Heliyon 9 (2023) e21428

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Factors affecting energy efficiency in herringbone and rotary milking parlours

F. Buckley [a,b], M.D. Murphy [a], R. Prendergast [a,b], L. Shalloo [b], J. Upton [b,*]

[a] Department of Process, Energy and Transport Engineering, Munster Technological University, Cork, Ireland
[b] Animal and Grassland Research and Innovation Centre, Teagasc Moorepark, Fermoy, Cork, Ireland

ARTICLE INFO

Keywords:
Energy efficiency
Milking efficiency
Herringbone milking parlour
Rotary milking parlour
Correlation analysis
Energy analysis

ABSTRACT

The United Nations Sustainable Development Goals aim to double the productivity of small-medium food producers (2015–2030), while food demand is estimated to increase by 60 % by 2050. The objectives of this paper were to identify and quantify the relationship between energy efficiency and milking efficiency, identify the main energy consuming processes associated with milking, and investigate whether milking efficiency, energy efficiency or the relationship between them varies depending on parlour type. Energy and milking efficiency data from 26 pasture-based dairy farms in the Republic of Ireland were analysed (17 herringbone, nine rotary). Energy consumption was monitored continuously on the herringbone farms and for two distinct, seven-day periods (observation periods 1 and 2) for the rotary farms. Milking performance was monitored for all 26 farms during these periods. During the observation periods, the rotary farms achieved superior energy efficiency (29.85 Wh kg_{Milk}^{-1}) and milking efficiency (152 cows/hour) than the herringbone farms (32.83 Wh kg_{Milk}^{-1}, 97 cows/hour). Moderate correlations existed between milking efficiency (cows/hour) and energy efficiency (Wh kg_{Milk}^{-1}) for rotary ($r = -0.58$, $R^2 = 0.34$) and herringbone ($r = -0.44$, $R^2 = 0.19$). These results indicated that higher levels of milking efficiency were moderately correlated with improved energy efficiency.

1. Introduction

1.1. Background

The EU 2030 Climate target plan aims to reduce greenhouse gas emissions, recorded in 1990, by 55 % by the year 2030 [1]. Meanwhile, the UN is aiming to increase food production to meet growing food demand [2,3]. As the agricultural industry is Ireland's largest contributor to greenhouse gas emissions, accounting for 37.1 % of emissions in 2020, it is a key area of focus for reductions. Irish policy aims to reduce emissions in the agricultural sector by 25 % by the year 2030 [4]. It is also recognized that the agricultural sector will have a part to play regarding the decarbonisation of the energy generation sector with targets to reduce agricultural energy use by 20 % and generate at least 20 % of energy consumed from renewable sources [5] by 2030. To encourage the uptake of renewable energy generation by farmers, the Irish government has introduced a clean export tariff which will guarantee payment to small generators of renewable energy for electricity exported to the national grid for 15 years [6]. Eligible installations must have a rated power output of 6–17 kWp for single phase systems or 11 to 50 kWp for three phase systems.

* Corresponding author. Animal and Grassland Research and Innovation Centre, Teagasc Moorepark, Fermoy, Cork, Ireland.
E-mail address: John.Upton@teagasc.ie (J. Upton).

https://doi.org/10.1016/j.heliyon.2023.e21428
Received 16 August 2023; Received in revised form 3 October 2023; Accepted 20 October 2023
Available online 29 October 2023

Nomenclature

KPI	key performance indicator
PV	photovoltaic
Q	energy
m	mass
C	specific heat capacity
t	temperature
η	efficiency
FPCM	fat and protein corrected milk
L	litre
kg_{Milk}	kilograms of milk
T_{Milk}	tonne of milk
DX	direct expansion
IB	ice-bank
VSD	variable speed drive
SD	standard deviation
n	number of instances
r	correlation coefficient

Against the backdrop of an increase in national herd sizes from an average of 58 dairy cows in 2010 to 90 dairy cows in 2020 [7], a number of significant issues have become more prevalent. The milking process accounts for a large proportion of working times on dairy farms representing 31 % of the work week [8]. It is estimated that by 2025, an additional 2,315 full-time equivalent employees will be required to sustain the expansion of the Irish dairy industry, while the rate of graduation from relevant educational programs is inadequate to meet these requirements [9]. The uncertainty generated by these issues has highlighted the need for an in-depth understanding of energy and milking efficiency on dairy farms and the relationship between these two factors.

1.2. Energy efficiency

Two categories of energy consumption can be identified in milk production, direct consumption and indirect consumption [10–12]. Energy consumed on farms, such as electricity, gas and oil are considered direct consumption while indirect consumption is energy which is not consumed directly on that farm, essentially it is energy embedded in purchased products. This study focused on direct energy consumption excluding the use of diesel fuel in vehicles. The watt-hours (Wh) consumed per kg of milk or per dairy cow will be used as the main key performance indicators (KPIs) to allow energy efficiency to be compared across farms of varying size and levels of production.

A recent review of the current literature undertaken by Shine et al. (2020) [11] found that direct energy consumption on dairy farms was responsible for 32 % of the total energy with 48 % of the direct energy being electrical energy. Shine et al. (2020) reviewed seven studies which monitored electrical energy consumption on dairy farms with conventional milking parlours across five countries. The mean electrical energy consumption per unit weight of milk produced was 48.91 Wh kg_{Milk}^{-1}. The three largest consumers of electrical energy were found to be milk cooling (15.32 Wh kg_{Milk}^{-1}), the milking machine (13.97 Wh kg_{Milk}^{-1}) and water heating (9.80 Wh kg_{Milk}^{-1}).

Many methods and technologies for reducing electricity consumption associated with the milking process currently exist. Milk pre-cooling using well water is the most common method of reducing milk cooling energy demand. Milk pre-cooling has been found to be effective, substantially reducing milk temperatures before entering the cooling system [13,14]. The use of variable speed drives in the milking machine, improved insulation of the hot water tank and switching to energy efficient lighting can also improve energy efficiency [11]. It is also possible to reduce energy costs related to milking through demand side management techniques. One such technique is changing the start time of morning milking to take advantage of cheaper night rate electricity reducing energy costs by 33 %–39 % [15]. The use of renewable energy systems, such as photovoltaic (PV) solar panels, can reduce energy costs on farms and the use of pre-existing hot water tanks as thermal energy storage for excess PV generation can remove the need for installing expensive battery systems [16].

1.3. Milking efficiency

The cost and availability of skilled labour has been identified as a weakness in the Irish dairy industry [17] while the mean age of Irish dairy farmers continues to increase, reaching 52 years old in 2020 [18]. Several different metrics have been used to describe milking efficiency. Tarrant et al. (2020) considered milking efficiency to be the number of cows milked, per milking cluster in the parlour per hour (cows/cluster/hour) [19]. Jago et al. (2010) used the metric of number of cows milked per hour (cows/hour) to measure milking efficiency [20]. Two studies published by Edwards et al. (2020 & 2013) used the number of cows milked per operator involved in the process per hour (cows/operator/hour) as milking efficiency metrics [21,22]. For the purposes of this paper cows/hour will be used as the metric for measuring milking efficiency. As a substantial amount of a dairy farms labour is consumed by the milking process (43 %–58 %) [21], it is important to consider how energy efficient technologies or practices could interact with milking efficiency. As a proportional relationship between parlour size and milking efficiency exists, higher levels of milking efficiency can be achieved in larger parlours [22]. However, it is not clear what impact increasing parlour sizes, facilitating higher levels of milking efficiency, has on the energy efficiency of the milking process.

To our knowledge, there is no peer reviewed literature which investigates the relationship between energy and milking efficiency on dairy farms. With the cost of energy and labour identified as challenges in the Irish dairy industry [17], the relationship between these two factors needs to be identified and understood. This understanding will allow farmers and farm managers to make informed purchasing and managerial decisions, improving their resilience to volatile milk prices, high energy costs and lack of skilled labour while reducing their carbon footprint through the integration of renewable energy systems. Therefore, the objectives of this paper are to:

1) Identify and quantify the relationship between energy efficiency and milking efficiency.
2) Identify the main energy consuming processes associated with milking.
3) Investigate whether milking efficiency, energy efficiency or the relationship between them varies depending on parlour type (herringbone/rotary).

2. Materials and methods

Total energy consumption (kWh) was defined as all energy consumed on the farm, excluding the use of diesel fuel in vehicles. Energy efficiency was defined as total energy consumption divided by the quantity of milk produced (Wh kg^{-1}_{Milk}) or per lactating cow (kWh/cow). Milking efficiency was described as the number of cows milked per hour (cows/hour).

