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SELECTED PARAMETERS AFFECTING THE ELECTRICITY CONSUMPTION OF AUTOMATIC MILKING SYSTEMS

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The paper presented is aimed at the determination of electricity consumption at selected dairy farms during milking employing automatic milking systems (AMS). The research was focused on the determination of electricity consumption during the performance of essential activities that are related to the AMS utilization, i.e., electricity consumption by a single AMS unit per day, by a single assembly compressor per day, by a single AMS unit and a single assembly compressor per day, per milking, and per 1 litre of milk. Measurements were conducted at eight dairy farms in Central Europe that house dairy cows of the black-spotted Holstein cattle breed. The cattle groups assessed comprised 95 to 105 animals subjected to milking over the entire observed period. On the basis of the measurements conducted, it was observed that the average amount of energy consumed per 1 litre of milked milk was 0.0232 kWh over the entire observed period. Regarding the essential activities, the results obtained indicate that the energy consumption throughout the year is relatively balanced, despite the fact that it is affected by a wide range of factors, including chiefly the herd management, as well as overall organization of entire farm, milk yield, health status of cattle, current climatic conditions, fodder quality, etc.

Keywords: dairy technology; milking robot; cattle; milk

Rational energy management, including electrical energy, is currently a highly emphasized topic. A sharp increase in human population and living standards belong to the main causes that result in a growing worldwide increment in negative phenomena, including the increase in the production of multiple gases, e.g., carbon dioxide, which originate from the combustion of fossil fuels. Among other reasons, these are processed for the purposes of obtaining electrical energy in power plants all around the world. For this very reason, reducing the energy intensity of agriculture currently represents a major topic, as agricultural production is one of the major CO₂ producers. Activities that significantly contribute to large electricity consumption include farmland irrigation, as well as milking (Dew et al., 2021). Questions related to the price and availability of energy, or relevant commodities and goods – whether natural gas, petroleum, or petroleum products – are currently even more topical, which is especially true for the context of the entire Central European region.

The production of milk and dairy products represents one of the main agricultural commodities. Analysing the last several decades, the assessment of energy intensity and energy demand of husbandry have become frequently discussed issues (Deming et al., 2013; Hansen et al., 2019; Přikryl et al., 2016). Monitoring and optimizing the operation of individual elements of milking systems, such as monitoring the energy consumption of a pump controlled via a frequency converter during milking cycle, are considered a significant part of a more complex issue (Vaculík et al., 2018).

Therefore, a number of financial analysis and multifunctional optimization procedures are introduced and adopted, e.g., the employment of renewable energy sources using photovoltaic systems at dairy farms (Breen et al., 2020; Neto and Lopes, 2020), as well as methods for determining energy consumption per 1 kg of produced milk (Shine et al., 2020; Breen et al., 2019).

Electrical energy is vital not only for the process of milking, but also for the processing of milk at farms – these are primarily the processes of cooling and pasteurising of milk (as well as delivering the milk to customers). However, other activities in animal husbandry – or cattle farming – are also monitored in terms of energy intensity. Ultimately, this issue translates to monitoring of the agricultural system from the perspective of the entire life cycle – monitoring of dairy farms not only in terms of their energy consumption, but also in terms of associated environmental impacts, which was investigated by e.g., Huysveld et al. (2015).

The process of machine milking employing automatic milking systems (AMS) belongs to the activities that utilise the highest degree of automation. The AMS use is one of the current trends in cattle husbandry with marketable milk production, with the number of installed machines growing quite rapidly every year (Piwczyński et al., 2020).

The paper presented observed the electricity consumption at selected dairy farms in Central Europe during the performance of milking processes via AMS, i.e., milking robots.

Material and methods

Eight farms with specific climate conditions in Central Europe were observed for the purposes of determining the electricity consumption at selected farms during milking utilising AMS. The selected dairy farms house black-spotted Holstein cattle breed. The field measurements at these farms were conducted from 1st January 2021 to 31th December 2021. The size of assessed groups of dairy cattle at individual farms ranged from 95 to 105 milked animals throughout the entire monitored period (i.e., the tests were aimed at herds with approx. 100 animals subjected to milking in order to ensure the comparability of results). Due to technical and organizational reasons, the number of cows in one herd during the monitored period cannot be constant. Observed groups of cattle were housed in either new or reconstructed stables. The technology of free housing was installed to these stables and each of them utilizes the AMS (milking robots) for milking. The farming technology applied at each observed farm perfectly complied with all animal welfare standards and other associated regulations.

