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Development and Validation of the Beef Farm Electricity Model[#]

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ABSTRACT

The objective of this paper was to define and demonstrate a model that simulates electricity consumption on pasture-based beef farms. The Beef Farm Electricity Model (BFEM) was designed to simulate electricity consumption across beef farm operations, including water pumping, electric fencing, lighting, and other electrically powered infrastructure. BFEM employed grey box modelling techniques that utilised empirical data for tuning model parameters and was trained using empirical data from 12 pasture-based Irish beef farms. The results showed strong agreement between simulated and actual electricity use, with moderate predictive accuracy for water pumps (RMSE = 12.79 kWh, MAPE = 8.13%) and lighting systems (RMSE = 9.53 kWh, MAPE = 11.00%). Prediction accuracy for electric fence electricity use was lower (RMSE = 9.85 kWh, MAPE = 58.46%). These findings demonstrated BFEM's potential as a decision-support resource for energy auditing, infrastructure planning, and facilitating the integration of renewable energy systems on beef farms.

Keywords: beef farm electricity, electricity demand modelling, grey box modelling, farm energy use

1. INTRODUCTION

Agriculture is a major contributor to global greenhouse gas (GHG) emissions, accounting for approximately 22% of total GHG emissions worldwide [1] and 37.8% [2] of Ireland's national GHG emissions. Electricity consumption on Irish beef farms has been estimated to account for less than 13% of total emissions on beef farms [3]. However, electrical emissions are relatively easy to abate via renewable energy integration and improved energy efficiency.

Previous studies on energy and GHG modelling of beef systems focused mainly on whole-farm or life cycle assessments [4, 5]. These studies did not simulate farm-level electricity consumption. Irish beef production is predominantly pasture-based. Cattle typically graze from spring to autumn (March - November) and are housed during winter months (December - February). Energy use on pasture-based beef farms can vary considerably between seasons, with greater electricity demand occurring during the winter housing period.

Multiple studies have developed models to assess dairy farm electricity consumption, CO_2 emissions, and cost efficiency. These highlight the progress in dairy farm electricity-focused modelling and decision-support tools [6, 7, 8]. However, similar research is lacking for pasture-based beef farms. This study aims to address this gap through the following objectives:

- Develop a model to simulate electricity demand on pasture-based beef farms.
- Validate the model's accuracy using empirical data from 12 pasture-based beef farms.

2. MATERIAL AND METHODS

BFEM was developed using MATLAB Simulink (version 2023b).

2.1 Data acquisition

Power data (W) were monitored using a Fluke 1732 Energy Logger (Fluke Corporation, Washington, USA) on 12 beef farms spread across eight counties in the Republic of Ireland. A diverse representation of farms was selected for measurement based on farm size and operational system. Farm-level power data were recorded for the main electricity-consuming subsystems, including water pumps, electric fences, lights, automatic feeders and other miscellaneous sources. The readings were collected in 15-minute intervals for two 10-day periods for each farm during grazing (July 2024 – August 2024) and winter housing (December 2024 – March 2025). In addition to the energy data, farm energy use practices and infrastructure information were collected through on-site surveys.

2.2 Data pre-processing

The recorded power data were not normally distributed; therefore, a modified z-score method was

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applied to identify and remove outliers, using a threshold of ±3.5 standard deviations. All missing or removed values were replaced using linear interpolation to maintain the dataset's temporal continuity. A total of 1.44% of the data were identified as outliers.

2.3 Model development and definition

BFEM is a mechanistic grey box model [6] that contains three main sub-models: a water pump model, an electric fence model, and a lighting model. Additionally, there are sub-models for automatic feeders and miscellaneous equipment. Calibration was performed to tune model parameters using empirical data.

