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Analysis of electric energy consumption of automatic milking systems in different configurations and operative conditions

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ABSTRACT

Automatic milking systems (AMS) have been a revolutionary innovation in dairy cow farming. Currently, more than 10,000 dairy cow farms worldwide use AMS to milk their cows. Electric consumption is one of the most relevant and uncontrollable operational cost of AMS, ranging between 35 and 40% of their total annual operational costs. The aim of the present study was to measure and analyze the electric energy consumption of 4 AMS with different configurations: single box, central unit featuring a central vacuum system for 1 cow unit and for 2 cow units. The electrical consumption (daily consumption, daily consumption per cow milked, consumption per milking, and consumption per 100 L of milk) of each AMS (milking unit + air compressor) was measured using 2 energy analyzers. The measurement period lasted 24 h with a sampling frequency of 0.2 Hz. The daily total energy consumption (milking unit + air compressor) ranged between 45.4 and 81.3 kWh; the consumption per cow milked ranged between 0.59 and 0.99 kWh; the consumption per milking ranged between 0.21 and 0.33 kWh; and the consumption per 100 L of milk ranged between 1.80 to 2.44 kWh according to the different configurations and operational contexts considered. Results showed that AMS electric consumption was mainly conditioned by farm management rather than machine characteristics/architectures.
Key words: automatic milking system, electric energy consumption, dairy farm management

INTRODUCTION

Automatic milking has been a revolutionary innovation in dairy cow farming. Switching from conventional milking to automatic milking results in big changes for both the farmers and the animals, requiring a different concept of herd management. The labor routine and the cow behavioral routine are modified, some conventional tasks are cancelled, while new activities become necessary (Spahr and Maltz, 1997). Changing of the nature of labor and computerized monitoring of individual animals are probably the greatest innovations related to robotic milking. Moreover, automatic milking enables milking frequency to be controlled on an individual cow basis, according to her production level or stage of lactation, without incurring extra labor costs. All else being equal, cows milked more frequently throughout a lactation usually tend to produce greater amounts of milk compared with cows milked twice a day (Castro et al., 2012; Jacobs and Siegford, 2012; Stelwagen et al., 2013; Wright et al., 2013). These aspects offer many potential advantages, while at the same time opening new challenges with the potential for a major drawback. The initial investment can be greater than that for a traditional system, and robotic equipment may not last as many years (Rotz et al., 2004). Thus, when deciding between investing in automatic or conventional milking systems, dairy producers must weigh the decreased labor needs of the automatic milking system (**AMS**) against the increased fixed costs (Jacobs and Siegford, 2012). Furthermore, an accurate analysis of the AMS operational costs has to be carried out considering that electric consumption is one of the most relevant and uncontrollable balance items, ranging between 35 and 40% of the total annual operational costs.

More than 10,000 dairy cow farms worldwide use AMS to milk their cows and this figure is expected to grow in the next years (de Koning, 2011; Lyons et al., 2014), increasing the energy consumption related to AMS. On the other hand, the removal of the milk quotas in the European Union in 2015 is likely to increase milk production per farm, possibly generating a drop in the milk price (Lips and Rieder, 2005; Bouamra-Mechemache et al., 2008). Therefore, dairy farmers have to focus on cost control of the milk production system and the efficient use of energy as one way to improve the cost competitiveness. Quantifying energy consumption is essential to achieve this objective.

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Different studies (Artmann and Bohlsen, 2000; Bijl et al., 2007) showed greater electricity costs with AMS in comparison to conventional milking systems, although these studies did not give detailed component breakdown information. Electricity and water consumption of AMS and conventional milking parlor were investigated in a farm test by Rasmussen and Pedersen (2004). A more recent study by Upton and O'Brien (2013) analyzed the energy consumption of an AMS as operated within a grass-based, seasonally calved dairy production in Ireland, highlighting that the largest energy-demanding processes associated with milk harvesting in the AMS were heating water, compressing air, and cooling milk.

Compared with previous studies, new AMS have been launched and previous models have been improved in recent years. The energy used by AMS depends on many factors (e.g., machine generations, machine configurations and settings, and operative conditions). The aim of the present study was to investigate the electricity consumption of 2 subsequent generations of the most diffused AMS installed in dairy farms of Northern Italy (about 80% of the current installations). The focus was to measure the electric consumption of these AMS under practical conditions in different operational contexts.