Each farm observed had utilised the AMS for at least five years before the monitoring, and the herd management was fully dependent on the maximum utilisation of the milking robots. Each farm installed the same type of AMS by Lely (the same manufacturer and with comparable technical parameters), the consumption of which was monitored during the period observed.

Electricity is vital in AMS as it employs electrical energy for multiple activities. The central control unit of milking robots controls the electricity, water, air pressure, and vacuum of the automatic milking units, ensures the heating of water to required temperature, and communicates data essential for AMS functioning. In order to ensure the comparability of collected data on electricity consumption between individual farms, the steam cleaning system was not put into operation.

The paper observes the electricity consumption associated with only milking via the AMS. Electricity consumption for the purposes of maintenance of technological equipment (i.e., for cleaning AMS boxes) and stables, feeding and cleaning animals, lighting, provision of optimal thermal conditions in husbandry (ventilation, etc.), stocking of feed, manure handling, etc., was not included in assessment.

For the purposes of determining electricity consumption, three-phase electricity meters were installed for the monitoring of individual devices. The electricity meter was an officially approved digital three-phase electricity meter LUNA LSM40 (capable of measuring the current with a range from 5 to 100 A). In addition to the total electricity consumption, the number of milkings per day and the amount of milk milked per day were read from the operational software of individual AMSs at regular intervals. The paper presented observes the following selected parameters, which are illustrated in more detail in Table 1 and graphs: the number of dairy cows in the herd per week, the number of milkings per day in the herd, the amount of milk milked in the herd per day, electricity consumption by one AMS per day, the number of hours of daily operation of assembly's compressor, compressor's electricity consumption, the total electricity consumption of a single AMS and a single assembly compressor per day, total electricity consumption per milking, and total electricity consumption per 1 l of milk.

The results showed by individual farms are not assessed here, but the final set is evaluated as whole for the entire observed period. For the interpretation of results, specific values, e.g., average electricity consumption per milking, etc., were subsequently calculated.

Statistical analysis was carried out via MS Excel, determining the means and deviations of selected parameters and conducting ANOVA analysis between test variants at significance level 0.05.

Results and discussion

Figures 1–8 illustrate the values of the entire data set acquired via measurements conducted at all monitored farms. Final curves (average) plotted in Figs 1–8 represent an arithmetic mean of the measurements from all the eight monitored farms.

Figure 1 depicts the number of milkings in the assessed herds throughout the entire observed period. The determined number of milkings ranges from 254.35 to 291.15 of milkings per day in the assessed herds. The curve showing the average number of milkings per day suggests that a lower number of milkings per day was recorded in January, May, October, and November; vice versa, higher numbers were observed in June, and at the turn of September and October.

Table 1 Herd and AMS parameters

Measurement date									
1 st January 2021 to 31 th December 2021									
Herd parameters									
Farm	(-)	A	B	C	D	E	F	G	H
Herd size	(pcs)	97	95	105	100	100	104	102	97
Breed	(-)	black-spotted Holstein cattle							
AMS parameters									
Type of AMS	(-)	lely Astronaut A4							
Steam cleaning system of AMS	(-)	was not put into operation							