Fig. 1 presents a schematic representation of a typical beef farm electricity system, illustrating the primary electricity-consuming subsystems, the external utility supply, and the dwelling house. The electric fence operates primarily during the grazing season, while the water pump operates year-round. In some instances, a water pump supplies water to the farm and the farm dwelling house; other farms receive their supply from group/public water schemes. Farm lighting systems are mainly active during the winter housing period. On calf-rearing farms, automatic feeders and water heating systems are typically used during the spring calf milk feeding period (March-April). Other miscellaneous equipment may include power washers and automatic animal brush grooming equipment. A summary of key characteristics of the farms included in this study is provided in Table 1.

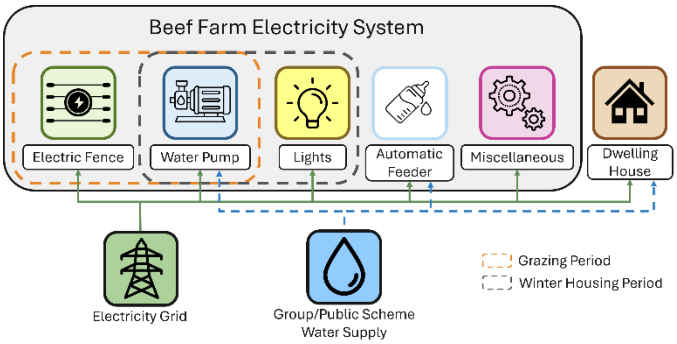

Fig. 1 Schematic of primary energy-consuming subsystems, external utility supplies and dwelling house

2.3.1 Water pump electricity demand sub-model

A water pump electricity demand sub-model was developed to estimate the electricity consumption associated with water supply on beef farms with private wells. This sub-model incorporates herd composition, livestock daily live weight gain, and the number of occupants in the farm dwelling to estimate overall farm water demand. Subsequently, the electricity requirement for water pumping systems was calculated.

Livestock live weight gain was simulated based on animal age and sex categories. Liveweight progression was determined based on standard average daily gain values for each category [9]. BFEM uses defined birth and transition weights to simulate livestock growth and life stage progression, with weights calculated using average daily gains over specific age periods. Calving distributions were generated using normal probability density functions constrained within farm-specific calving periods. Transition days for weaning and dairy calf purchases were also specified to capture key events affecting herd structure. Livestock water demand factors (L/kg live weight/day) corresponding to 10 °C [10] were used to calculate herd daily water demand. For farms that had a dwelling house situated on-site, a domestic water demand component was modelled using a standardised consumption rate (133 L/day/person) [11].

Equation (1) was used to calculate the total water pump electricity requirement, E_{pump} (kWh/L).

$$E_{pump} = \frac{P_{pump}}{C_{pump}} \quad (1)$$

Where P_{pump} was the rated power (kW), and C_{pump} was the estimated flow rate (L/h) of the water pump.

Equation (2) calculated the total water demand of the water pump, WD_{pump} (L).

$$WD_{pump} = (\alpha)N_o + WD_{feeder} + \sum_{i=1}^{n_c}(N_{l,i})(m_i)(\beta_i) \quad (2)$$

Where α was the water requirement per dwelling house occupant per day (L), N_o was the number of dwelling house occupants, WD_{feeder} was the water demand of automatic calf feeders (L), n_c was the total number of animal categories, i represents each animal category, $N_{l,i}$ was the number of livestock per animal category, m_i was the estimated live weight per animal (kg), and β_i was the water demand factor per kg of body weight per day (L/kg/day) for each animal category.

Equation (3) calculated the water demand of the automatic calf feeders.

$$WD_{feeder} = (\gamma_{milk})(V_{milk}) + (\gamma_{wash})(N_{feeder})(n_{wash}) \quad (3)$$

Where γ_{milk} was the water requirement to prepare 1 L of milk, V_{milk} was the total milk volume per day (L), calculated based on the number of calves fed and their average daily milk intake as described in Section 2.3.4, γ_{wash} was the water requirement per one wash cycle, N_{feeder} was the number of automatic feeders, and n_{wash} was the number of wash cycles per day.

