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A mechanistic model for electricity consumption on dairy farms: Definition, validation, and demonstration

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ABSTRACT

Our objective was to define and demonstrate a mechanistic model that enables dairy farmers to explore the impact of a technical or managerial innovation on electricity consumption, associated CO_2 emissions, and electricity costs. We, therefore, (1) defined a model for electricity consumption on dairy farms (MECD) capable of simulating total electricity consumption along with related CO_2 emissions and electricity costs on dairy farms on a monthly basis; (2) validated the MECD using empirical data of 1 yr on commercial spring calving, grass-based dairy farms with 45, 88, and 195 milking cows; and (3) demonstrated the functionality of the model by applying 2 electricity tariffs to the electricity consumption data and examining the effect on total dairy farm electricity costs. The MECD was developed using a mechanistic modeling approach and required the key inputs of milk production, cow number, and details relating to the milk-cooling system, milking machine system, water-heating system, lighting systems, water pump systems, and the winter housing facilities as well as details relating to the management of the farm (e.g., season of calving). Model validation showed an overall relative prediction error (RPE) of less than 10% for total electricity consumption. More than 87% of the mean square prediction error of total electricity consumption was accounted for by random variation. The RPE values of the milk-cooling systems, water-heating systems, and milking machine systems were less than 20%. The RPE values for automatic scraper systems, lighting systems, and water pump systems varied from 18 to 113%, indicating a poor prediction for these metrics. However, automatic scrapers, lighting, and water pumps made up only 14% of total electricity consumption across all farms, reducing the overall impact of these poor predictions. Demonstration of the model showed that total farm electricity costs increased by between 29 and 38% by moving from a day and night tariff to a flat tariff.

Key words: energy, electricity, milk production, mechanistic model

INTRODUCTION

Grass-based production of 1 L of milk leaving the farm gate (i.e., including on-farm energy consumption and energy consumption of farm inputs) requires a total energy input of about 2.5 MJ (Upton et al., 2013). On Irish farms, about 12% of this energy use is represented by electricity consumption, of which 60% is used in the period with the highest tariff (i.e., from 0900 to 2400 h).

Innovations that reduce on-farm electricity consumption might not only reduce total energy consumption of milk production but also electricity costs and CO_2 emissions related to energy consumption. Reducing electricity costs might be attractive to farmers, because electricity prices have increased by 32% in the last 5 yr for European farmers (Eurostat, 2013). Moreover, European dairy farmers are approaching a period of change driven by the removal of the milk quota regimen. Without a quota regimen, farmers are allowed to produce milk unrestrictedly, which is expected to cause increased volatility of the milk price, ultimately resulting in volatility in farm profitability (Lips and Rieder, 2005).

An increase in price volatility warrants attention for cost price minimization. By 2020, however, 80% of all electricity consumers in Ireland are expected to be connected to the smart grid (CER, 2011). The new Irish electricity grid infrastructure implies a pricing system based on the electricity demand on the national grid, resulting in higher electricity rates during peak periods of consumption and lower rates during off-peak periods. Peak demand is currently from 1700 to 1900 h. If dairy farmers carry out their evening milking during this peak period, they may be exposed to increases in energy costs under the dynamic pricing structure. This dynamic pricing structure, however, could also

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present opportunities to reduce overall energy costs if equipment is managed intelligently to optimize energy consumption in off-peak periods (currently from 0000 to 0900 h) (Upton et al., 2013). Evaluation of the potential effect of electricity pricing tariff changes on dairy farm electricity costs requires the development of a specific electricity consumption model.

Similarly, changing one technology in favor of another (e.g., the addition of a water-cooled plate heat exchanger to precooled milk) or one management strategy over another (e.g., milking once or twice per day), however, not only affects electricity costs of producing milk but also energy consumption and associated CO_2 emissions. A model that supports decision making of one innovation over another, therefore, should not only evaluate the impact of technology, management practices, and pricing structures on the electricity costs of a farm, but also predict the impact of that innovation on energy consumption and associated CO_2 emissions. To our knowledge, such a decision-support model has not been reported. The aim of this study was to define and demonstrate a mechanistic model that enables dairy farmers to explore the impact of a technical or managerial innovation on electricity consumption, associated CO_2 emissions, and electricity costs. We, therefore, first defined the model for electricity consumption on dairy farms (**MECD**). Subsequently, we validated this model by comparing model outputs with empirical data on farm electricity consumption gathered through a physical auditing process. Finally, we demonstrated an application of the model by evaluating the effect of 2 electricity pricing tariffs on total dairy farm electricity costs.

MATERIALS AND METHODS

Model Definition

The model described in this paper was developed to predict the electricity consumption, associated CO_2 emissions, and electricity costs on dairy farms. The model is a mechanistic mathematical representation of the electricity consumption under the following key headings: milk-cooling system, water-heating system, milking machine system, lighting systems, water pump systems, and winter housing facilities (Figure 1). A monthly time step was chosen because milk production information is available from all commercial farms at the end of each month.

Electricity Consumption Calculations

The model used key inputs such as monthly herd milk yield, number of cows, and farm infrastructure details (e.g., milk tank size and vacuum pump size, among others) and management practices (e.g., grazing season length), and calculated the electricity consumed by each of the 7 infrastructural systems for 24 h on 1 d each month. Further key inputs of electricity pricing tariff structure and CO_2 emission factors were then applied to compute component running costs and CO_2 emissions on a monthly basis. All inputs, calculations, and outputs were based on a month × daily hour (12 × 24) matrix structure.

Milk Cooling. The milk-cooling electricity consumption was computed using Equation 1:

$$Q_{mc}(i,j) = \frac{C_m \times \Delta T(i,j) \times M_m(i,j)}{COP(i,j) \times 3{,}600}, \quad [1]$$

where

$$\Delta T(i,\ j) = T_{bulk}(i,\ j) - T_{final} \quad [2]$$

and

$$COP(i,j) = \left[\frac{T_{evap}}{T_{amb}(i,j) - T_{evap}}\right] \times a, \quad [3]$$

where $Q_{mc}(i,\ j)$ = predicted energy consumption for milk cooling in month i (1–12) and hour j (1–24; kWh), C_m = specific heat capacity of milk [kJ/(kg·°C)], and $\Delta T(i,\ j)$ = difference in temperature between the milk entering the storage tank [$T_{bulk}(i,\ j)$] and the milk tank set point (T_{final}; °C). The $T_{bulk}(i,\ j)$ was calculated using information about plate cooling from Upton et al. (2010) assuming a milk:water flow ratio of 1:2 in the plate cooler using ground water temperatures from a 100-m borehole well from Goodman et al. (2004). The variable $M_m(i,\ j)$ was the mass of milk in month i and hour j to be cooled (kg). It was assumed that 60% of the milk was extracted in the morning milking (O'Callaghan and Harrington, 2000). The variable $COP(i,\ j)$ was the milk-cooling system coefficient of performance (**COP**; dimensionless). A submodel was developed to compute the cooling system COP based on a modified Carnot cycle (ideal refrigeration cycle) formula, as described by Henze and Krarti (1998). This approach allows the COP of a specific cooling system to vary according to ambient temperature. It was not designed to represent exactly the vapor compression refrigeration cycle performance of an individual cooling system but rather provide a dynamic element to the COP value of a generalized direct expansion (**DX**) or ice bank (**IB**) cooling system. The variable T_{evap} was the evaporator temperature of the refrigeration system [assumed to be 268 Kelvin (K) for DX and 265 K for