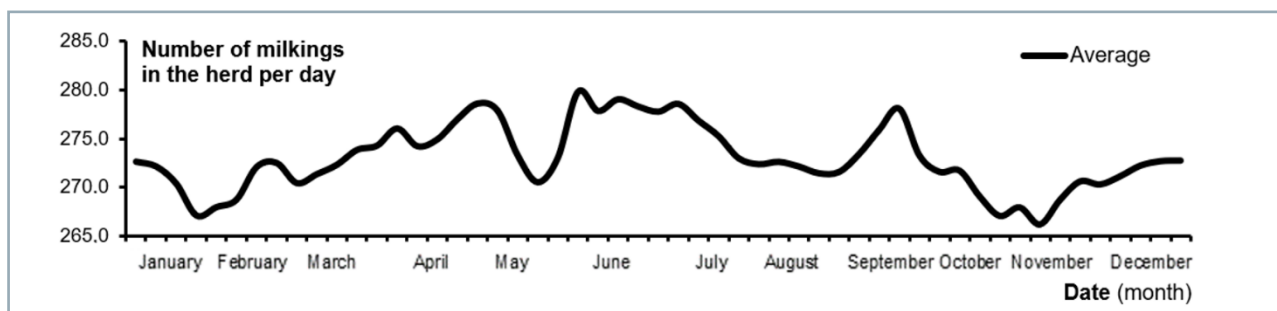


Fig. 1 Number of milkings in the herd per week

The average number of milking in the herds of dairy cows was 273.02 milkings per day, implying that individual dairy cows were milked 2.73 times per day on average during the observed period with regard to the number of cows milked in the assessed herds (the average number of dairy cows in the assessed herds was 99.79 cows per herd and week).

Figure 2 illustrates the amount of milk milked in the assessed herds of dairy cows per day (l) during the entire observed period. The curve portraying the average amount of milk milked per day shows that the lower amounts of milk milked per day were recorded at the beginning of January, in March, and at the end of June and July; on the contrary, higher amounts were recorded in May and October. There is a quite large number of factors that influence this fluctuation in daily milk yield. A significant increment in group milk yield can result from, e.g., changes in climate and improved welfare of animals that is associated with it. The majority of individual factors affecting milk yield can be neglected in those herds where the total numbers of cattle reached around 800 animals.

The average values range from 2.460 to 2.738 l of milk per day in the assessed groups. Group milk yields at evaluated

farms were relatively uniform throughout the observed period. On average, 2.599 l-day^{-1} was milked daily over the entire monitored period (with regard to the average number of animals in the group of dairy cows).

Figure 3 depicts electricity consumption (kWh) by a single AMS in assessed dairy herds per day throughout the entire observed period. The curve portraying the average electricity consumption by a single AMS per day implies that the lower amounts of electricity were consumed at the beginning of January, in March, August, and December. Inversely, higher consumptions were recorded at the end of January, in June, and September.

The average determined values range from 30.30 to 34.75 kWh per a single AMS per day. It is not possible to unequivocally determine the reasons for higher or lower values of electricity consumption by AMS. There are multiple factors that affect electricity consumption occurring randomly, e.g., the number of rejected dairy cows (their refusal to be milked), the time necessary for putting on the teat cups, milk yield, AMS cleaning time (e.g., depending on the detection of non-consumable milk), the setting of the method of disinfection of the teat cups, the