MATERIALS AND METHODS

The study was carried out at 4 dairy farms, all located in Lombardy Region (Northern Italy) and equipped with Lely Astronaut A3 Next (Lely Holding, Maassluis, the Netherlands) single box (farm 1) and Lely Astronaut A4 (Lely Holding) with a central unit featuring a central vacuum and cleaning system for one cow unit (farm 2) or 2 cow units (farm 3 and farm 4). All tests were carried out in the same period (winter 2014). The main characteristics and settings of the AMS tested are summarized in Table 1.

Free cow traffic was adopted in all the farms. Vacuum for milking was supplied by a frequency-controlled lobe vacuum pump powered by a 1.1- and 1.3-kW motor for the A3 and A4 AMS, respectively. Compressed air for opening/closing the entrance and exit gates of the milking stall and for moving the robotic arm toward the udder was supplied by a 3.7-kW scroll compressor (SF4, Atlas Copco AB, Stockholm, Sweden) in the A4 milking systems installed in farms 2, 3, and 4. A 7.5-kW rotary screw compressor (K-MID 10, Fini Nuair S.p.A., Turin, Italy) was used in the A3 installed in farm 1. In the latter case, the air compressor served a second unit A3 not involved in the test, so its electricity consumption was shared equally between the 2 units. All the AMS were equipped with the Pura steam cleaning system (Lely Holding) to clean the milk unit with hot steam (temperature about 150°C) between every milking. The Pura system of the A4 installed in farm 3 was disabled as decided by the farmer, and the milk unit was cleaned only with water at room temperature between every milking.

Experimental Measurements

All AMS were powered by Three-Phase 380 V/50 Hz. The electrical power absorbed by each AMS (milking unit + air compressor) was measured using 2 three-phase power and energy analyzers Qualistar CA 8334 with internal memory (Chauvin Arnoux Metrix, Paris, France) applied to the AMS and to the compressor electricity panels (Figure 1A). In the energy use of AMS milking unit are included vacuum and milk pumps, electric and electronic devices (printed circuit board, touch screen, frequency inverter, and so on), actuators, water heater, and steam cleaning system.

The Power and Energy Analyzer used alligator clips and current clamps connected to each phase line and neutral to measure, respectively, voltages and currents. To operate safely and in agreement with the International Electrotechnical Commission, between the AMS electricity panel and both the milking unit and the air compressor, a 5-pole 16 A International Electrotechnical Commission extension plug was inserted and, on the same extension plug, the alligator clips and current clamps were connected (Figure 1B).

Table 1. Main characteristics and settings of the automatic milking system (AMS) monitored

Item	Cows milked	AMS[1]	Control unit	Milking unit	Installation date	Working vacuum (kPa)	Pulsation frequency (beats/min)	Pulsation rate
1	61	A3 Next	1	1	2010	43	60	65:35
2	68	A4	1	1	2013			
3	117	A4	1	2	2012			
4	117	A4	1	2	2013			

[1]A3 Next = Lely Astronaut A3 Next (Lely Holding, Maassluis, the Netherlands); A4 = Lely Astronaut A4 (Lely Holding).

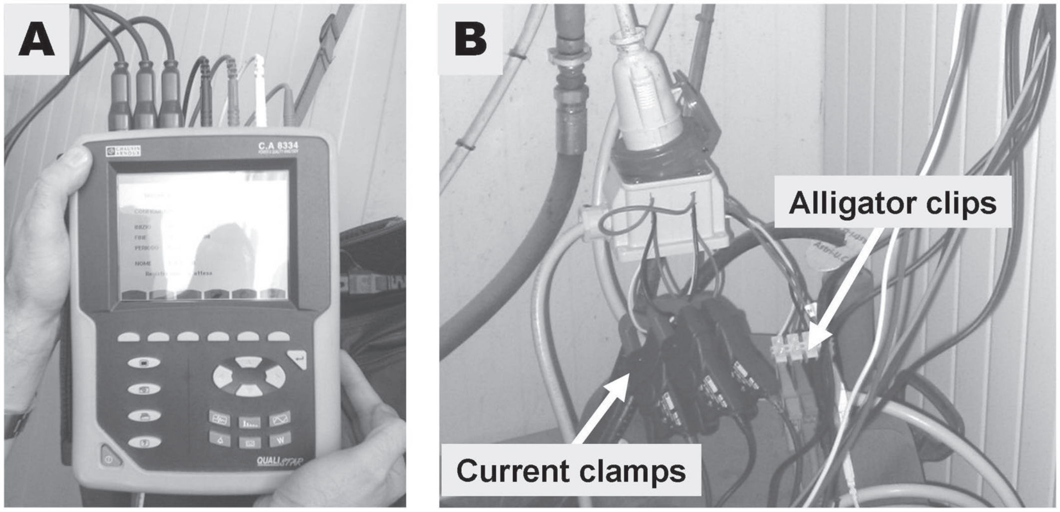

Figure 1. (A) The Qualistar CA 8334 analyzer (Chauvin Arnoux Metrix, Paris, France), and (B) the connection between the analyzer and the automatic milking system (AMS) electric line.