Table 1 Farm specific characteristics

Variable	Farm Size	Enterprise	Stocking Rate	Electricity Consumption (measured over 10-day periods)							
				Total	Summer	Winter	Water Pump (Summer + Winter)	Electric Fence (Summer)	Lights (Winter)	Misc (Summer + Winter)	Automatic feeder (Summer)
Unit	ha		LU/ha	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
Farm 1	20.5	WB	0.82	52.53	12.73	39.81	43.57	2.01	6.95	-	-
Farm 2*	8.3	DB; DW	2.29	108.92	23.00	85.92	-	2.00	95.33	102.00	-
Farm 3	22	WB, FB; Other	2.27	265.01	22.33	242.68	162.23	-	102.79	-	-
Farm 4	142	DB	2.71	1751.24	77.55	1685.72	561.59	35.00	120.85	-	1003.26
Farm 5*	58	SB	2.30	110.35	11.83	107.07	-	5.53	31.21	50.95	-
Farm 6*	120	DB; SB	2.33	79.33	35.00	44.33	-	35.00	44.33	-	-
Farm 7*	44	SB	1.67	95.35	14.11	81.24	-	14.11	81.24	-	-
Farm 8*	36	DB; SB	1.46	104.06	16.55	87.51	-	16.55	87.51	-	-
Farm 9	39	SB	1.95	209.35	64.89	144.46	48.79	34.00	126.56	-	-
Farm 10	65	SB; Other	0.59	62.13	27.40	34.73	34.73	11.10	15.86	-	-
Farm 11	74	SB	0.97	181.57	77.34	104.23	129.01	37.13	15.20	-	-
Farm 12*	57	FB	1.95	36.28		36.28	-	8.91	19.48	16.80	-

ha = hectares, WB = Weanling to Beef, DB = Dairy calf to Beef, DW = Dairy calf to Weanling, FB = Forward store to Beef, SB = Suckler to Beef, kWh = kilowatt hours, '-' = not applicable, Misc = miscellaneous, * = farms with group/public water supply

Equation (4) calculated the total electricity consumption of the water pump, Q_{pump} (kWh).

$$Q_{pump} = (1+\tau)\left(WD_{pump}\right)\left(E_{pump}\right) \quad (4)$$

Where τ was the estimated leakage factor.
The optimum tuning parameters of the water pump energy demand sub-model were C_{pump} in Equation (1) and τ in Equation (4). Calibration methods described in section 2.3.6 were used to estimate these parameters.

2.3.2 Electric fence electricity demand sub-model

The electric fence sub-model was developed to estimate the electricity consumption of livestock containment during the grazing season. The sub-model calculates the electricity usage based on farm-specific fence system parameters, environmental factors, and farm management practices.

Equations (5) to (8) were used to calculate a fence energiser unit's total electricity consumption.

$$P_{out} = \frac{(E_{out})\left(f_{pulse}\right)}{\eta_{pulse}} \quad (5)$$

Where P_{out} was the output power (W), E_{out} was the energy per pulse output (J), f_{pulse} was the pulse repetition frequency (Hz), and η_{pulse} was the pulse efficiency.

$$P_{leak} = \left(f_{veg}\right)\left(L_f\right)(d)\left(V_{pulse}\right) \quad (6)$$

Where P_{leak} was the leakage power losses (W), f_{veg} was the estimated leakage current due to vegetation/ faults (A/km), L_f was the fence length (km), d was the duty cycle, and V_{pulse} was the pulse voltage (V).

Fence lengths were calculated using QGIS software (QGIS Development Team 2025) and available maps from 10 of the surveyed farms. The total fence length (km) was divided by the farm size (ha) for each mapped farm to determine the fence length-to-area ratio. The average of these ratios $\bar{R}_{f:a}$ was calculated using Equation (7).

$$\bar{R}_{f:a} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{L_{f,i}}{A_i}\right) \quad (7)$$

Where n was the number of farms and A was the farm area (ha).