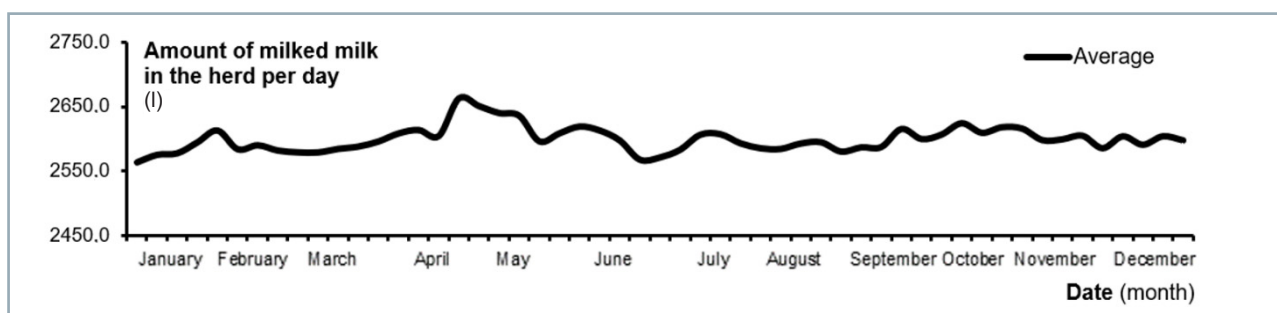


Fig. 2 Amount of milk milked in a herd per day

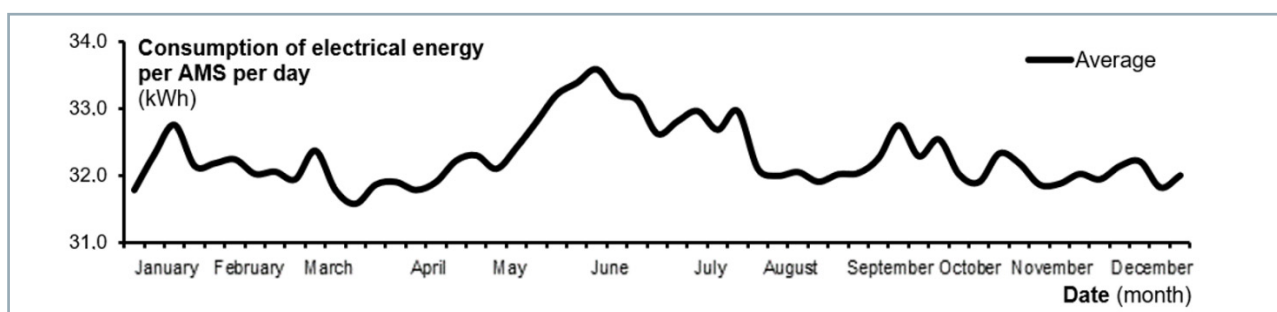


Fig. 3 Electricity consumption by a single AMS per day

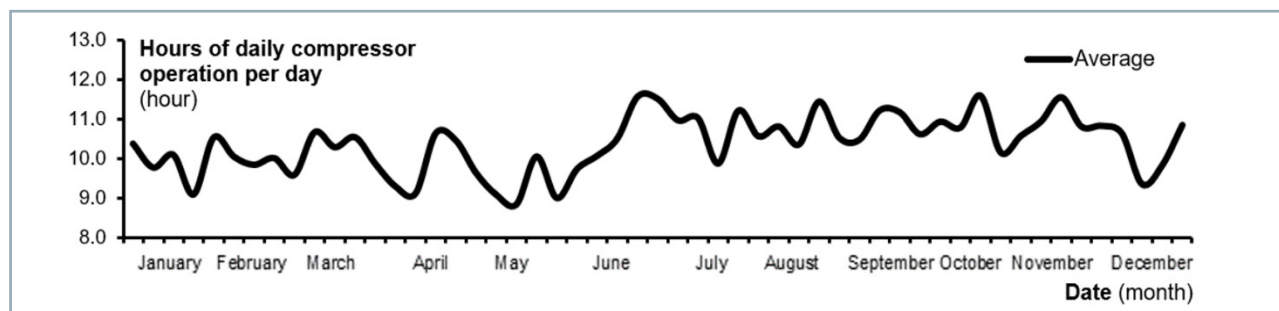


Fig. 4 Number of hours of assembly compressor operation per day

layout of machinery, or the location of individual groups of animals in the housing area (i.e., it also involves different construction lengths of milk pipelines between the AMS in the milking parlour and the dairy, which is caused by the different needs of the specific farmer and the given facility). The measurement results show that a single AMS consumed 32.29 kWh per a single AMS per day on average during the entire observed period.

Figure 4 depicts the average number of hours of assembly compressor operation in the assessed herds of dairy cows per day during the entire observed period. The assembly compressor used was a scroll compressor SF4 (Atlas Copco AB), 3.7 kW. The determined number of hours of assembly compressor operation ranges from 7.64 to 13.31 h·day⁻¹. The curve showing the average number of hours of assembly compressor operation per day illustrates that lower consumption values were observed mainly in January, April, May, June, and December. On the other hand, higher values were detected in the period from August to November. These values are also related to the total electricity consumption, or rather to the total time during which milking takes place in the AMS, or to other activities associated with milking.