Energy consumption and the milking process were monitored on 26 commercial dairy farms throughout the Republic of Ireland. All herds in this study were grass based and operating a spring calving production system. This group included 17 herringbone milking parlours, of which 16 were swing-over parlours and one was a double-up parlour, the remaining nine were rotary milking parlours. Energy consumption and the milking process were monitored on all 26 parlours for two distinct week-long periods of the milking season. These periods consisted of seven days of monitoring, per farm between late August 2020 and early October 2020 (observation period 1) and early April 2021 to early May 2021 (observation period 2). Observation period 1 coincided with the late lactation period of the herds while observation period 2 coincided with the peak lactation of the herds. In addition to this, total farm energy and water consumption was monitored on all 17 herringbone parlours, continuously, commencing in January 2020. Energy consumption was monitored on these 17 farms between August 2020 and July 2021. One of the 17 herringbone parlours underwent renovations during this study causing the loss of two months of energy data. For this reason, the data from this parlour was not included in this study.

2.1. Data acquisition

Data were collected via autonomous cumulative electricity readings, an on-site survey of parlour equipment and characteristics, milking process observation via video recording and milk production and herd data from the Irish Cattle Breeding Federation (ICBF) [23].

2.1.1. On-site survey

On-site surveys were conducted by Teagasc researchers in the final quarter of 2020. Specifications of all major electricity consuming systems were recorded including milk cooling, water heating, milking machine and milk pumps. Details of the milking parlour, holding areas and drafting systems, if applicable, were also recorded. Table A1 in Appendix A presents a breakdown of selected electricity consuming systems and details of the milking parlours.

2.1.2. Electricity and water consumption

Two methods were used to record electricity consumption in the parlours for this analysis.

For all herringbone parlours, autonomous electricity and water metering equipment was installed in January 2020 using metering equipment by Carlo Gavazzi Automation SpA, Lainate, Italy. Type EM24 DIN energy analysers (Carlo Gavazzi Automation SpA, Lainate, Italy) were used and received electrical pulses from electricity and/or water meters which were installed throughout the parlours. A daisy chain network (RS485 Modbus) (Carlo Gavazzi Automation SpA, Lainate, Italy) was used to connect each of these meters. An UR5i Libratum v2 modem (Carlo Gavazzi Automation SpA, Lainate, Italy) was connected to this network where cumulative consumption measurements were sent through a 3 g/GPRS network in 15 min intervals to a receiver on site at the Teagasc research centre in Cork, Ireland. Powersoft data logging and recording software (Carlo Gavazzi Automation SpA, Lainate, Italy) were employed on-site. This software recognized each meter via a virtual VPN. Upon autonomously reaching the Powersoft software, cumulative consumption data for each individual farm was in turn transferred to a database for storage. Only the volume of water heated for washing purposes was used in this study. For the nine rotary parlours, cumulative electricity meters were installed on the parlour side of the electrical consumer unit. For these parlours, electricity meters were installed in each parlour for observation period 1 and observation period 2 only. E-Tracker Synergy meters (SynergyMeters, Cheshire, UK) were used with type F30-1000 dual range flex-eclamp CTs 30 cm–1000Amps/200Amps (SynergyMeters, Cheshire, UK). Energy readings were taken every 15 min and stored on an internal hard drive within the meters. Upon completion of the monitoring period, the meters were collected from each farm and the data downloaded onto a USB memory stick.

Data from both collection methods were downloaded and stored in a secure database in Teagasc.

2.1.3. Milk yield and livestock

Milk production records for 12 months between August 2020 and July 2021 were collected. The litres of milk produced as well as associated fat content (%) and protein content (%) were extracted from the ICBF database. The total number of cows in each herd and the number of lactating cows were also acquired through the same ICBF database.

2.1.4. Milking process analysis

The milking process was recorded using ABUS OneLook Outdoor Cameras model ppdf14520 (ABUS August Bremicker Sohne KG). The cameras were HD 1080p with an IP rating of 66. Four cameras were installed on each farm in positions where the milking process and cow flow through the parlour could be fully observed. Video and audio data recorded by the cameras were transmitted via encrypted digital radio to a digital monitoring display (model: PPDF16000) (ABUS August Bremicker Sohne KG) where the data were stored on internal memory. Once the observation period was completed the camera systems were collected by researchers based in Teagasc Moorepark and the data were downloaded onto a secure database in Teagasc for the researchers to analyse. The milking procedure was observed a total of 689 times across all farms over observation periods 1 and 2. For this analysis, the milking process was considered to begin when the first cow entered the holding yard and ended when the washing of the milking parlour was completed.

2.1.5. Gas and oil consumption

On nine farms where gas or oil was used to heat water, the amount of energy consumed (kWh) was estimated. If the volume of hot water used by the parlour was metered and the farm used gas/oil to heat water, the amount of energy required to heat water by gas and oil was calculated using equation (1).

$$Q_{fuel} = (m_w * C_w * \Delta t) \Big/ \eta_{fuel} \tag{1}$$

where Q is energy (kWh), m_w is the mass of water heated (kg), C_w is the specific heat capacity of water (4180J kg_K^{-1}), Δt is the change in temperature of the water. The set point for the water tank was assumed to be 353 K (80 °C) and the water inlet temperature was based on the temperatures of water from a 100-m borehole well [24], η_{fuel} is the efficiency of the water heating system depending on the fuel used (gas – 90 % [25] or oil – 84 % [26]).

On parlours where the volume of hot water used by the parlour was not metered, and gas/oil was used to heat water, the volume of fuel (gas/oil) used by the parlour to heat water was used to determine the energy used to heat water (kWh).

2.1.6. Milk pre-cooling performance

The temperature of milk entering and exiting the plate cooler was measured to determine the level of milk pre-cooling which took place on each farm. Comark N2014 (Comark, Norfolk, UK) temperature data loggers with type K thermocouples were installed on the milk input and output pipes of the plate cooler. Readings were recorded in 1-min intervals. The temperature data loggers were installed for one week on each farm by a researcher based in Teagasc Moorepark to determine the level of pre-cooling achieved by each plate cooler. At the end of the week, the temperature data loggers were collected, and the data were downloaded onto a secure Teagasc database.

2.2. Data processing

2.2.1. Domestic energy removal

Total energy consumption was defined as all energy consumed on farm for milking purposes. This energy included energy consumed in the processes of milk cooling, operating the milking machine, water heating and miscellaneous. Of the 16 farms which had permanent meters installed, 11 farms included a domestic component in the miscellaneous energy category. To estimate, and remove, the domestic component, the miscellaneous energy use was calculated for two groups of farms, group one (with domestic) and group two (without domestic). The difference in average miscellaneous energy use between group one farms and group two farms was assumed to be the domestic component and was therefore deducted from the total energy use of the farms in group one (see Table A2 and Appendix: B for details).

2.2.2. Outlier detection

Negative energy data were identified and removed. In a few cases, errors occurred in the metering software causing the energy consumption in a single 15-min period to increase by an obviously unrealistic amount. To resolve this issue, any points in the data which were in the top 99th percentile of energy consumption were identified and removed. Once such outliers were removed, a z-score was used to identify and remove any remaining outliers. A limit of 3.5 standard deviations from the mean was implemented. The outlier detection process, in total, resulted in 0.11 % of the data being removed. The removed data were then replaced using linear interpolation.

2.3. Data analysis

2.3.1. Summary statistics

Summary statistics are presented in Table 1 for the farms which participated in this study. These statistics were organised into categories based on availability of data. Data were available for all herringbone parlours between August 2020 and July 2021, so an analysis was carried out on the herringbone farms for those 12 months. Data were available for the rotary farms for observation periods 1 and 2 so the summary statistics analysis undertaken for these farms includes data from those periods only. This sampling period was chosen to capture seasonal variations and is in line with previous studies [26,27]. On farm operation was not impacted by the COVID-19 pandemic. An analysis was also carried out on the 16 herringbone farms for observation periods 1 and 2 to allow for comparison between the two parlour types. To allow easy comparison between our study and other international studies, the fat and protein corrected milk (FPCM) equivalent was calculated in line with Shine et al. (2020) [11] and is included in the summary statistics.

Full season – Energy consumption kg_{Milk}^{-1} produced and per cow were summarised for the period August 2020–July 2021 for 16 sub-metered herringbone parlours. Full list of variables given in Table 1.

Herringbone and rotary comparison – Energy consumption kg_{Milk}^{-1} produced and per cow were summarised for observation periods 1 and 2 for nine rotary parlours and 16 herringbone parlours. Full list of variables given in Table 2.