The fence length of a given farm can be estimated using Equation (8).

$$L_f = \left(\bar{R}_{f:a}\right)(A) \quad (8)$$

Equation (9) calculated the total electricity consumption of a fence's energizer unit, Q_{fence} (Wh).

$$Q_{fence} = (P_{out} + P_{leak})\Delta t_{fence} \quad (9)$$

Where Δt_{fence} was the fence operated time (h).

The optimal tuning parameters of the electric fence electricity demand sub-model were f_{veg} and V_{pulse} in Equation (6), which were calibrated using the methods described in section 2.3.6.

The sub-model assumed a constant impulse duration of 10 ms and an impulse repetition rate of 1 Hz, following safety requirements outlined in IEC 60335-2-76 [12]. The sub-model incorporates farm-specific housing and turnout dates to determine the active fencing period.

2.3.3 Lighting electricity demand sub-model

The lightning sub-model was developed to represent seasonal lighting variations between winter housing and summer grazing periods. This sub-model considered

various lighting types commonly used in livestock sheds and outdoor yards, including LED, CFL, halogen, T5, fluorescent, high-pressure sodium, and bulkhead fixtures.

This sub-model distinguished between the winter and summer periods using farm-specific housing dates and turnout dates as inputs. Equation (10) calculated the total electricity consumption of lights, Q_{lights} (Wh).

$$Q_{lights} = \left(P_{light,y}\right)\left(N_{lights,y}\right)\Delta t_y + \left(\sum_{i=1}^{n_s}\left(P_{light,i}\right)\left(N_{lights,i}\right)\right)\Delta t_s \quad (10)$$

Where P_{light} was the power rating (W) of the lighting type in the yard (y) or shed (i), $N_{lights,y}$ was the number of outside yard lights, Δt_y was the turn-on duration of yard lights (h), n_s was the number of cattle sheds with lights, $N_{lights,i}$ was the number of lights in cattle shed i, and Δt_s was the turn-on duration of shed lights (h).

2.3.4 Automatic feeder electricity demand sub-model

An automatic calf feeder sub-model was developed to calculate the electricity usage of automatic feeders operated on a scheduled timer. Automatic feeders were used to feed dairy calves after purchase (typically at 14–21 days of age) on some beef farms. Each calf was assumed to drink 6 L of milk daily for their first four weeks on the farm and then 4 L per day until weaning at 8 weeks [13].

Equation (11) calculated the electricity consumed by automatic feeders.

$$Q_{feeder} = \sum_{i=1}^{n_f}\left(P_{feeder,i}\right)\left(\eta_{feeder,i}\right)\Delta t_{feeder,i} \quad (11)$$

Where Q_{feeder} was the total electricity consumed by automatic feeders (kWh), $P_{feeder,i}$ was the power rating (kW) for an individual feeder i, n_f was the total number of feeders, $\eta_{feeder,i}$ was the feeder efficiency, and $\Delta t_{feeder,i}$ was the turn-on duration of the automatic feeder i (h).

In some farms, water heaters were used to heat water for manual mixing of milk powder to feed calves. Equation (14) calculated the electricity consumption of a water heater, Q_{heater} (kWh).

$$Q_{heater} = \sum_{i=1}^{n_h}\left(P_{heater,i}\right)\Delta t_{heater,i} \quad (14)$$

Where $P_{heater,i}$ was the power rating (kW) for an individual water heater i, n_h was the total number of water heaters, and $\Delta t_{heater,i}$ was the turn-on duration of the water heater i (h).

2.3.5 Miscellaneous

The miscellaneous sub-model calculated the annual electricity usage of specific appliances, focusing on power washers and cow brushes, which are commonly used on beef farms. Equation (15) computed the total electricity consumption based on the appliances' power ratings and daily usage durations.

$$Q_{misc} = (P_{washer})(N_{washer})\Delta t_{washer} + (P_{brush})(N_{brush})\Delta t_{brush} \quad (15)$$

Where Q_{misc} was the total electricity consumed by miscellaneous appliances (kWh), P_{washer} and P_{brush} were the power ratings (kW) for the power washer and cow brush, Δt_{washer} and Δt_{brush} were the turn-on durations (h) of the power washer and cow brush, respectively. N_{washer} was the number of power washers and N_{brush} was the number of cow brushes.