Similarly to other selected parameters of electricity consumption, the differences in the observed values of compressor operation per day in individual herds result from a variety of reasons, e.g., from the number of rejected dairy cows (their refusal to be milked), the time necessary for putting on the teat cups, milk yield, machinery layout, or the location of individual groups of animals in the barn. Nevertheless, measured values were quite balanced over the entire monitored period.

The average number of hours of assembly compressor operation per day was 10.36 h·day⁻¹ throughout the entire observed period.

Figure 5 characterises the electricity consumption of assembly compressor (kWh) in the monitored herds of dairy cows per day during the entire observed period. The assembly compressor used was a scroll compressor SF4 (Atlas Copco AB), 3.7 kW. The determined values of electricity consumption of the assembly compressor range from 20.67 to 38.20 kWh. The curve showing the average number of hours of assembly compressor operation per day indicate that lower consumption values were observed mainly in April, May, and early December. On the other hand, higher consumption values were observed mainly in August, October, and November. As in case of the number of hours of assembly compressor operation per day, the dissimilar values of assembly compressor's consumption per day in individual herds result from multiple reasons, e.g., from the number of rejected dairy cows (their refusal to be milked), the time necessary for putting on the teat cups, milk yield, machinery layout, or the location of individual groups of animals in the housing area.

Based on the amount of energy consumed by the assembly compressor, the average compressor consumption was 28.11 kWh·day⁻¹ during the entire observed period.

Figure 6 portrays the total electricity consumption (kWh) per day, i.e., the total electricity consumption of a single AMS and a single compressor in the assessed herds of dairy cows throughout the entire observed period. The determined values of electricity consumption range from 51.79 to 71.78 kWh·day⁻¹. The curve illustrating the average electricity consumption per day shows that lower consumptions were detected mainly in March, April, May, and December. Vice versa, higher consumptions were