2.3.2. Energy analysis

The energy efficiency (Wh kg_{Milk}^{-1}) of the milking machine, the milk cooling and water heating process were calculated for the 16 herringbone parlours. To determine energy costs associated with the milking process, a day/night pricing scheme was used with a day rate tariff of €0.19/kWh and a night rate tariff of €0.09/kWh [28].

Similarly, milking efficiency, in terms of cows milked $hour^{-1}$, were determined for the nine rotary parlours and 16 herringbone parlours for observation periods 1 and 2. This analysis compared the energy and milking performance of herringbone and rotary parlours.

Milking and energy efficiency, of all main energy consuming systems, were determined for observation periods 1 and 2 on the 16 herringbone parlours. This analysis investigated how milking and energy efficiency vary during the milking season and which energy consuming sub systems are impacted the most by seasonality.

2.3.3. Correlation and regression analysis

Two separate univariate correlation analysis were conducted using the same methodology as used by Shine et al. [27]. First, the normality of the dataset being investigated was checked using a Shapiro-Wilk test. If both sets of data were found to be normally distributed, Pearson's Product-Moment correlation was used. If at least one dataset was found not to have a normal distribution, Spearman's Rank correlation was used. In line with Parish et al. (1957) [29], correlations of $0 \leq |r| < 0.2$ were referred to as slight (almost negligible relationship), $0.2 \leq |r| < 0.4$ were referred to as low (definite but small relationship), $0.4 \leq |r| < 0.7$ were referred to as moderate (substantial relationship), $0.7 \leq |r| < 0.9$ were referred to as high (marked relationship) and $0.9 \leq |r| < 1$ were referred to as very high (very dependable relationship). The parameters selected for each analysis were designed to investigate how energy efficiency (Wh kg_{Milk}^{-1}) of milking parlours is affected by milking efficiency and farm size.

The first analysis investigated potential relationships between energy efficiency (Wh kg_{Milk}^{-1}), and a selection of variables, for the herringbone parlours. The purpose of this analysis was to investigate the possible existence of economies of scale, investigate if any relationship exists between milking efficiency and energy efficiency and if different energy consuming processes have a relationship with milking efficiency. This analysis was conducted on data gathered between August 2020 and July 2021. Variables analysed in this correlation analysis include; Total energy consumed (kWh), energy consumed for each main energy consumer (kWh), no. milking cows (n), milk yield (kg_{Milk}), total energy efficiency (Wh kg_{Milk}^{-1}), duration of milking (hours), milking efficiency (cows/hour).

The second analysis compared results from two univariate correlation analysis carried out on the 16 herringbone and nine rotary parlours separately. The purpose of this analysis was to investigate whether a relationship exists between milking efficiency (cows/hour) and energy efficiency (Wh kg_{Milk}^{-1}) and how this relationship may differ between parlour types. Only data gathered during observation periods 1 and 2 were included. Variables analysed in both the herringbone and rotary correlation analysis included total energy consumption (kWh), no. milking cows, milk yield (kg_{Milk}), total energy efficiency (Wh kg_{Milk}^{-1}), no. milking units, milking duration (hours), milking efficiency (cows/hour). The analysis for the rotary parlours included rotation time, defined as the amount of

Table 1
Population descriptions for annual electricity consumption, milk production, dairy cows and related KPIs for 16 herringbone farms with continuous metering.

Variable	Unit	min	mean	SD	median	max
Milk yield	L	583,621	1,169,209	442,298	947,186	1,951,093
FPCM	kg	665,657	1,256,243	470,485	1,009,752	2,080,532
Dairy cows	n	79	164	77	130	322
Fat content	%	3.89	4.34	0.26	4.31	4.97
Protein content	%	3.29	3.58	0.18	3.53	3.94
Energy consumption	kWh	21,694	39,563	14,127	34,520	75,719
Energy per kg milk	Wh/kg_{milk}	21.84	34.63	4.89	35.24	41.19
Energy per cow	kWh/Cow	123	257	47	267	312

time taken for the rotating platform to complete one rotation.

Two regression analysis were also conducted. The first, using the energy efficiency (Wh kg^{-1}_{Milk}) and milking efficiency (cows/hour) data recorded on the 16 herringbone farms over the 12-month period. The second, using the energy efficiency (Wh kg^{-1}_{Milk}) and milking efficiency (cows/hour) data recorded over observation periods 1 and 2 for the 16 herringbone and nine rotary farms. The purpose of these analysis was to further investigate the relationship between energy efficiency and milking efficiency.

3. Results

3.1. Summary statistics

Population descriptions of energy consumption, herd size and milk production for the period Aug. 2020–July 2021 for 16 herringbone parlours are presented in Table 1. The average herd size of these 16 farms was 164 dairy cows, which was larger than the average herd size of Irish dairy farms (90 cows) in 2020 [7]. The average energy consumption of the farms in this study was 39,563 kWh (SD = 14,127 kWh) while average consumption efficiencies of 34.63 Wh kg^{-1}_{Milk} (SD = 4.89 Wh kg^{-1}_{Milk}) and 257 kWh/Cow (SD = 47 kWh/Cow) were observed.

Table 2 presents population descriptions of 16 herringbone parlours and nine rotary parlours for observation periods 1 and 2. On average the rotary parlours milked 404 cows (SD = 97) while the herringbone parlours milked 193 cows (SD = 80). The rotary parlours consumed 29.85 Wh kg^{-1}_{Milk} (SD = 10.25 Wh kg^{-1}_{Milk}) compared to the herringbone parlours which consumed 32.83 Wh kg^{-1}_{Milk} (SD = 5.14 Wh kg^{-1}_{Milk}). The average milking efficiency achieved by the rotary parlours was 152 cows/hour (SD = 30 cows/hour) while the herringbone parlours achieved an average 97 cows/hour (SD = 29 cows/hour).

3.2. Consumption breakdown

3.2.1. Full season analysis

In this study, milk cooling consumed the largest amount of energy, accounting for 33 % of all energy consumption. Water heating was the second largest energy consumer (31 %) followed by the milking machine (16 %). The remaining 20 % can be attributed to miscellaneous energy consuming processes, such as lighting and scrapers, as well as winter housing.

On average, 43 % (SD = 6 %) of the energy consumed by the herringbone parlours in this study was consumed during the night-time period. The water heating system achieved the highest average percentage of night rate energy consumption of 50 % (SD = 21 %), while the milk cooling system and milking machine achieved slightly lower night rate percentages with averages of 45 % (SD = 8 %) and 45 % (SD = 6 %) respectively. The average cost of energy consumed per tonne (T) of milk produced on the herringbone parlours was €4.97 T^{-1}_{Milk} (SD = €1.01 T^{-1}_{Milk}), see Table 3. The milk cooling system was the largest energy expense costing, on average, €1.56 T^{-1}_{Milk} (SD = €0.35 T^{-1}_{Milk}). The water heating system was the second most expensive, costing an average of €1.40 T^{-1}_{Milk} (SD = €0.59 T^{-1}_{Milk}). The milking machine was the least expensive to power with average energy costs of €0.80 T^{-1}_{Milk} (SD = €0.29 T^{-1}_{Milk}), as shown in Table 3.

A variety of different technologies were in use on the 16 herringbone parlours. These technologies and the energy efficiency (Wh kg^{-1}_{Milk}) of the associated systems are presented in Table 3. Technologies associated with the milk cooling system were a plate cooler for pre-cooling milk and different milk cooling systems. The most common milk cooling system in this study was direct expansion (DX). DX milk cooling systems were in use on 94 % of parlours included in this analysis while one ice bank (IB) cooling system was in use. The only variance in technology regarding the milking machine was the inclusion of variable speed drives (VSD) on the vacuum pumps of

Table 2
Population descriptions for electricity consumption, milk production, dairy cows and related KPIs for 16 herringbone farms and nine rotary farms for observation periods 1 and 2.

	Variable	Unit	Min	mean	SD	max
Herringbone	Milk yield	Litre	29,913	53,408	19,060	92,028
	FPCM	kg	34,330	57,736	20,991	101,769
	Dairy cows	n	102	193	80	356
	Fat content	%	4.12	4.50	0.23	4.93
	Protein content	%	3.60	3.91	0.13	4.14
	Energy consumption	kWh	932	1,671	598	3,179
	Energy per kg milk	Wh kg^{-1}_{milk}	23.22	32.83	5.14	44.86
	Energy per Cow	kWh Cow^{-1}	4.53	9.00	1.64	12.21
	Milking efficiency	Cows $hour^{-1}$	63	97	29	167
Rotary	Milk yield	Litre	77,852	106,069	25,482	153,530
	FPCM	kg	80,488	116,877	27,258	176,010
	Dairy cows	n	282	404	97	605
	Fat content	%	4.46	4.72	0.18	5.02
	Protein content	%	3.88	4.00	0.07	4.11
	Energy consumption	kWh	1,940	3,151	860	4,647
	Energy per kg milk	Wh kg^{-1}_{milk}	19.52	29.85	10.25	49.24
	Energy per Cow	kWh Cow^{-1}	3.90	8.22	2.93	14.17
	Milking efficiency	Cows $hour^{-1}$	100	152	30	211

Table 3
Average energy efficiency and energy costs of each main energy consumer of 16 herringbone milking parlours over a 12-month period. Average energy efficiency is provided for variations in technologies used for each system and their percentage difference presented.