On each phase, the following parameters were measured: root mean square voltage (V), root mean square current (A), power (W), power factor cos ϕ.

The measurement period lasted 24 h for each AMS (milking unit + air compressor) with a sampling frequency of 0.2 Hz (one sample every 5 s). Data were recorded into the Power and Energy Analyzer's internal memory and then downloaded, via RS232 interface, to a notebook. Using the software Qualistar View 2.4 (Chauvin Arnoux Metrix, Paris, France), data were exported as a CSV file for further processing in Excel (Microsoft Corp., Redmond, WA).

The electrical power absorbed (W_t, kW) by the milking unit and the air compressor of each AMS was expressed by the following equation:

$$W_t = W_{L1} + W_{L2} + W_{L3}, \quad [1]$$

where W_{L1}, W_{L2}, and W_{L3} = electrical power absorbed, respectively, on phases 1, 2, and 3.

The electrical energy used per day (E_{Ed}, kWh) by the milking unit and by the air compressor of each AMS was calculated by the following equation:

$$E_{Ed} = \frac{\sum W_t \cdot \Delta_t}{n}, \quad [2]$$

where n = number of samples collected in 24 h (one sample every 5 s for a total of 17,280 samples/24 h).

Finally, the total electrical energy used per day (E_{ESd}, kWh) by each AMS was calculated, adding the electrical energy demanded by the milking unit and by the air compressor, as

$$E_{ESd} = E_{Ed\text{Milking unit}} + E_{Ed\text{Air compressor}}. \quad [3]$$

Cow and Milk Data

Data including number of cows milked (n/AMS), daily milk yield (L/AMS), average daily milk yield per cow (L/cow), visiting box time (h/d), average milk harvesting rate (L/min), daily number of milkings (n/AMS), and daily number of milkings per cow (n/cow) were automatically collected for each AMS by the Lely T4C management software (Lely Holding).

Electricity Consumption

The following values of electricity consumption were calculated for each AMS: daily consumption, daily consumption per cow milked, consumption per milking, and consumption per 100 L of milk.

RESULTS AND DISCUSSION

The number of cows milked was 61 for the A3 Next single box (farm 1), 68 for the A4 with one cow unit (farm 2), and 117 for both the 2 A4 with 2 cow units installed on farm 3 and farm 4.

The number of milkings carried out in the single-box AMS was similar ranging between 183 and 189 milkings per 24 h. The AMS with 2 cow units showed a differ-

Table 2. Electricity consumption of the automatic milking system (AMS) tested

Farm	Milking unit consumption per day (kWh)	Air compressor consumption per day (kWh)	Total consumption per day (kWh)	Total consumption per cow (kWh)	Total consumption per milking (kWh)	Total consumption per 100 L of milk (kWh/100 L)
1	19.97	40.35	60.32	0.99	0.33	2.44
2	28.82	16.61	45.43	0.67	0.24	2.07
3	36.71[1]	32.11	68.82[1]	0.59[1]	0.21[1]	1.80[1]
4	51.52	29.82	81.34	0.70	0.27	2.25
Average	34.26	29.72	63.98	0.74	0.26	2.14

[1]Pura steam cleaning system disabled.

ence of about 10% in the number of milkings, which ranged between 271 and 298 milkings per 24 h.

The average number of milkings per cow per 24 h ranged between 2.8 and 3.0 and between 2.6 and 2.8, respectively, in the single-box AMS and in the AMS with 2 cow units.

The daily milk production varied between 2,193 and 2,470 L for the single-box AMS and between 3,609 and 3,827 L for the AMS with 2 cow units. The daily milk production per cow varied between 32.2 and 40.5 L for the single-box AMS and between 30.8 and 32.7 L for the AMS with 2 cow units.

The range in the average visiting box time (calculated as the difference between the time of entry to the AMS box and the time of exit from the box) and in the average milk harvesting rate was, respectively, 5.82 to 6.13 min and 1.99 to 2.20 L of milk/min for single-box AMS. In the AMS with 2 cow units, the average visiting box time and the average milk flow varied, respectively, between 5.83 and 7.06 min and between 1.71 to 2.01 L milk/min.