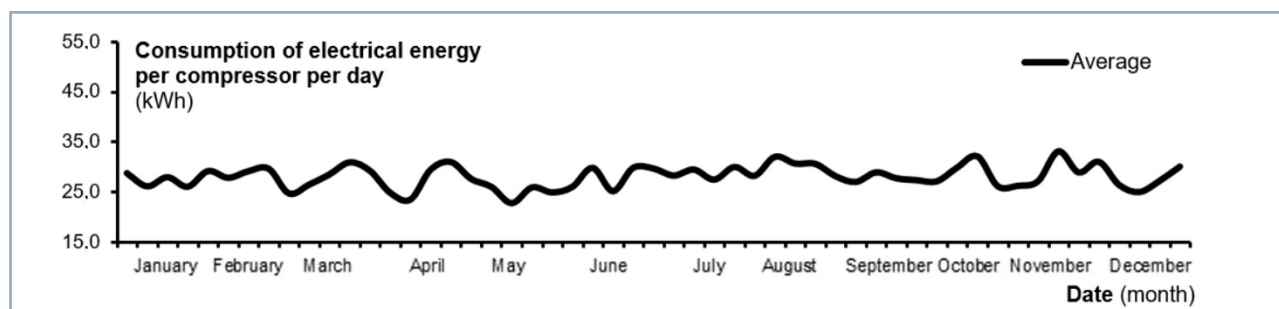


Fig. 5 Electricity consumption of assembly compressor per day

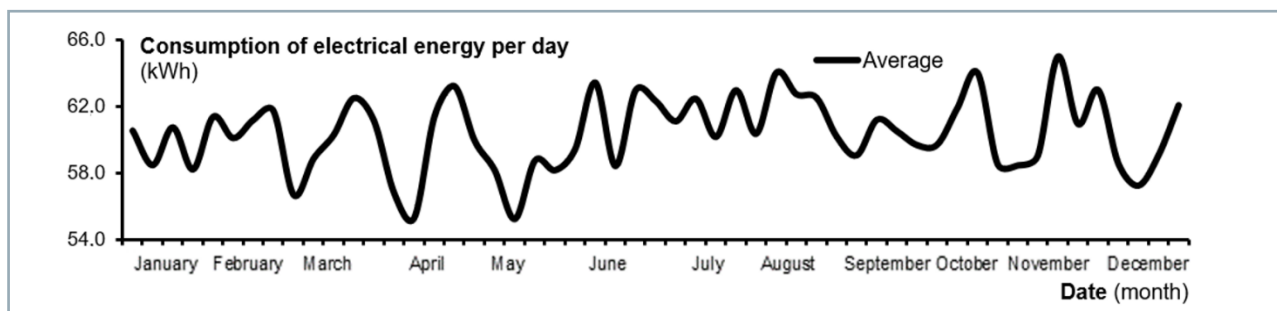


Fig. 6 Electricity consumption per day

observed mainly in August, October, and November. The variation in electricity consumption per day is associated with electricity consumption by a single AMS and a single compressor assembly.

Based on electricity consumption examined, on average, $60.39 \text{ kWh} \cdot \text{day}^{-1}$ was consumed throughout the entire evaluated period.

Figure 7 shows the electricity consumption (kWh) per milking in the assessed herds of dairy cows during the entire evaluated period. The determined values of electricity consumption per milking range from 0.19 to 0.26 kWh per milking. The curve illustrating the average electricity consumption per milking shows that lower consumptions were examined mainly in April, May, and December, while higher consumptions mainly in October and November.

Based on electricity consumption per milking, 0.22 kWh per milking on average was consumed during the entire observed period.

Figure 8 depicts electricity consumption (kWh) per 1 l of milked milk in the assessed herds of dairy cows during the entire observed period. The determined values of electricity consumption (kWh) per 1 l of milked milk range from 0.0200

to 0.0274 kWh. The curve illustrating the average electricity consumption per 1 l of milked milk shows that lower consumptions were observed mainly in April and May, while higher consumptions were observed mainly in October and November.

Based on electricity consumption (kWh) per 1 l of milked milk, 0.0232 kWh on average was consumed during the entire monitored period.

Based on the determined average values of all assessed groups of dairy cows, the dependence of total electricity consumption of a single AMS and a single compressor per day, the dependence of total electricity consumption per milking, and the dependence of total electricity consumption per 1 l of milked milk were tested by the analysis of variance (ANOVA). The ANOVA results of measured values of electricity consumptions are listed in Table 2.

The ANOVA results of measured values of electricity consumption (the default significance level $\alpha = 0.05$) showed that electricity consumption is dependent on the total energy consumption of a single AMS and a single compressor per day, energy consumption per milking, and energy consumption spent on milking per 1 l of milk.