System		n	Energy Cost (€ T_{Milk}^{-1}) (SD)	Energy Efficiency (Wh kg_{Milk}^{-1}) (SD)		% Difference
Milk Cooling				Milk Cooling System		
	Average	16	€1.56 (€0.35)	9.90 (2.02)		
	Plate Cooler	15			9.68 (1.90)	36 %
	No Plate Cooler	1			13.20 (0)	
	DX	15			9.74 (1.99)	26 %
	IB	1			12.25 (0)	
Milking Machine				**Milking Machine**		
	Average	16	€0.80 (€0.29)	5.13 (1.76)		
	VSD	9			4.59 (1.92)	27 %
	No VSD	7			5.82 (1.22)	
Water Heating				**Water Heating System**		
	Average	16	€1.40 (€0.59)	9.62 (3.66)		
	Heat Recovery	2			6.82 (1.44)	56 %
	No Heat Recovery	14			10.66 (3.63)	
	Electric Water Heating	12			8.80 (2.79)	62 %
	Gas/Oil Water Heating	4			14.31 (2.75)	
Total				**Parlour Total**		
	Average	16	€4.97 (€1.01)	34.63 (4.89)		
	Solar PV	3			36.96 (4.69)	8 %
	No Solar PV	13			34.10 (4.30)	

Direct expansion = DX, ice bank = IB, variable speed drive = VSD, photovoltaic = PV.

56 % of the farms. Heat recovery was used to pre-heat water on 13 % of farms and 25 % of farms used gas/oil to heat water while on the remaining farms electricity was used to heat water. Solar photovoltaic panels were used to provide electricity to 19 % of the parlours.

Parlours which used a plate cooler to pre-cool milk used on average 9.68 Wh kg_{Milk}^{-1} (SD = 1.90 Wh kg_{Milk}^{-1}) to cool milk compared to 13.20 Wh kg_{Milk}^{-1} (SD = 0 Wh kg_{Milk}^{-1}) on the parlour with no plate-cooler. The average temperature change of milk passing through the plate coolers was 10.34 °C (SD = 5.15 °C). Parlours operating DX milk cooling systems used 26 % less electricity than the parlour which operated an IB milk cooling system. The parlours on which VSDs were in use with the milking machine consumed 4.59 Wh kg_{Milk}^{-1} (SD = 1.92 Wh kg_{Milk}^{-1}) in comparison to the parlours where VSDs were not used where 27 % more electricity per kg_{Milk} was consumed, averaging, 5.82 Wh kg_{Milk}^{-1} (SD = 1.22 Wh kg_{Milk}^{-1}). Parlours where heat recovery systems were used to pre-heat water consumed 6.82 Wh kg_{Milk}^{-1} (SD = 1.44 Wh kg_{Milk}^{-1}) to heat water, 56 % less than parlours which did not use heat recovery which consumed 10.66 Wh kg_{Milk}^{-1} (SD = 3.63 Wh kg_{Milk}^{-1}). The 12 parlours which heated water using electricity consumed 8.80 Wh kg_{Milk}^{-1} (SD = 2.79 Wh kg_{Milk}^{-1}) to heat water while the four parlours which used gas or oil to heat water consumed 14.31 Wh kg_{Milk}^{-1} (SD = 2.75 Wh kg_{Milk}^{-1}). The average total parlour energy consumption, per kg_{Milk} produced, on parlours with solar PV panels was 36.96 Wh kg_{Milk}^{-1} (SD = 4.69 Wh kg_{Milk}^{-1}) while parlours with no solar PV panels consumed 34.10 Wh kg_{Milk}^{-1} (SD = 4.30 Wh kg_{Milk}^{-1}). On average, farms with PV panels produced 7,687 kWh (SD = 3,523 kWh) of electricity over the 12-month period.

3.2.2. Herringbone and rotary comparison

Energy and milking performance of herringbone and rotary parlours were compared for observation periods 1 and 2. Table 4 presents the average and standard deviations of some KPIs. The herringbone parlours used more energy per kg_{Milk} produced than the rotary parlours, consuming averages of 32.83 Wh kg_{Milk}^{-1} (SD = 5.14 Wh kg_{Milk}^{-1}) and 29.85 Wh kg_{Milk}^{-1} (SD = 10.25 Wh kg_{Milk}^{-1}), respectively. The rotary parlours paid less for energy per T_{Milk} produced than the herringbone parlours with averages of €4.33 T_{Milk}^{-1} (SD = €1.55 T_{Milk}^{-1}) and €4.59 T_{Milk}^{-1} (SD = €0.72 T_{Milk}^{-1}) respectively. On average the milking process for the herringbone parlours lasted 1.93 h (SD = 0.47 h) while the rotary parlours had average milking durations of 2.68 h (SD = 0.39 h). Milking efficiency for the herringbone parlours was on average 97 cows/hour (SD = 29 cows/hour) while the rotary parlours averaged milking efficiency rates of 152 cows/hour (SD = 30 cows/hour). Herringbone and rotary parlours consumed the same % of electricity during night-rate pricing time with an average of 44 % for both parlours.

3.2.3. Recording period effect

Energy and milking performance of the 16 herringbone parlours were compared for observation periods 1 and 2. Table 5 presents

Table 4
Average milking performance and energy efficiency and costs for 16 herringbone parlours and nine rotary parlours calculated using data from observation periods 1 and 2.

Parlour	Energy Efficiency (Wh kg_{Milk}^{-1}) (SD)	Energy Costs per T_{Milk} (€ T_{Milk}^{-1}) (SD)	Milking Duration (hours) (SD)	Milking Efficiency (cows/hour) (SD)
Herringbone	32.83 (5.14)	€4.59 (€0.72)	1.93 (0.47)	97 (29)
Rotary	29.85 (10.25)	€4.33 (€1.55)	2.68 (0.39)	152 (30)

Table 5
Breakdown of energy efficiency, costs and night rate energy consumption for all main energy consuming systems of 16 herringbone parlours calculated using data from the observation periods 1 and 2.

		Milk Yield (Avg. Litre) (SD)	Energy Efficiency (Avg. Wh kg_{Milk}^{-1}) (SD)	Energy Cost (Avg. € T_{Milk}^{-1}) (SD)	Nigh Rate (Avg. %) (SD)
Observation Period 1	Parlour Total	18,293 (7,052)	31.88 (5.77)	€4.58 (€0.89)	45 % (7 %)
	Milk Cooling		9.18 (2.23)	€1.29 (€0.37)	50 % (9 %)
	Milking Machine		5.98 (1.94)	€0.86 (€0.28)	46 % (5 %)
	Water Heating		10.39 (4.35)	€1.39 (€0.58)	47 % (24 %)
Observation Period 2	Parlour Total	35,115 (12,140)	26.95 (5.13)	€3.89 (€0.68)	42 % (6 %)
	Milk Cooling		9.14 (1.68)	€1.35 (€0.27)	42 % (9 %)
	Milking Machine		4.11 (1.40)	€0.58 (€0.20)	48 % (5 %)
	Water Heating		8.73 (4.50)	€1.17 (€0.53)	44 % (22 %)

KPIs across all main energy consuming systems, associated energy costs for those systems and % night rate energy consumed. Energy costs, per T_{Milk} produced, were higher in observation period 1 costing on average €4.58 T_{Milk}^{-1} (SD = €0.89 T_{Milk}^{-1}) compared to average costs of €3.89 T_{Milk}^{-1} (SD = €0.68 T_{Milk}^{-1}) in observation period 2. Higher levels of energy efficiency (Wh kg_{Milk}^{-1}) were observed in observation period 2, across all the main energy consumers, with average total energy efficiency of 26.95 Wh kg_{Milk}^{-1} (SD = 5.13 Wh kg_{Milk}^{-1}) and 31.88 Wh kg_{Milk}^{-1} (SD = 5.77 Wh kg_{Milk}^{-1}) in observation period 1. Milking durations in observation period 1 were on average shorter than in observation period 2 averaging 1.79 h (SD = 0.42 h) and 2.14 h (SD = 0.55 h) respectively. Higher rates of milking efficiency were achieved in observation period 1 averaging 103 cows/hour (SD = 37 cows/hour) compared to observation period 2 where an average rate of 93 cows/hour (SD = 25 cows/hour) was achieved.