The single-box AMS were occupied by cows for a similar number of hours during a day, ranging between 18.3 and 18.7 h/d that equated to an overall occupation rate of 76.3 to 77.9%. For the AMS with 2 cow units, the visiting box time per day varied between 15.9 and 17.6 h/d, equating to an overall occupation rate of 66.3 to 72.9%. The washing time was approximately 1 h/d including 3 main washing period of about 20 min each for all the AMS investigated.

The electricity consumption per AMS is summarized in Table 2. The daily total energy consumption (milking unit + air compressor) for the A3 Next single box (farm 1) and the A4 with one cow unit (farm 2) was at 60.3 and 45.4 kWh, respectively. The difference between the 2 systems was mainly due to the rotary screw compressor used in the A3 Next, that was oversized compared with the real needs and less efficient compared with the scroll compressor used in the A4. The daily electricity consumption of the 2 air compressors represented about 66.8 and 36.6% of the daily total electricity consumption, respectively, recorded in the A3 Next and A4 systems. The milking unit of the A3 Next consumed 20.0 kWh per 24 h, whereas A4 milking unit consumed 28.8 kWh. This difference could be mainly due to the robot arm and to the vacuum pump of the 2 AMS. In the A4 system, the former's air-operated ram for horizontal movements has been replaced with an electric drive that in our field test showed a 24-h consumption of about 3.0 kWh. The vacuum pump is actuated by an electric motor 15% more powerful than in the A3 Next (1.3 vs. 1.1 kW). The AMS electricity consumption per cow milked, milking, and 100 L of milk was 0.99, 0.33, and 2.44 kWh for the A3 Next, whereas they were 0.67, 0.24, and 2.07 kWh for the A4 with one cow unit. In a farm test carried out in 2002 on a different Lely Astronaut single-box AMS, Rasmussen and Pedersen (2004) highlighted an average daily electricity consumption of 18 kWh for the compressor and 19 kWh for the milking unit, with the daily number of milking cows 57 to 60, the number of milkings at 146 to 184/d, and milk production ranging between 1,448 and 2,006 L/d. In those conditions, the authors measured electricity consumption per cow milked, per milking, and per 100 L of milk, ranging, respectively, between 0.63 and 0.64 kWh, 0.21 and 0.25 kWh, and 2.00 and 2.06 kWh. These values are comparable with the electric consumption of the A4 with one cow unit analyzed in our field test.

The 24-h total electricity consumption (milking unit + air compressor) for the A4 with 2 cow units was at 68.8 kWh (farm 3) and 81.3 kWh (farm 4). The 24-h electricity consumption of the 2 air compressors were, respectively, 32.1 and 29.8 kWh, representing about 47 and 37% of the 24-h total electricity consumption. The milking unit of the A4 installed at farm 3 consumed 36.7 kWh per 24 h, whereas A4 milking unit of farm 4 consumed 51.5 kWh. This difference (29%) was mainly due to a difference of the teat cups cleaning system between all milkings. At farm 4, the Lely Pura cleaning system was in order and the teats cups were cleaned with heated steam (150°C) followed by a short rinse with plain water, whereas at farm 3 the Pura system was disabled by the farmer and the teat cups were rinsed only with plain water. This choice, while providing significant energy savings, could have adverse effects on udder health status (i.e., mastitis), with higher veterinary costs, milk yield losses, and poor milk quality (Mutze et al., 2009). The higher 24-h electricity consumption of the A4 milking unit installed at farm 4 could be also ascribed to the average visiting box time, which is 17% (7.06 vs. 5.83 min) higher than in farm 3. The AMS electricity consumption per cow milked, milking, and 100 L of milk was 0.59, 0.21, and 1.80 kWh at farm 3, whereas at farm 4 the consumption was, respectively, 0.70, 0.27, and 2.25 kWh.

The A4 with 1 cow unit and the A4 with 2 cow units installed, respectively, in farms 2 and 4, were characterized by different number of milkings/d (189 vs. 298) and average milk production/cow (32.2 vs. 30.8 L). The total visiting box time for box was similar (18.3 vs. 17.6 h/d) and the occupation of the 2 AMS was used to calculate the electricity consumption per hour of box occupation. The A4 with one cow unit had an electric consumption of 2.5 kWh/box, whereas the A4 with 2 cow units showed an electric consumption of 2.3 kWh/box. This slight difference would seem to make the choice between the 2 AMS not dependent on energetic considerations but primarily on the purchase price (the A4 with 2 cow units cost about 15% less than 2 A4 with 1 cow unit) and the barn layout.

