Energy Efficiency on Dairy Farms (Alberta Government, 2014) ^[b]	Alberta, Canada	-	Not Specified	Energy saving on the life of the vacuum pump by using a VSD	60%
				Replacement an oversized pump with a VSD	80%
				Refrigeration heat recovery	20%-50%
				Replacement of traditional water heater with tank less (on demand) heater	60%
Dairy Farm Retro-commissioning: Retrofit Study of HVLS and Tunnel Ventilated Barns. (Brinker et al., 2013) ^[c]	Wisconsin, U.S.	192	Confined – FS	Installation of VSD and staged controls with tunnel ventilation systems (cold climate)	34%
				Installation of VSD and staged controls with tunnel ventilation systems (warmer climate)	5%
Energy Efficient Technology Selection for Dairy Farms: Milking Cooling and Electric Water Heating (Corscadden et al., 2014) ^[d]	Nova Scotia, Canada	17 – 380	Confined – FS/TS	Water heating for smaller farms A combination of water heating and pre-cooling heat exchangers for larger farms.	-
Energy savings achieved from heat recovery systems (Kammel and Patoch, 1993) ^[d]	Wisconsin, U.S.	32 – 120	Various	Heat recovery system recaptured on heating water	48%
				Heat recovery system recaptured on cooling milk	7%
Energy use and management in dairy farms (Murgia et al., 2008) ^[c]	Sassari, Italy	40 – 300	Confined	Installing a VSD	50%
Rapid milk cooling control with varying water and energy consumption (Murphy et al., 2013) ^[d]	Cork, Ireland		Pasture	Optimizing water rates	34%
Analysis of Milking Center Energy Use (Peebles et al., 1994) ^[d]	Wisconsin, U.S.	60 – 400	Confined	Heat recovery system	42%-48%
				Pre-cool heat exchanger	38%-46%
Electric energy consumption of milking process on some Finnish dairy farms (Rajaniemi et al., 2017) ^[d]	Helsinki, Finland	72 – 91	Confined – FS	Placing the condenser of the refrigeration system outside	30%
				Installing milk pre-coolers and a heat recovery system from the milk cooling process	25%
Electricity & direct water consumption on Irish pasture based dairy farms: A statistical analysis (Shine et al., 2018b) ^[d]	Muster, Ireland	116	Pasture	Pre-cooling milk with ground water	21%
Strategies to reduce energy use in dairy milking facilities (Upton et al., 2014b) ^[c]	Munster, Ireland	45 – 195	Pasture	Ice bank milk cooling systems, kWh	21%-26%
				Savings cost savings (peak-load shifting)	38%-46%
				Solar thermal water heating, kWh savings	8%-18%

[a] MH = herd size (milking cows), FS = free-stall, TS = tie-stall, VSD = variable speed drive, LED = light emitting diode.

[b] Technical report/factsheet.

[c] Conference paper/presentation.

[d] Peer reviewed publication.

The effect of combining multiple technologies using theoretical scenarios is shown in table 5, illustrating how multiple conservation technologies reduce annual electricity consumption. For example, on a 250-cow confined North American dairy farm, adding conservation technology to the milking, milk cooling, water heating, and lighting systems can result in savings of between 11,200 kWh y⁻¹ and 19,200 kWh y⁻¹ for each system, for a total combined savings of roughly 76,500 kWh y⁻¹, a 30% reduction. At the

same time, the EUI_c can potentially decrease to 715 kWh cow⁻¹ y⁻¹. Similar proportional savings are realized, overall, in pasture-based systems, despite lower initial electricity use (table 5). Interdependence between different types of conservation technologies may have an effect on the theoretical savings presented, but for the sake of simplicity, this potential interaction has not been considered in the analysis.

Table 5. Theoretical electricity use scenarios for a 250 milking cow dairy farm with contrasting management systems.^[a]

Farm Characteristics		Before		Theoretical Savings					After		Total Savings	
System	Milking Cows	kWh cow ⁻¹ y ⁻¹	kWh y ⁻¹	MS	MC	H	L	CC	kWh y ⁻¹	kWh cow ⁻¹ y ⁻¹	kWh cow ⁻¹ y ⁻¹	%
Confined	250	1021	255,250	11,494	17,272	19,159	17,336	11,212	178,777	715	306	30%
Pasture-based	250	405	101,250	5,323	13,249	13,249	709	0	68,691	275	130	32%

[a] The EUI for confined systems and their components are based on North America and for pasture are from European studies (tables 1 and 2). The potential savings was calculated for: milking system (MS; VSD pumps), water/space heating (H, tankless water heater), milk cooling (MC; heat exchanger), lighting (L; LED), and cow comfort (CC; VSD ventilation). The theoretical savings per component applied are 20%, 60%, 40%, 30%, and 30% for MS, H, MC, L, and CC, respectively.