3.3. Correlation and regression analysis

3.3.1. Full season analysis

Fig. 1 shows the results of a correlation analysis carried out on 16 herringbone farms. A high correlation existed between total energy consumption (kWh) and milk yield (kg_{Milk}) where r = 0.88. A high correlation also existed between total energy consumption and the number of dairy cows where r = 0.80. A moderate correlation existed between total energy consumption and the number of milking units present in the parlour (r = 0.48). Low negative correlations were observed between total energy efficiency (Wh kg_{Milk}^{-1}) and the number of dairy cows and milk yield (kg_{Milk}) where r values of −0.36 and −0.32 were observed. Total energy efficiency (Wh kg_{Milk}^{-1}) showed a low negative correlation with the number of units in the parlour (r = −0.26). Energy efficiency (Wh kg_{Milk}^{-1}) of the milking machine had moderate negative correlations with number of dairy cows (r = −0.52), milk yield (r = −0.46) and the number of

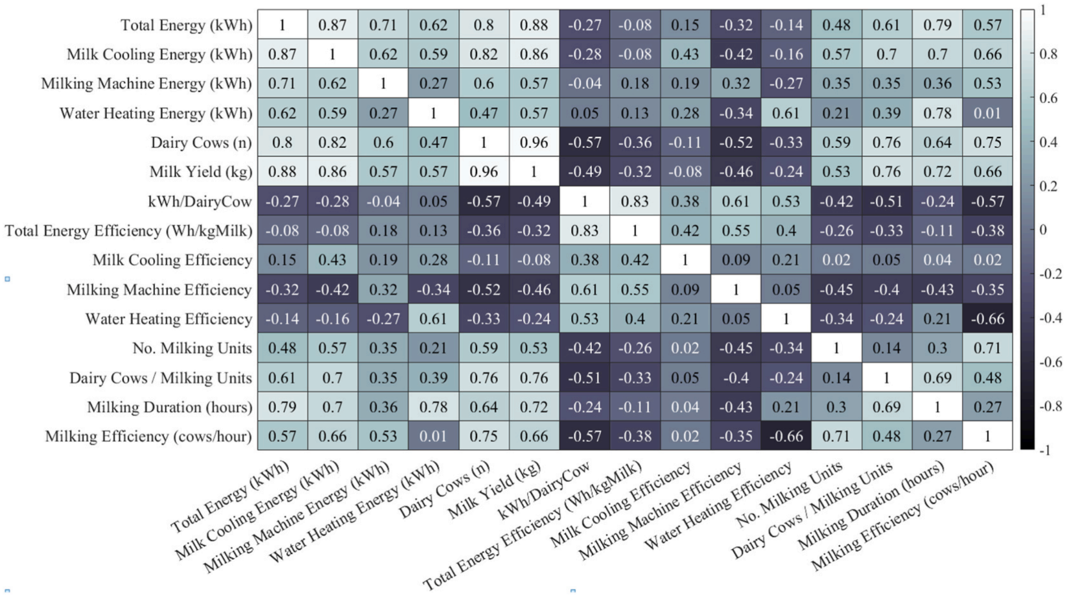

Fig. 1. Matrix describing correlations between total energy consumption, and energy consumption of the main energy consumers, and several analysis variables for 16 herringbone parlours over 12 months. Strength of correlation between variables is between a maximum of 1 and a minimum of −1. This is illustrated in the colour scale presented on the right-hand side of the figure.

milking units (r = −0.45). The energy efficiency (Wh kg^{-1}_{Milk}) of the water heating system showed a low negative correlation with the number of dairy cows (r = −0.33) and with milk yield (r = −0.24). A low negative correlation was observed between the efficiency of the water heating system and the number of units (r = −0.34). Milking duration (hours) was found to have high correlations with total energy consumption, milk cooling energy consumption and water heating energy consumption where r = 0.79, 0.70 and 0.78 respectively. Milking duration also had a high correlation with milk yield (r = 0.72) and moderate correlations with the number of dairy cows and cows per unit where r = 0.64 and 0.69 respectively. Milking efficiency (cows/hour) was found to have high correlations with the number of dairy cows and the number of milking units (r = 0.75 and 0.71) and a moderate correlation with milk yield (r = 0.66). Low negative correlations existed between milking efficiency, total energy efficiency (Wh kg^{-1}_{Milk}) and milking machine energy efficiency (Wh kg^{-1}_{Milk}) where r = −0.38 and −0.35 respectively, while milking efficiency had a moderate negative correlation with water heating energy efficiency (Wh kg^{-1}_{Milk}) where r = −0.66. Milking efficiency also had a moderate negative correlation with energy efficiency in terms of cows (kWh/cow) were r = −0.57.

Fig. 2 presents the results of a regression analysis carried out using data gathered from the 16 herringbone farms over 12 months. Results showed a low relationship (R^2 = 0.15) existed between milking efficiency (cows/hour) and energy efficiency (Wh kg^{-1}_{Milk}) (Fig. 2).

3.3.2. Herringbone and rotary comparison

Fig. 3 shows the results of a correlation analysis conducted using data from observation periods 1 and 2 for the 16 herringbone farms. High correlations existed between total energy consumption and milk yield (r = 0.89) as well as total energy consumption and the number of dairy cows (r = 0.87). Milking duration showed a moderate correlation with total energy consumption (r = 0.69). Milking duration showed high correlations with milk yield and the number of dairy cows where r = 0.84 and 0.78 respectively. Milking efficiency had a high correlation with the number of milking units (r = 0.72) and a moderate correlation with the number of dairy cows (r = 0.69), while milking efficiency also showed a moderate negative correlation with energy efficiency (Wh kg^{-1}_{Milk}) (r = −0.44).

Fig. 4 presents a correlation analysis that was conducted using data from observation periods 1 and 2 for the nine rotary parlours. This analysis showed a moderate negative correlation between energy efficiency (Wh kg^{-1}_{Milk}) and milk yield (r = −0.49). Energy efficiency (Wh kg^{-1}_{Milk}) showed a moderate negative correlation with the number of dairy cows (r = −0.52). Milking efficiency (cows/hour) had a high correlation with the number of dairy cows (r = 0.72) and a moderate correlation with the number of milking units (r = 0.59).

Fig. 5 presents the results of a regression analysis carried out using data gathered from the 16 herringbone and nine rotary farms from observation periods 1 and 2. Results showed a moderate relationship existed between milking efficiency (cows/hour) and energy efficiency (Wh kg^{-1}_{Milk}) on herringbone (R^2 = 0.19) and rotary (R^2 = 0.34) farms (Fig. 5).

4. Discussion

4.1. Full 12-month energy performance analysis

The sample of farms selected for this study were larger than the national average with an average herd size of 164 cows for the herringbone parlours investigated, compared to the national average herd size of 90 cows in 2020 [7]. Larger farm sizes were selected for this study to reflect future farm sizes as further increases in herd size has been forecasted [14]. As larger herd sizes have been linked to improved energy efficiency (Wh kg^{-1}_{Milk}), it was expected that the farms in this study would have better energy efficiency (Wh kg^{-1}_{Milk}) than groups of smaller farms from previous studies [30,31]. Previous studies conducted on Irish dairy farms reported energy efficiencies of 41.11 Wh kg^{-1}_{Milk} Upton et al. (2013) [12] and 38.68 Wh kg^{-1}_{Milk} Shine et al. (2018) [27] compared to the energy efficiency of 34.63 Wh kg^{-1}_{Milk} reported in our study (Table 1). Though energy efficiency (Wh kg^{-1}_{Milk}) tends to increase with farm size it is worth

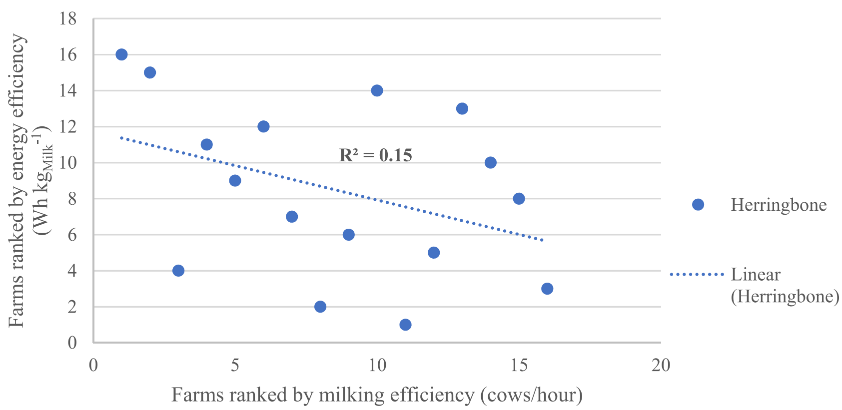

Fig. 2. Spearman's rank plot showing the relationship between milking efficiency (cows/hour) and energy efficiency (Wh kg^{-1}_{Milk}) for data gathered over 12 months on 16 herringbone farms.