CONCLUSIONS

The AMS tested showed electric consumption mainly conditioned by farm management (i.e., use of the steam cleaning system for the teat cups, and choice of an efficient and correctly sized air compressor for opening/closing the entrance and exit gates of the milking stall and for moving the robotic arm toward the udder) rather than machine characteristics/architectures. In the Astronaut A4, the electricity consumption per hour of box occupation was similar independent of the number of cow units (1 or 2) when the total visiting box time for the box and the machine settings were equal. This suggest that the electricity consumption is not the key factor in choosing between the 2 different Astronaut A4 architectures.

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REFERENCES

Artmann, R., and E. Bohlsen. 2000. Robotic milking. Pages 221–231 in Proc. Int. Symp. Lelystad, The Netherlands, 17–19 August 2000. Wageningen Press, Wageningen, the Netherlands.

Bijl, R., S. R. Kooistra, and H. Hogeveen. 2007. The profitability of automatic milking on Dutch dairy farms. J. Dairy Sci. 90:239–248. http://dx.doi.org/10.3168/jds.S0022-0302(07)72625-5.

Bouamra-Mechemache, Z., R. Jongeneel, and V. Réquillart. 2008. Removing EU milk quotas, soft landing versus hard landing. Pages 1–13 in 12th Congress of the European Association of Agricultural Economists–EAAE 2008. People, Food and Environments: Global Trends and European Strategies, 26–29 August 2008, Ghent, Belgium.

Castro, A., J. M. Pereira, C. Amiama, and J. Bueno. 2012. Estimating efficiency in automatic milking systems. J. Dairy Sci. 95:929–936. http://dx.doi.org/10.3168/jds.2010-3912.

de Koning, K. 2011. Automatic milking: Common practice on over 10,000 dairy farms worldwide. Pages 14–31 in Proc. Dairy Research Foundation Symp. 2011. The University of Sydney, Camden, Australia, Camden, NSW, Australia,.

Jacobs, J. A., and J. M. Siegford. 2012. *Invited review:* The impact of automatic milking systems on dairy cow management, behavior, health, and welfare. J. Dairy Sci. 95:2227–2247. http://dx.doi.org/10.3168/jds.2011-4943.

Lips, M., and P. Rieder. 2005. Abolition of raw milk quota in the European Union: A CGE analysis at the member country level. J. Agric. Econ. 56:1–26. http://dx.doi.org/10.1111/j.1477-9552.2005.tb00119.x.

Lyons, N. A., K. L. Kerrisk, and S. C. Garcia. 2014. Milking frequency management in pasture-based automatic milking systems: A review. Livest. Sci. 159:102–116. http://dx.doi.org/10.1016/j.livsci.2013.11.011.

Mutze, K., W. Wolter, T. Bonsels, and H. Bernhardt. 2009. Milking hygiene and milk quality in Hessian dairy farms with automatic milking systems. Landtechnik 64:436–438.

Rasmussen, J. B., and J. Pedersen. 2004. Electricity and water consumption at milking. Farm Test–Cattle nr. 17, 1–42. Danish Agricultural Advisory Service.

Rotz, A., K. Soder, and S. Riley. 2004. Is Robotic Milking a Viable Option? USDA/Agricultural Research Service, Penn State University. Accessed Jun. 10, 2015. http://extension.psu.edu/animals/dairy/news/2004/is-robotic-milking-a-viable-option.

Spahr, S. L., and E. Maltz. 1997. Herd management for robot milking. Comput. Electron. Agric. 17:53–62. http://dx.doi.org/10.1016/S0168-1699(96)01225-2.

Stelwagen, K., C. V. Phyn, S. R. Davis, J. Guinard-Flament, D. Pomiès, J. R. Roche, and J. K. Kay. 2013. Invited review: Reduced milking frequency: Milk production and management implications. J. Dairy Sci. 96:3401–3413. http://dx.doi.org/10.3168/jds.2012-6074.

Upton, J., and B. O'Brien. 2013. Analysis of energy consumption in robotic milking. Proceedings of 6th European Conference on Precision Livestock Farming. Leuven, Belgium, 10–12 September 2013, 465–470.

Wright, J. B., E. H. Wall, and T. B. McFadden. 2013. Effects of increased milking frequency during early lactation on milk yield and udder health of primiparous Holstein heifers. J. Anim. Sci. 91:195–202. http://dx.doi.org/10.2527/jas.2012-5692.