Milking and Milk-Cooling Systems

Milking and milk cooling systems are major components of electricity consumption on dairy farms, accounting, on average, for approximately 40% to 50% of a dairy's electricity budget (fig. 1). A pre-cooling heat exchanger can reduce milk temperature before it enters the bulk tank by up to 26°C (to within 4°C of the water temperature; Rajaniemi et al., 2017), which in turn reduces the electricity required for refrigeration by roughly 25% to 60% (Sanford, 2003b; table 4). In the best case scenario, on a confined dairy operation, this could translate into a savings of up to 91 kWh cow⁻¹ y⁻¹, or roughly 10% of the budget. Placing the refrigeration condenser outdoors is an option in cold climates, and doing so can reduce cooling-related electricity consumption by up to 30%, which, by our estimates is equivalent to roughly 45 kWh cow⁻¹ y⁻¹ (Rajaniemi et al., 2017; table 4). In addition, replacing a reciprocating compressor with a scroll compressor as the driver of the pre-cooling heat exchangers can reduce milk cooling electricity demand by 20% (Ludington et al., 2004). Ebinger (2015) illustrated a case where doing so led to a savings of roughly 26.5 kWh cow⁻¹ y⁻¹. Applying the 20% savings suggested by Ludington et al. (2004) to the EU_{lc} of confined dairies (769 kWh cow⁻¹ y⁻¹ total; 125 kWh cow⁻¹ y⁻¹ for milk cooling) gives a savings of close to 25 kWh cow⁻¹ y⁻¹. In addition to this technology, it has been reported that if the milking system vacuum pump is fitted with a VSD, electricity use reductions of 60% to 80% are observed for that component (Alberta Government, 2014; Dice, 2017; table 4). Ebinger (2015) found this to be equivalent to roughly 60 kWh cow⁻¹ y⁻¹. Assuming a reduction of 70% and using the partitioning of EU_{lc} for confined dairies, one can expect savings of as much as ca. 100 kWh cow⁻¹ y⁻¹. Another application of VSD is to optimize milk flow rate through the pre-cooling heat exchanger to improve heat transfer, which can increase efficiency by another 30% (Murphy et al., 2013; Alberta Government, 2014; table 4).

Water and Space Heating

Hot water is used for cleaning equipment (i.e., pipeline) after each milking, as well as for cleaning the bulk tank. On average, water heating and, to a lesser extent, space heating account for roughly 16% of a dairy's total electricity budget (ranging from 2% to 32%). Here again, energy can be conserved by using recovered heat (from RHR units) to preheat water. It is estimated that 20% to 50% of the waste heat energy from the milk refrigeration system can be captured (Alberta Government, 2014; table 4). Ebinger (2015) found that RHR was capable of conserving roughly 8,000 kWh y⁻¹ on dairies averaging 75 cows. Beard (2012) estimated that insulating water heater tanks can reduce the electricity demand of that component by 4% to 9%. Alternatively, tankless (i.e., on-demand) water heaters can be used, which require less electricity than conventional heaters (Alberta Government, 2014). House et al. (2014) noted that cleaning protocols used on milking equipment can vary greatly from farm to farm. Variation in the amount of hot water used as a result of different wash protocols would affect total electricity demand. The cleaning of pipelines and bulk tanks has traditionally been done with hot water, but low temperature detergents have recently been approved for use in the dairy industry

(DFC, 2017) and are commercially available. For example, a chlorinated alkaline detergent is available from De Laval (Kansas City, Mo.) and according to the manufacturer it uses dispersants and hydrotopes to clean at a reduced temperature. Although not widely adopted, such detergents and cleaning practices can reduce the need for hot water and have been shown to be effective in a case-study (Gentilini and Lopez-Benavides, 2014).