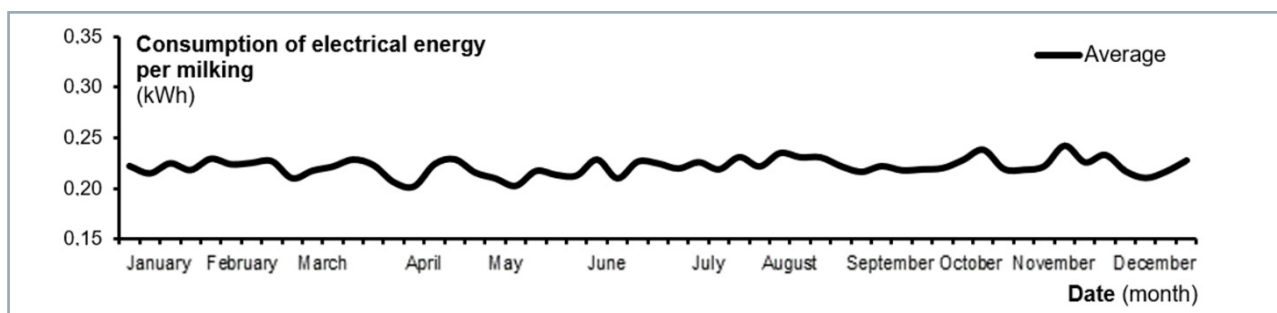


Fig. 7 Electricity consumption per milking

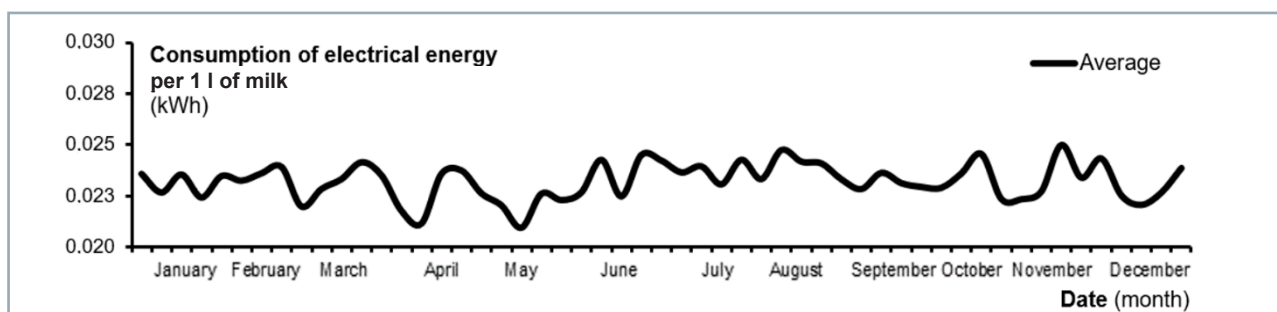


Fig. 8 Electricity consumption per 1 l of milked milk

Table 2 The analysis of variance of measured values of electricity consumption (the default significance level $\alpha = 0.05$)

Variance/source	Total variance	Expected value of variance	Test criterion	Significance level	Critical test criterion
	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F_{crit}</i>
Analysis of variance of the overall electricity consumption of a single AMS and a single compressor per day					
Inter selections	111.1350	15.8764	3.8520	0.5448	2.0316
All selections	7751.7789	18.6341	–	–	–
Total	7862.9139	–	–	–	–
$F > F_{krit}$ (the alternative hypothesis is true) – the overall electricity consumption is dependent on electricity consumption by a single AMS and a single assembly compressor per day					
Analysis of variance of the total electricity consumption per milking					
Inter selections	0.0026	0.0004	2.4557	0.1815	2.0316
All selections	0.1064	0.0003	–	–	–
Total	0.1089	–	–	–	–
$F > F_{krit}$ (the alternative hypothesis is true) – the overall electricity consumption is dependent on electricity consumed per milking					
Analysis of variance of total energy consumption per 1 l of milk					
Inter selections	0.0001	0.0059	2.1444	0.0382	2.0316
All selections	0.0012	0.0028	–	–	–
Total	0.0013	–	–	–	–
$F > F_{krit}$ (the alternative hypothesis is true) – the overall electricity consumption is dependent on the electricity consumption spent on milking of 1 l of milk					

The resulting measured values of selected parameters affecting the total energy consumption of AMS are shown in Table 3.

The comprehension of electricity consumption of cattle dairy farms is essential not only in terms of optimising energy consumption for the sake of environmental protection,

Table 3 The average values of selected parameters in terms of the total AMS's electricity consumption in the monitored herds

Min	Max	Mean	Standard deviation
Number of animals in herd (pcs)			
95.000	105.00	99.790	2.782
Number of milkings in herd per day			
254.347	291.148	273.025	8.336
Amount of milk milked per day (l)			
2460.000	2738.377	2599.871	63.619
Electricity consumption by a single AMS unit per day (kWh)			
30.303	34.750	32.287	0.969
Number of operation hours of assembly compressor per day (h)			
7.645	13.312	10.358	1.499
Electricity consumption by assembly compressor per day (kWh)			
20.673	38.196	28.106	4.234
Total electricity consumption per day (kWh)			
51.793	71.775	60.393	4.306
Electricity consumption per milking (kWh)			
0.189	0.259	0.221	0.016
Electricity consumption per 1 l of milked milk (kWh)			
0.020	0.027	0.023	0.002

but also for ensuring the food and energy security of the respective region. Concurrently, the overall optimisation of electricity consumption of a given region or country is highly topical, which is especially vital under the conditions of Central European countries. In addition to monitoring and evaluating the energy intensity of farms, the options for reducing the dependence on energy produced from fossil fuels include expansion in terms of the utilisation of renewable energy sources, e.g., by employing photovoltaic systems. Design proposals for the adoption of photovoltaic systems – which are already almost standard in newly established or reconstructed agricultural farms in Central Europe (Neto and Lopes, 2020) – represent a clear trend and can significantly influence the overall energy balance of a given agricultural facility.