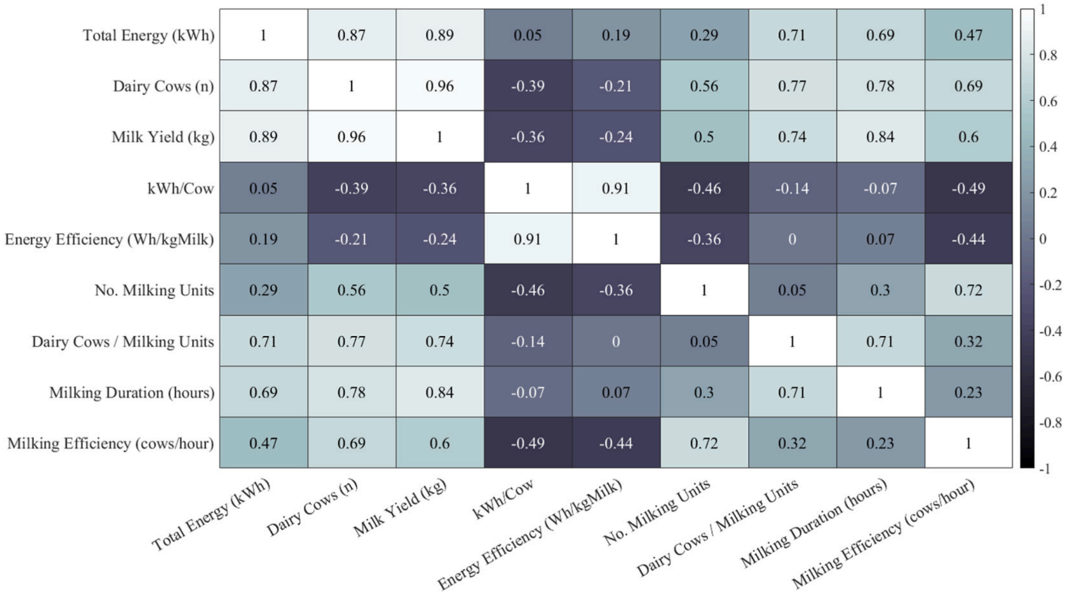

Fig. 3. Matrix describing correlations between energy consumption, milking efficiency, and several analysis variables for 16 herringbone parlours during observation periods 1 and 2.

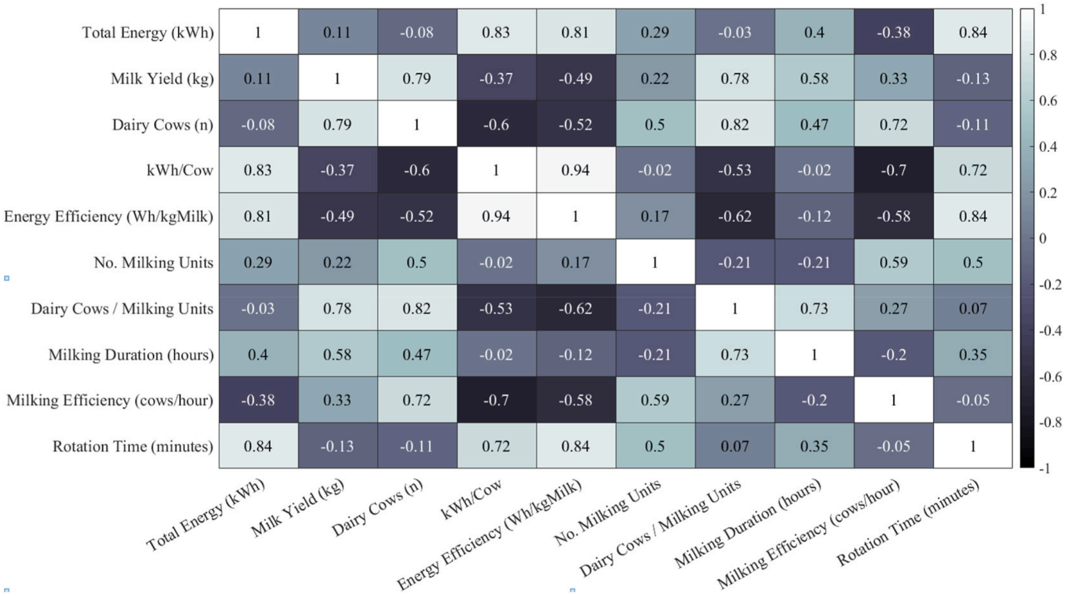

Fig. 4. Matrix describing correlations between energy consumption, milking efficiency, and several analysis variables for nine rotary parlours during observation periods 1 and 2.

noting that the improved energy efficiency (Wh kg_{Milk}^{-1}) resulting from higher milk yield can be negated or reduced due to larger farms adopting more energy consuming technologies [30]. The average farm sizes investigated by Upton et al. (2013) were 118 cows while Shine et al. (2018) reported average herd sizes of 116 cows. Previous studies carried out by Murgia et al. (2013) [32] and Todde et al. (2018) [33] on Italian dairy farms reported total energy efficiencies of 42.84 Wh/kg_{Milk}^{-1} and 73.00 Wh kg_{Milk}^{-1}, respectively. Todde et al. (2018) reported average herd sizes below 142 cows while Murgia et al. (2013) reported 320 cows. The milk cooling systems and milking machines of parlours in this study used less energy per kg_{Milk} than similar studies undertaken on farms with smaller herds. Todd et al. (2018) reported energy efficiencies of 13.87 Wh kg_{Milk}^{-1} for the milk cooling system and 16.79 Wh kg_{Milk}^{-1} for the milking machine. The farms in our study averaged efficiencies of 9.90 Wh kg_{Milk}^{-1} for the milk cooling system and 5.13 Wh kg_{Milk}^{-1} for the milking machine (Table 3). Similarly, a study by Rajaniemi et al. (2017) [34] undertaken on dairy farms in Finland with an average of 82 cows

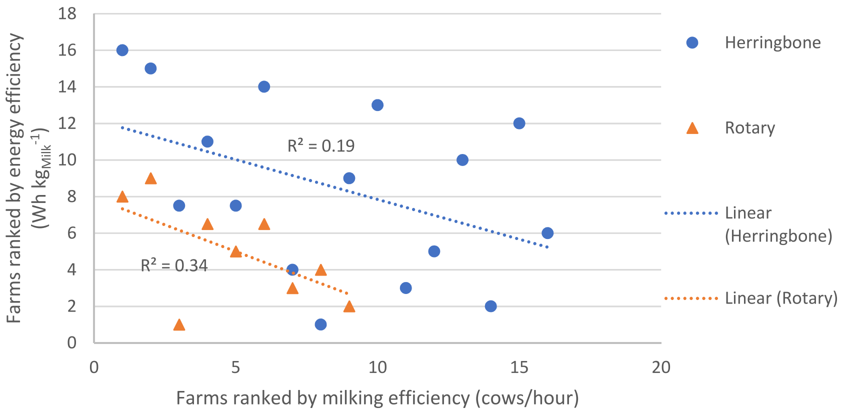

Fig. 5. Spearman's rank plot showing the relationship between milking efficiency (cows/hour) and energy efficiency (Wh kg_{Milk}^{-1}) for data collected in observation periods 1 and 2 from 16 herringbone and nine rotary farms.

found energy efficiency rates for the milk cooling system of 21.70 Wh kg_{Milk}^{-1} and 12.00 Wh kg_{Milk}^{-1} for the milking machine. The average energy efficiency of the water heating system in our study was 9.62 Wh kg_{Milk}^{-1} (Table 3) which were similar to efficiencies reported by Shine et al. (2018) and Upton et al. (2013) of 7.66 Wh kg_{Milk}^{-1} and 9.54 Wh kg_{Milk}^{-1} respectively.