Lighting

Electricity use for lighting in confined dairies accounts for between 13% and 42% of total electricity use, for an average of 23%. The observed variability is likely due to the type of lighting used and to factors such as barn design, natural light, and stocking density. Clarke and House (2006) estimated that a roughly 75% reduction in electricity use can be achieved by switching from incandescent to T8 fluorescent lighting. Numerous studies have demonstrated the advantages of LED lighting over other lighting sources. LED lighting can deliver higher output while reducing electricity consumption by up to 90% compared to incandescent bulbs (Clarke and House, 2006; Ebinger, 2015; EnSave, 2015). This would correspond to a decrease of up to 197 kWh cow⁻¹ y⁻¹ for EU_{lc} in confined dairies. By applying this theoretical savings to one of the least lighting-efficient studies presented in table 1 (244 cows, 198,000 kWh y⁻¹), a reduction of roughly 46,000 kWh y⁻¹ could be achieved (23% of the annual usage). Lighting-related savings are likely to be most impactful in confined dairies, especially those that employ "long-day lighting" management strategies to reduce seasonal fluctuations in milk production (Ludington et al., 2004). Due to a natural physiological response, increasing light exposure from 12 to 16 or 18 h d⁻¹ increases milk production by 2.5 kg cow⁻¹ d⁻¹ on average (Dahl et al. 2000). Gould and Go (2015) found that increasing the photoperiod with LED lighting improved milk yield by 8% and expected to reduce electricity cost by half compared to metal halide lighting. Besides the lighting type, the design of lighting and windows can not only lower electricity usage, but also increase milk production (Clarke and House, 2006). Natural lighting, which is more prevalent in more modern barn design (i.e., curtain walls) and farm management strategies (i.e., free-stall), can help reduce lighting requirements of dairy buildings.

Cow Comfort

Heat stress negatively affects dairy cows, which in turn can reduce milk production (Bernabucci et al., 2014). To maintain good air quality and to keep cows cool during warm weather, barns are ventilated using either passive (e.g., natural air movement through curtain walls) or mechanical strategies (e.g., tunnel or cross-flow ventilation). Both designs use fans and may have additional water-based cooling using misters or sprinklers. These cow comfort components account for 15% of the total electricity use on confined dairies (table 1). Passive ventilation uses little electricity (e.g., to control curtains) so it is best from an electricity conservation point of view. However, natural ventilation is not ideal in every location or climate, and supplemental fans in the barn are usually still required.

Where air circulation is needed, high-volume, low-speed (HVLS) fans are more energy-efficient than smaller low-volume high-speed (LVHS) fans, achieving the same circulation rate using roughly 85% less electricity. Applying this to the EUI_c of confined dairies, this could translate to a reduction of over 100 kWh cow⁻¹ y⁻¹ if HVLS were not already implemented in the barn. HVLS fans are best suited to free-stall barns with high ceilings and open sides (Sanford, 2003a). LVHS fans blowing air over the cows may be more effective at cooling the cows. Increasing the size of LVHS fans can improve energy efficiency. By switching from 24 in. fans to fans measuring 50 in. or larger, a 43% increase in efficiency per fan can be achieved (from 0.008 m³ s⁻¹ W⁻¹ to 0.011 m³ s⁻¹ W⁻¹; Sanford, 2003a). Fans can be equipped with VSDs, which use environmental parameters to optimize the ventilation rate in real-time (Sanford, 2003a). Smart controls can be used to optimize ventilation by adjusting the fan speed (variable or multi-stage) or on-off cycles according to barn temperature. For example, in cold climates, efficient ventilation with automated control systems can reduce the electricity demand of fans by as much as 34% compared to manually controlled fans (table 4; Brinker et al., 2013). Although the potential savings are unquantified, in barns equipped with LVHS fans, cows can be cooled more efficiently by adding water sprinkling to fans (Sanford, 2003a). Therefore, electricity savings could be achieved through water-based cow cooling, depending on the electricity demand of the water delivery system, especially in barns where HVLS ventilation is not possible.