2.3.6 Model calibration

Four parameters were selected as tuning parameters (C_{pump}, τ, f_{veg}, and V_{pulse}). The sum of square errors (SSE) was employed as the error function (Equation (16)). The generalised reduced gradient (GRG) nonlinear method in Visual Basics for Applications (Microsoft 365) was used to minimise the error function during calibration. The constraints were established with reasonable upper and lower limits, restricting the calibration and preventing the tuning algorithm from selecting unrealistic values.

$$SSE = \sum_{i=1}^{N}\left(Q_{Fi,M} - Q_{Fi,S}\right)^2 \quad (16)$$

Where $Q_{Fi,M}$ was the measured farm electricity consumption, $Q_{Fi,S}$ was the simulated farm electricity consumption, and N was the total number of farms.

3. RESULTS AND DISCUSSION

3.1 Model accuracy overview

Measured and simulated electricity consumption were compared across three key components: water pumps, electric fences, lighting, and total farm consumption. Fig. 2 compares the measured and simulated daily electricity consumption profiles for farms 1, 7, 8, and 9 during the winter period. Farms 7 and 8 were representative of farms with only an electric fence and lights, while farms 1 and 9 were representative of farms with a water pump, electric fence and lights.

BFEM's performance was evaluated using statistical metrics: Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Mean Percentage Error (MPE),