4.2. Full 12-month correlation analysis

A high correlation between milking duration and energy consumption was observed for herringbone parlours in this study with an r value of 0.79 (Fig. 1). This link between milking duration and energy consumption is likely due to milk yield having a high correlation with both milking duration (r = 0.72, Fig. 1) and energy consumption (r = 0.88, Fig. 1). As milk cooling is the largest consumer of energy related to milking (33 % of the total energy consumption in our study) it stands to reason that longer milking durations produce larger volumes of milk which in turn require more energy to cool. Considering milking duration had a high correlation with energy consumption, reducing milking time could result in lower energy consumption. In this study, milking efficiency (cows/hour) was found to have a moderate negative correlation with kWh/cow (r = −0.57, Fig. 1) and a low negative correlation with Wh kg_{Milk}^{-1} (r = −0.38, Fig. 1). As milking efficiency was found to have a moderate negative correlation with energy efficiency (Wh kg_{Milk}^{-1}) of the water heating system (r = −0.66, Fig. 1) and a low negative correlation with energy efficiency (Wh kg_{Milk}^{-1}) of the milking machine (r = −0.35, Fig. 1), improved milking efficiency correlated with low to moderate improvements in energy efficiency. The energy efficiency (Wh kg_{Milk}^{-1}) of the cooling system was found to have a slight correlation with milking efficiency (r = 0.02, Fig. 1). For total energy consumption, and across the main energy consuming sub-processes, slight, low, and moderate correlations were found between milking efficiency and energy efficiency. The regression analysis carried out on 12 months of data from the 16 herringbone farms found a low relationship between milking efficiency (cows/hour) and energy efficiency (Wh kg_{Milk}^{-1}) (R^2 = 0.15, Fig. 2). The top 10 % of farms, in terms of milking efficiency, in this study consumed on average €3.80 (26 kWh) in direct energy per T_{Milk} produced compared to the bottom 10 % of farms, in terms of milking efficiency, which consumed on average €5.47 (37 kWh) in direct energy per T_{Milk}. The average annual milk yield for the farms in this study was 1,169,209 L_{Milk} which would equate to lower annual energy costs between the top and bottom 10 % of farms, in terms of milking efficiency, of €1,950 (13,880 kWh).

4.3. Herringbone and rotary correlation comparison

The rotary parlours in our study were found to have a different relationship with energy consumption compared to the herringbone parlours. The rotary parlours had a slight correlation between milk yield and energy consumption (r = 0.11, Fig. 4) while the herringbone parlours had a high correlation between these two variables for the same periods of observation (r = 0.89, Fig. 3). The rotary parlours showed a slight correlation between energy consumption and the number of cows milked (r = −0.08, Fig. 4) while the herringbone parlours had a high correlation between these two variables (r = 0.87, Fig. 3). These findings suggest that, from an energy perspective, the rotary parlours were better suited to milking larger numbers of cows without incurring larger energy costs. From a milking efficiency perspective, the rotary parlours showed a high correlation between cows/hour and the number of dairy cows (r = 0.72, Fig. 4) and a moderate correlation between cows/hour and the number of units in the parlour (r = 0.59, Fig. 4). The herringbone parlours showed a moderate correlation between cows/hour and the number of dairy cows (r = 0.69, Fig. 3) and a high correlation between cows/hour and the number of units in the parlour (r = 0.72, Fig. 3). Moderate negative correlations were observed between cows/hour and Wh kg_{Milk}^{-1} for the herringbone parlours (r = −0.44, Fig. 3) and the rotary parlours (r = −0.58, Fig. 4). Results of a regression analysis carried out on data from observation periods 1 and 2 showed a moderate relationship existed between milking efficiency (cows/hour) and energy efficiency (Wh kg_{Milk}^{-1}) on herringbone (R^2 = 0.19) and rotary (R^2 = 0.34) farms (Fig. 5).

5. Conclusion

We found that higher rates of milking efficiency were observed on the rotary parlours, achieving 152 cows/hour while the herringbone parlours achieved 97 cows/hour. The energy use for rotary parlours was 9 % lower than that of herringbone parlours (29.85 Wh kg_{Milk}^{-1} for rotary vs 32.83 Wh kg_{Milk}^{-1} for herringbone). We found that the milk cooling system (33 % of total), water heating system (31 % of total) and the milking system (16 % of total) were the largest energy users, in agreement with previous literature.

For both milking system types studied we identified a moderate negative correlation between milking efficiency and energy efficiency ($r = -0.58$, $R^2 = 0.34$ for rotary parlours and $r = -0.44$, $R^2 = 0.19$ for herringbone parlours). Therefore, as milking efficiency increased, energy efficiency moderately improved. For example, the most efficient herringbone farms in terms of milking efficiency (top 10 %), consumed 11 kWh less energy per tonne of milk harvested than the least efficient herringbone farms (bottom 10 %). Hence, we can conclude that, on average, higher rates of milking efficiency translated to moderately higher rates of energy efficiency regardless of parlour type in this study.

Data availability statement

The authors are unable or have chosen not to specify which data has been used.

CRediT authorship contribution statement

F. Buckley: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft. **M.D. Murphy:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **R. Prendergast:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – review & editing. **L. Shalloo:** Funding acquisition, Resources, Writing – review & editing. **J. Upton:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

FundingThe Authors acknowledge the used of the energy monitoring equipment supplied through Smart Agri Hubs [FIE 1 ID: 818182]; This work was partially supported by the SEAI RD&D funding programme [19/RDD/453].

Appendix A. Additional Tables

Table A.1
Breakdown of technology specifications and parlour details.

	Variable	Unit	n	min	mean	SD	max
Herringbone	No. Units	–	17	12	20	6.06	36
	Bulk Tank Volume	Litres		4,400	13,465	7,910	32,000
	Hot Water Tank Capacity	Litres		210	624	411	1,500
	Water Heating Element Power Rating	kW		2	5	2.58	11
	Vacuum Pump Power Rating	kW		3	7	2.76	15
	Number of Lights in the Parlour	–		4	11	4.50	22
Rotary	No. Units	–	9	44	51	6.67	64
	Bulk tank Volume	Litres		16,000	23,922	5,390	32,695
	Hot Water Tank Capacity	Litres		500	34	17	64
	Water Heating Element Power Rating	kW		5	8	2.41	11
	Vacuum Pump Power Rating	kW		14	15	0.60	17
	Number of Lights in the Parlour	–		2	6	4.18	16

Table A.2
Miscellaneous energy use of farms with and without domestic loads and the percentage of which is estimated to be farm related. (n is the number of farms in each group)

Month	Average Monthly kWh/Cow (Non-Domestic) (n = 5)	Average Monthly kWh/Cow (Domestic) (n = 11)	% Of misc. kWh/Cow (Farm use only)
Jan.	4.63	13.52	34 %

(*continued on next page*)

Table A.2 (*continued*)

Month	Average Monthly kWh/Cow (Non-Domestic) (n = 5)	Average Monthly kWh/Cow (Domestic) (n = 11)	% Of misc. kWh/Cow (Farm use only)
Feb.	4.28	13.16	33 %
Mar.	3.88	13.22	29 %
Apr.	3.21	10.46	31 %
May	2.88	8.17	35 %
June	2.33	6.94	34 %
July	2.37	6.55	36 %
Aug.	3.33	9.81	34 %
Sept.	2.04	6.86	30 %
Oct.	2.81	8.54	33 %
Nov.	4.08	11.38	36 %
Dec.	4.19	11.64	36 %

Appendix B. Method for domestic energy removal

As described in section 2.2.1, of the 16 farms which had permanent energy meters installed, 11 included a domestic component in the miscellaneous category while the remaining five farms did not. To estimate and remove the domestic energy consumption, the farms were divided into two groups. The first group consisted of the 11 farms with a domestic component in the miscellaneous energy category (group 1), while the second group consisted of the five farms which did not include a domestic component in the miscellaneous energy category (group 2). The miscellaneous energy consumed per dairy cow (kWh_{misc}/cow) was calculated for each month for the group 2 farms. The average kWh_{misc}/cow of all group 2 farms was calculated for each month. These monthly kWh_{misc}/cow figures were used as an estimate for how much miscellaneous energy farms consume per cow in every month. The same procedure was followed for the group 1 farms to determine how much miscellaneous energy, including a domestic component, the group 1 farms consumed. The monthly kWh_{misc}/cow consumed by the group 2 farms was divided by the monthly kWh_{misc}/cow consumed by the group 1 farms to determine the percentage kWh_{misc}/cow which was only related to farm energy use. The monthly miscellaneous energy consumption of the group 1 farms was then scaled down by this percentage so only the miscellaneous energy use related to the farm remained.

References

[1] European Commission, Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people, J. Chem. Inf. Model. 53 (9) (2020) 1689–1699 [Online]. Available:the benefit of our peopl https://knowledge4policy.ec.europa.eu/publication/communication-com2020562-stepping-europe's-2030-climate-ambition-investing-climate_en#:~:text=17 September 2020-,Communication COM%2F2020%2F562%3A Stepping up Europe's 2030 climate.