Milking Robots (Automated Milking Systems)

Milking robots are an alternative to in-stall milking or milking parlors. The electricity implications of milking robots can be observed by looking at two pasture-based studies with similar sized farms: one focused on farms with milking robots (114 cow average, Shortall et al., 2017) and one focused on farms with parlors (118 cow average, Upton et al., 2013). On average, the overall electricity usage for the farms with milking parlors was nearly half that of farms with milking robots (24,000 and 38,000 kWh y⁻¹, respectively) which is consistent with the annual electricity use for milking parlors (4,800 kWh y⁻¹) being considerably less than milking robots (roughly 12,500 kWh y⁻¹). Similarly, the review by Örs and Oğuz (2018) indicated 39% higher electricity consumption with robotic milking systems compared to conventional milking parlors. This is likely due to the fact that milking robots are always “on” (i.e., standby), even when not in operation, and therefore are always consuming electricity.

Electricity Monitoring

Electricity monitoring systems have been developed to inform users of energy use patterns. Although studies have not been conducted within a dairy context specifically, research on households have shown the potential of feedback in supporting changes in electricity use through behavior change (Stinson, 2015). Some electricity providers provide high-resolution consumption data which enable dairy farms to monitor or react in real time to changes in total electricity consumption. Electricity metering and submetering can be used to track patterns of overall electricity use and use at the component and equipment level. This approach is often used

in industrial settings, but is less common in agriculture (Hinck, 2018). Monitoring can be used with a maintenance program to detect equipment problems before they lead to electricity waste. A pilot study of real-time electricity consumption tracking on farms in Minnesota has begun to use this approach to analyze and improve the energy efficiency of dairy barns (Hinck, 2018). In The United States and Canada, smart meters have been recently introduced on farms in some regions.

Generating Electricity

One option for on-farm electricity generation is anaerobic digestion. This process uses manure and other organic wastes to produce biogas (a mixture of methane and other gases), which in turn can be used to generate electricity as well as a significant amount of process heat (from the generator). Biogas typically has an energy content of 22 to 27 MJ m⁻³ (6.1 to 7.5 kWh m⁻³) (Biogas Association, 2013). On average, a biodigester has the capacity to produce at least 3 kWh cow⁻¹ d⁻¹ (roughly 1095 kWh cow⁻¹ y⁻¹), or 2 to 3 times more if high energy co-feedstocks are co-digested with the manure (El-Mashad and Zhang, 2006; Yiridoe et al., 2009; OMAFRA, 2016; Purdy et al., 2018). Since the average EUI_c for confined dairy farms is 769 kWh cow⁻¹ y⁻¹, a biodigester with manure as the only feedstock can cover the on-farm electricity requirements of most herds. Nelson and Lamb (2002) provide a case where the biodigester on a 750-milking-cow dairy is able to produce all its electricity needs as well as generate a surplus able to power roughly 75 homes. In addition, excess heat from the biodigester could be used to heat water and spaces. Economic analyses show that larger farms are best suited to biodigesters (e.g., >2,600 cows; Lauer et al. 2018); however, small scale operations are viable with sufficient incentives for renewables (e.g., case study of a 75 cow operation; IEA 2020).

Another option for generating electricity is photovoltaic solar panels. Net metering enables the dairy farm to use the grid as a no-cost storage system for times when the PV array produces more electricity than is needed on the farm. Louwen and van Sark (2020) show that there have been rapid price decreases for PV modules in the past (e.g., dropping over 90% from 2008 to 2018) and costs are forecast to continue decreasing in the coming decades. With these trends it is likely that PV electricity will be cost-competitive in many locations, even where irradiance is relatively low. Since dairy farms often have large barns, roof-mounted panels are a good fit and are less expensive to install than panels mounted on a ground-based racking system. Potential PV output can be estimated using the National Renewable Energy Laboratory calculator, PVWatts® (<https://pvwatts.nrel.gov/pvwatts.php>). Consider a 250-milking-cow herd housed in a 2,750 m² barn with 50% of the roof being south-facing, located in eastern Ontario (44.25° N, 75.82° W). This region has an average annual insolation of 4.37 kWh m⁻² d⁻¹. A 200 kW DC system on south-facing panels (20° tilt) would have the potential to produce roughly 240,000 kWh y⁻¹ of electricity (960 kWh cow⁻¹ y⁻¹). Based on the North American EUI_c of confined dairies, this system would generate almost all the electricity that the farm is expected to consume.