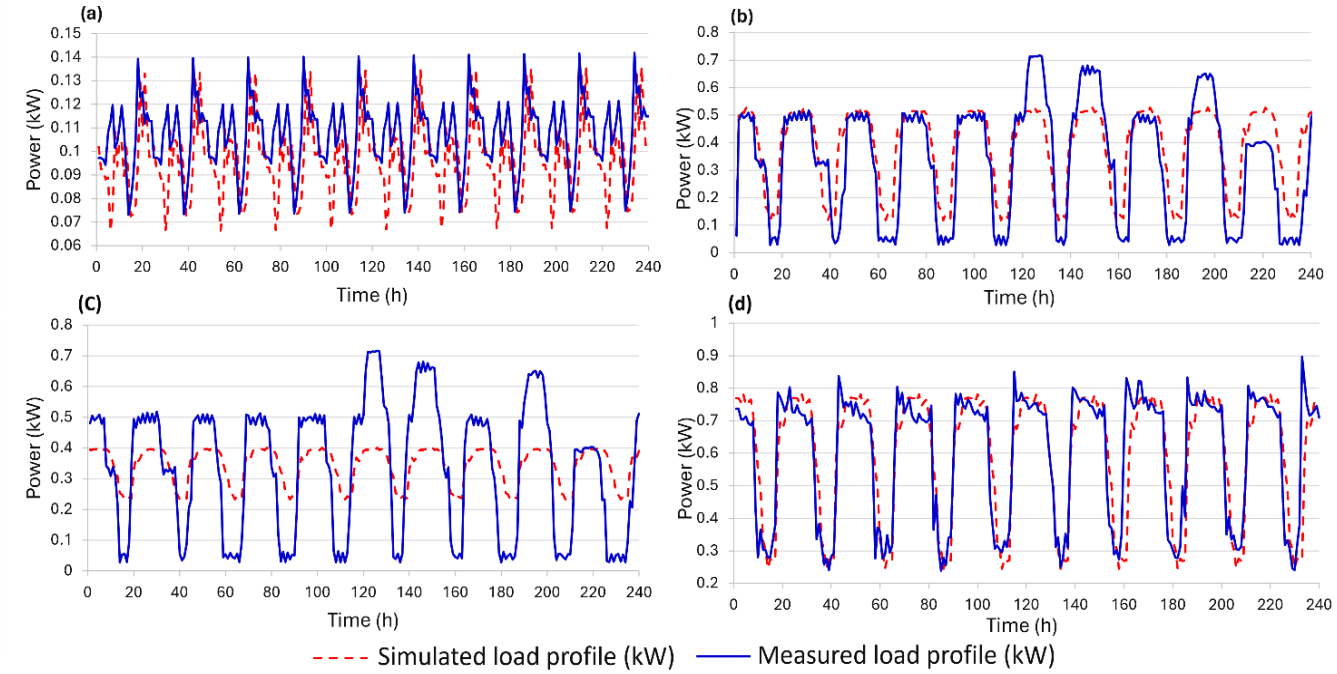

Fig 2 Measured vs simulated total electrical load profiles for (a) Farm 1, (b) Farm 7, (c) Farm 8, and (d) Farm 9 on 10 representative days in the winter housing period

Relative Prediction Error (RPE), and Coefficient of Determination (R^2). These are summarised in Table 2.

Table 2 Calibration results (RMSE, MAPE, MPE, RPE, and R^2) averaged across the 12 farms for 10 days of data.

	RMSE (kWh)	MAPE (%)	MPE (%)	RPE (%)	R^2
Total	26.10	12.60	-5.34	6.79	0.997
Water Pump	12.79	8.13	6.42	5.05	0.996
Electric fence	9.85	58.46	-2.73	43.01	0.47
Lights	9.53	11.00	-3.67	10.47	0.97

3.2 Water pump energy use

Water pumps were used on six of the surveyed farms to supply water to farm operations and on-site dwellings. Measured water pump electricity use varied considerably across farms and was influenced by differences in pump-rated power, flow rate, pump efficiency, water demand, and the number of dwelling occupants. BFEM showed high accuracy in predicting electricity consumption for water pumps (RMSE = 12.37 kWh, MAPE = 8.13%). However, the MPE of 6.42% suggests that the model underestimates actual consumption. While BFEM captured the general trend in pump energy demand across different farms, further refinement is needed through sub-metering, more accurate estimations of domestic water consumption, and consideration of leakage losses. Higham et al. [14] found that up to 26% of livestock drinking water was lost due to leakage.

3.3 Electric fence and lighting consumption

BFEM was moderately accurate at predicting electric fence consumption (RMSE = 9.85 kWh, MAPE = 58.46%) with low bias (MPE = -2.73%). The higher error was attributed to the use of a single average output pulse voltage across all farms, as individual output pulse voltages were typically unavailable. For lighting, the model showed good predictive ability (RMSE = 9.53 kWh). However, the MPE of -3.67% indicates a slight overestimation of lighting loads, likely due to variability in lighting hours relating to individual farmer behaviour.

3.4 Total energy consumption

Larger or more intensively managed farms (Farm 4) with additional high-power-consuming appliances showed elevated electricity usage. BFEM's prediction of total energy consumption across farms showed reasonable agreement with measured values (RMSE = 26.10 kWh). BFEM achieved a MAPE of 12.60%, an MPE of -5.34%, and a satisfactory RPE of 6.79%, indicating good overall accuracy. These results emphasise the importance of enhancing subsystem-level modelling to more accurately represent farm-specific variability in equipment specifications and operational behaviour. These findings are applicable to pasture-based beef production in temperate regions throughout the globe.

4. CONCLUSIONS

BFEM demonstrated acceptable performance for electric fences (RMSE = 9.85 kWh), lighting (RMSE = 9.53 kWh), and water pumps (RMSE = 12.79 kWh), showing BFEM's ability to reliably simulate electricity consumption for standard farm components. This accuracy highlights BFEM's value as a tool for electricity auditing, benchmarking, and efficiency planning on pasture-based beef farms. While refinement is needed for systems with variable or dual-purpose loads, BFEM's baseline performance provides a strong foundation. With further calibration and validation, it can support broader sustainability goals, including cost forecasting, renewable integration, and demand-side management.

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