In contrast to conventional milking methods (Ózsvári and Iványos, 2021) – in which the consumption of both electricity and water (Vaculík et al., 2021) is largely affected by the discipline of operators – it is possible to infer that electricity consumption when using AMS is not influenced by operator's activity, but by a number of other factors, which primarily include the management of the herd employed at the given farm, herd milk yield, the number of detections of non-consumable milk (which is clearly related to the health of animals), current climatic conditions, as well as unwarranted visits to the AMS as reported by Stefanowska et al. (1999).

The measured values of electricity consumption and milking processes using AMS are in accordance with the values published in the articles by Přikryl et al. (2016) or Boďo et al. (2022).

Additionally, the genetic potential of dairy cows and the variety of forages also represent vital factors in the assessment of milking by AMS and milk quality (Kyselová et al., 2019; Piwczyński et al., 2020).

The essential prerequisites for an optimal husbandry of dairy cows, or rather optimal electricity consumption during milking using AMS, are the consistent following of all principles resulting from the employment of AMS and optimal farm management (Sitkowska et al., 2020; Kolenda et al., 2021). Ultimately, it is always important to search for and adhere to appropriate solutions that prevent, e.g., the occurrence of stress in animals (Lürzel et al., 2018; Boďo et al., 2022), and observe the relevant welfare principles of cattle husbandry (Jago and Kerrisk, 2011) not only with regard to energy requirements.

Conclusion

The following values were determined based on the results from the monitoring of selected parameters affecting the total electricity consumption of AMS at selected dairy – i.e., in groups with an average of 100 dairy cows.

The electricity consumption of a single AMS in the assessed herds ranged from 30.30 to 34.75 kWh per AMS per day. There are numerous factors influencing this electricity consumption, which occur randomly. The measurement results show that a single AMS's average electricity consumption was 32.29 kWh per AMS per day over the entire observed period.

The electricity consumption of the assembly compressor ranged from 20.67 to 38.20 kWh per compressor per day. The difference in the values of assembly compressor operation

per day are caused by a number of factors, e.g., the number of rejected dairy cows, the time necessary for putting on the teat cups, milk yield, machinery layout within the housing area, or the location of individual groups of animals in barn. On the basis of the amount of energy consumed by the assembly compressor, the average compressor energy consumption was 28.11 kWh per compressor per day during the entire observed period.

In the monitored herds of dairy cows, the total electricity consumption of a single AMS and a single compressor ranged from 51.79 to 71.78 kWh per day over the entire observed period. Although the values of total electricity consumption of a single AMS and a single compressor are different, they can be considered relatively balanced over the entire observed period. The average electricity consumption was 60.39 kWh per day over the entire observed period.

The determined values of electricity consumption per milking ranged from 0.19 to 0.26 kWh per milking. On average, the amount of electricity consumed per milking was 0.22 kWh per milking over the entire monitored period. The determined values of electricity consumption per 1 l of milked milk range from 0.0200 to 0.0274 kWh per 1 l of milk. The amount of electricity consumed per 1 l of milked milk was 0.0232 kWh per 1 l of milk on average over the entire observed period.

The ANOVA at a 0.05 significance level showed that the total electricity consumption is dependent on the electricity consumption of a single AMS and a single compressor per day, electricity consumption per milking, and electricity consumed per milking of 1 l of milk.

The measurement results indicate that the total electricity consumption is not completely constant throughout the year, but it fluctuates. The results obtained at the evaluated farms suggest that the total electricity consumption is influenced by the manner in which the herd is managed (herd management), milk yield, and the current status of herd health rather than by the AMS properties.

Ultimately, it can be concluded that milking with the employment of the AMS allows for careful and frugal energy management, regardless of, e.g., employee discipline, which frequently represents a major issue in conventional milking methods.

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