Table 6. Summary of models and decision support systems.^[a]

Source	Format	Scope	Notable Output(s) / Result(s)
agSTAR handbook (US EPA, 2004)	PDF document with preliminary screening questionnaire to determine feasibility of on-farm biogas generation	BG	N/A
Validation of a biogas production model and determination of thermal energy from plug-flow anaerobic digesters. (Gebremedhin and Inglis, 2007)	Theoretical biogas production model from peer reviewed paper	BG	Biogas production ($\text{m}^3 \text{d}^{-1}$)
PVWatts®, National Renewable Energy Laboratory	Photovoltaic electricity production calculator https://pvwatts.nrel.gov/pvwatts.php	PV	kWh mo^{-1}
Dairy farm energy efficiency tool. (EECA, 2020)	Direct input into website text fields (New Zealand only)	WF	Potential savings from efficient technology ($\text{t CO}_2\text{e emissions}$)
Regression modelling of on-farm direct water and electricity consumption on pasture based dairy farms (Shine et al. 2018a)	Electricity consumption linear regression model from peer reviewed paper	WF	Electricity demand (kWh mo^{-1})
Dairy Energy Prediction (DEP) model: A tool for predicting energy use and related emissions and costs in dairy farms. (Todde et al., 2017)	Downloadable combined cost, energy, and emission model (Microsoft Excel format) from peer reviewed paper. http://bit.ly/DEPTOOL	WF	Electricity demand (kWh) EUI _c ($\text{kWh cow}^{-1} \text{y}^{-1}$) EUI _m (kWh 100 kg^{-1})
A mechanistic model for electricity consumption on dairy farms: Definition, validation, and demonstration. (Upton et al., 2014a)	Peer reviewed paper with component-specific models for predicting energy demand on dairy farms	MC, H, L, MS, MP, MH	Electricity demand (kWh)
Modelling and benchmark development for electrical energy use and energy efficiency on NOVA SCOTIA dairy farms. (Pradhanang, 2015)	M.Sc. thesis with section on modeling energy use on a component-specific basis	MC H, MS, L, MH, FH, CC	Heat removed (MJ d^{-1}) Electricity demand (kWh y^{-1})
USDA energy estimator version: 2.2.0.623 (USDA, 2019)	Direct input into website text fields to predict annual electricity demand of dairy farm components. Note: requires USA zip code.	MS, MC, H, L, CC	Electricity demand (kWh y^{-1})

^[a] BG = Biogas, PV=Photovoltaic, WF = Whole Farm, MS = Milking System (parlor system, vacuum pumps), MC = Milk Cooling, H = Heating (space / water), L = Lighting, CC = Cow Comfort (ventilation / misting), FH = Feed Handling, WH = Waste/Manure Handling, MP = Motors and Pumps (excl. milk production).

MODELS AND DECISION SUPPORT SYSTEMS

Various modeling tools are available to farm managers, policy makers, and researchers to estimate the electricity usage of a farm and inform decision making (see summary in table 6). The complexity ranges from simple tables of the expected electricity usage of typical farm equipment to comprehensive modeling studies. Similarly, the input data vary from a few general farm characteristics to detailed farm information. For example, the USDA (2019) energy estimator has input questions regarding energy saving technologies discussed in the previous section and provides users with annual monetary savings realized by converting to more efficient technologies. Some of these tools are designed for specific regions (EECA, 2020; USDA, 2019) or farm management types (Shine et al., 2018a).

CONCLUSION

The quantity of electricity required on dairy farms varies widely by farm management system, barn design, available technology, region, herd size, and irrigation (tables 1 and 2). Energy utilization indices (EUI_c, EUI_m) can be used to characterize the importance of the dairy sector to local, regional and national energy policies. Considerable progress has been made to demonstrate conservation measures that can reduce electricity consumption and costs on dairy farms. The most impactful technologies include the installation of VSD for milk vacuum pumps and milk transfer systems as well as the

installation of pre-cooling heat exchangers, RHR systems, energy-efficient light fixtures, and efficient ventilation systems. Electrical metering and submetering can be used to track usage patterns at the component and equipment level and to analyze and improve the energy efficiency of dairy farms. Monitoring could be used with a maintenance program to detect and prevent equipment problems. More work needs to be done to assess new and emerging technology from an energy efficiency point of view. With a better understanding of the impact of these technologies, better electricity use models can be created. By combining conservation technologies with renewable generation technologies (e.g., anaerobic digestion, solar), net zero electricity is within reach for many dairy operations. With the right combination of education, policy, and industry support, the dairy sector is well positioned to reduce its electricity demand and even be a net producer of renewable electricity.

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