[2] Goal 2: Zero Hunger - The Global Goals" https://www.globalgoals.org/goals/2-zero-hunger/(accessed Aug. 09, 2022)..

[3] J.G. Da Silva, Feeding the World Sustainably | United Nations, United Nations Organisation, 2019. https://www.un.org/en/chronicle/article/feeding-world-sustainably. accessed Oct. 01, 2022.

[4] G. of Ireland, Government Announces Sectoral Emissions Ceilings, Setting Ireland on a Pathway to Turn the Tide on Climate Change, Climate Action and Environment, 2022. https://www.gov.ie/en/press-release/dab6d-government-announces-sectoral-emissions-ceilings-setting-ireland-on-a-pathway-to-turn-the-tide-on-climate-change/. Aug. 10, 2022.

[5] [Online]. Available:, Department of Agriculture Food and the Marine, "Ag Climatise - A Roadmap towards Climate Neutrality, 2020, p. 30 https://www.gov.ie/en/publication/07fbe-ag-climatise-a-roadmap-towards-climate-neutrality/.

[6] 0–38, [Online]. Available: https://www.cru.ie/document_group/remuneration-of-renewables-self-consumers-exported-electricity/, Remuneration of Renewables Self-consumers for exported electricity : Interim Clean Export Guarantee (2021).

[7] Livestock - Cso - Central Statistics Office. https://www.cso.ie/en/releasesandpublications/ep/p-coa/censusofagriculture2020-preliminaryresults/livestock/ accessed Jan. 20, 2022.

[8] C. Hogan, J. Kinsella, B. O'Brien, M. Gorman, M. Beecher, An examination of labor time-use on spring-calving dairy farms in Ireland, J. Dairy Sci. 105 (7) (2022) 5836–5848, https://doi.org/10.3168/jds.2022-21935.

[9] Teagasc, The People in Dairy Project - a Report on the Future People Requirements of Irish Dairy Farming to Support Sustainable and Profitable Dairy Expansion [Online]. Available:, 2017 https://www.teagasc.ie/media/website/publications/2017/The-People-in-Dairy-Project.pdf.

[10] M. Rajaniemi, M. Turunen, J. Ahokas, Direct energy consumption and saving possibilities in milk production, Agron. Res. 13 (1) (2015) 261–268.

[11] P. Shine, J. Upton, P. Sefeedpari, M.D. Murphy, Energy consumption on dairy farms: a review of monitoring, prediction modelling, and analyses, Energies 13 (5) (2020) 1–25, https://doi.org/10.3390/en13051288.

[12] J. Upton, J. Humphreys, P.W.G. (Peter, Groot Koerkamp, P. French, P. Dillon, I.J.M. Boer, Energy demand on dairy farms in Ireland.," J Dairy Sci 96 (2013), https://doi.org/10.3168/jds.2013-6874. Aug. 2013.

[13] M.D. Murphy, J. Upton, M.J. O'Mahony, Rapid milk cooling control with varying water and energy consumption, Biosyst. Eng. 116 (1) (2013) 15–22, https://doi.org/10.1016/j.biosystemseng.2013.05.007.

[14] P. Shine, T. Scully, J. Upton, M.D. Murphy, Annual electricity consumption prediction and future expansion analysis on dairy farms using a support vector machine, Appl. Energy 250 (May 2019) (2019) 1110–1119, https://doi.org/10.1016/j.apenergy.2019.05.103.

[15] J. Upton, M. Murphy, L. Shalloo, P.W.G. Groot Koerkamp, I.J.M. De Boer, Assessing the impact of changes in the electricity price structure on dairy farm energy costs, Appl. Energy 137 (2015) 1–8, https://doi.org/10.1016/j.apenergy.2014.09.067.

[16] M. Breen, J. Upton, M.D. Murphy, Photovoltaic systems on dairy farms: financial and renewable multi-objective optimization (FARMOO) analysis, Appl. Energy 278 (January) (2020), 115534, https://doi.org/10.1016/j.apenergy.2020.115534.

[17] DAFM, Food Wise [Online]. Available: 2025 A 10-year vision for the Irish agri-food industry," A 10-year vision for the Irish agri-food industry (2015) 103 http://www.agriculture.gov.ie/media/migration/agri-foodindustry/foodwise2025/report/FoodWise2025.pdf.

[18] CSO, "Demographic Profile of Farm Holders - Central Statistics Office, Census of Agriculture 2020 - Preliminary Results, 2021. https://www.cso.ie/en/releasesandpublications/ep/p-coa/censusofagriculture2020-preliminaryresults/demographicprofileoffarmholders/. (Accessed 27 June 2022).

[19] K. Tarrant, D. Armstrong, An economic evaluation of automatic cluster removers as a labour saving device for dairy farm businesses, AFBM Journal 9 (1) (2012) 43–48, https://doi.org/10.22004/AG.ECON.131752.
[20] J.G. Jago, J.L. Burke, J.H. Williamson, Effect of automatic cluster remover settings on production, udder health, and milking duration, J. Dairy Sci. 93 (6) (2010) 2541–2549, https://doi.org/10.3168/jds.2009-2949.
[21] J.P. Edwards, B. Kuhn-Sherlock, B.T. Dela Rue, C.R. Eastwood, Short communication: technologies and milking practices that reduce hours of work and increase flexibility through milking efficiency in pasture-based dairy farm systems, J. Dairy Sci. 103 (8) (2020) 7172–7179, https://doi.org/10.3168/jds.2019-17941.
[22] J.P. Edwards, J.G. Jago, N. Lopez-Villalobos, Milking efficiency for grazing dairy cows can be improved by increasing automatic cluster remover thresholds without applying premilking stimulation, J. Dairy Sci. 96 (6) (2013) 3766–3773, https://doi.org/10.3168/jds.2012-6394.
[23] I.C.B.F. Home. https://www.icbf.com/. Dec. 09, 2021.
[24] Geothermal Mapping System. https://gis.seai.ie/geothermal/. Mar. 29, 2022.
[25] Purchasing Energy-Efficient Residential Gas Boilers| Department of Energy." https://www.energy.gov/eere/femp/purchasing-energy-efficient-residential-gas-boilers (accessed Mar. 29, 2022)..
[26] J. Upton, M. Murphy, P. French, P. Dillon, Dairy Farm Energy Consumption [Online]. Available:, Teagasc National Dairy Conference 2010, 2010, pp. 87–97 https://www.teagasc.ie/media/website/rural-economy/farm-management/DairyFarmEnergyConsumptionDairyConference2010.pdf.
[27] P. Shine, T. Scully, J. Upton, L. Shalloo, M.D. Murphy, Electricity & direct water consumption on Irish pasture based dairy farms: a statistical analysis, Appl. Energy 210 (2018) 529–537, https://doi.org/10.1016/j.apenergy.2017.07.029.
[28] J. Upton, Dairy - Reducing Energy Costs on Dairy Farms - Teagasc | Agriculture and Food Development Authority, 2021. https://www.teagasc.ie/news–events/daily/dairy/reducing-energy-costs-on-dairy-farms.php. Aug. 03, 2022.
[29] L. Parish, J.P. Guilford, Fundamental statistics in psychology and education, Br. J. Educ. Stud. 5 (2) (May 1957) 191, https://doi.org/10.2307/3118885.
[30] A. Moerkerken, S. Duijndam, J. Blasch, P. van Beukering, A. Smit, Determinants of energy efficiency in the Dutch dairy sector: dilemmas for sustainability, J. Clean. Prod. 293 (2021), 126095, https://doi.org/10.1016/j.jclepro.2021.126095.
[31] G. Todde, L. Murgia, M. Caria, A. Pazzona, A multivariate statistical analysis approach to characterize mechanization, structural and energy profile in Italian dairy farms, Energy Rep. 2 (2016) 129–134, https://doi.org/10.1016/j.egyr.2016.05.006.
[32] L. Murgia, G. Todde, M. Caria, A. Pazzona, A partial life cycle assessment approach to evaluate the energy intensity and related greenhouse gas emission in dairy farms, Journal of Agricultural Engineering 44 (2s) (2013) 186–190, https://doi.org/10.4081/jae.2013.s2.e37.
[33] G. Todde, L. Murgia, M. Caria, A. Pazzona, A comprehensive energy analysis and related carbon footprint of dairy farms, part 1: direct energy requirements, Energies 11 (2) (2018) 1–14, https://doi.org/10.3390/en11020451.
[34] M. Rajaniemi, T. Jokiniemi, L. Alakukku, J. Ahokas, Electric energy consumption of milking process on some Finnish dairy farms, Agric. Food Sci. 26 (3) (2017) 160–172, https://doi.org/10.23986/afsci.63275.