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Effect of electricity tariffs and cooling technologies on dairy farm electricity consumption, related costs and greenhouse gas emissions

John Upton and Laurence Shalloo, Animal and Grassland Research and Innovation Centre, Teagasc Moorepark Fermoy, Co. Cork, Ireland
Michael Murphy, Department of Process Energy and Transport, Cork Institute of Technology, Cork, Ireland
Peter Groot Koerkamp Farm Technology Group Wageningen University, Wageningen, The Netherlands
Imke De Boer, Animal Production Systems Group, Wageningen University, Wageningen, The Netherlands

Abstract

The aim of this study was to provide insight into the variations in dairy farm electricity costs across five electricity tariffs. The effect of four milk cooling scenarios is also simulated to illustrate the effect of technologies on the electricity consumption, related costs and CO_2 emissions of a dairy farm. Helping dairy farmers to make informed business decisions when confronted with future options in the sphere of electricity tariffs and energy efficient cooling systems will contribute to optimum farm profitability and will help to improve the profitability and sustainability of the industry. A previously developed model capable of simulating electricity consumption, related costs and CO_2 emissions of dairy farms was used to simulate five electricity tariffs (Flat, Day&Night, Time of Use Tariff 1 (TOU1), TOU2 and Real Time Pricing (RTP)) on a dairy farm with 195 milking cows. The Flat tariff consisted on one electricity price for all time periods, the Day&Night tariff consisted of two electricity prices, a high rate from 09:00 to 00:00 h and a low rate thereafter. The TOU tariff structure was similar to that of the Day&Night tariff except that a third peak price band was introduced between 17:00 and 19:00 h. The RTP tariff varied dynamically according to the electricity demand on the national grid. The model used in these simulations is a mechanistic mathematical representation of the electricity consumption that simulates farm equipment under the following headings; milk cooling system, water heating system, milking machine system, lighting systems, water pump systems and the winter housing facilities. Direct expansion, ice bank and pre-cooling milk cooling systems were simulated to determine how dairy farm electricity consumption, related costs and CO_2 emissions vary according to the milk cooling system installed on the farm.

Annual simulated electricity consumption of the farm was 32,670 kWh when a direct expansion milk cooling system without pre-cooling of milk was included in the model. The annual electricity consumption of the farm on the day & night tariff was €4,571. Adding pre-cooling with ground water to the direct expansion milk cooling system reduced annual electricity consumption by 28% to 23,660 kWh and reduced annual electricity costs by 38% to €2,875. The addition of a pre-cooling system to the direct expansion milk cooling system saved 3,973 kg of CO_2.

Simulation of an ice bank milk cooling system without pre-cooling resulted in annual simulated electricity consumption of 34,777 kWh. The annual electricity consumption on the day & night tariff was €3,793. Adding pre-cooling with ground water to the ice bank milk cooling system reduced annual electricity consumption by 30% to 24,181 kWh and reduced annual electricity costs by 33% to €2,527. The addition of a pre-cooling system to the ice bank milk cooling system saved 5,044 kg of CO_2.

Keywords: electricity costs, milk cooling, tariff structure

1. Introduction

A number of external factors are currently acting on dairy farming businesses that may increase the electricity costs associated with milk harvesting and storage, thereby affecting overall farm profitability and, therefore, economic sustainability. The importance of strategic planning and goal setting to position the farm business for profitable and environmentally sustainable milk production in the future is widely acknowledged (Bell, 2009). Two main developments that challenge energy efficiency in dairy production are described below.

First, government policies in countries such as Ireland encourage increases in milk output after the abolition of European Union (EU) milk quotas in 2015 (DAFM, 2010). Food Harvest 2020 is the Irish Department of Agriculture Food and the Marines white paper for the development of the agricultural sector. This paper predicts a strong increase in international demand for quality added food products due to the expansion of developing eastern markets and the rapid increase in global population. The paper identifies potential for increasing total agricultural exports by 42%, whereas milk production is estimated to increase by over 50% aided by the abolishment of EU milk quotas in 2015. If dairy farmers expand in line with this policy incentive, they will require an increased consumption of resources, such as land, water and energy. Furthermore, expansion of a dairy enterprise requires significant capital investment in milk harvesting equipment such as milking systems, cooling systems and heating systems, which will increase their demand for electricity.

Second, European Union members are to achieve overall goals of the 20-20 by 2020 initiative. This initative aims to reduce greenhouse gas (GHG) emissions by 20% compared to 2005 levels, to increase the share of renewables in energy use to 20% and to improve energy efficiency by 20% by the year 2020 (EC, 2008). The European Directive 2006/32/EC was enacted to drive improvements in energy efficiency through the implementation of improved metering of electricity coupled with incentivised demand side management (DSM) of electricity for the consumer (EU, 2006). By the end of 2009, the Energy Services Directive (Directive 2006/32/EC) was transposed into Irish law. Also in 2009 the Irish Government adopted the National Energy Efficiency Action Plan 2009-2020 (NEEAP) in order to achieve Ireland's energy efficiency targets. One of the principal measures contained within this action plan was the encouragement of more energy efficient behaviour by electricity consumers through the introduction of smart meters (DCENR, 2009). A series of customer behaviour trials were started by the Irish commission for energy regulation (CER) in 2010 to deliver the evidence for the energy efficiency potential of smart metering (CER, 2011). Smart metering 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 17:00 to 19:00 h. If dairy farmers continue to carry out their evening milking during this peak period after the introduction of smart metering, they may be exposed to increases in energy costs.

The aim of this study was to provide insight into the variations in dairy farm electricity costs across five electricity tariffs. The effect of four milk cooling scenarios was also modelled to illustrate the effect of technologies on the electricity consumption, related costs and CO_2 emissions. Helping dairy farmers to make informed business decisions when confronted with future options in the sphere of electricity tariffs and energy efficient cooling systems will contribute to optimum farm profitability and will help to improve the profitability and sustainability of the industry.

2. Materials and methods

2.1 Electricity consumption model

A model for electricity consumption on dairy farms (MECD), developed by Upton, Murphy, Shalloo, Groot Koerkamp and De Boer (2014 in press), was used to apply five electricity tariffs to four simulated milk cooling systems on a spring calving grass based dairy farm in Ireland. The MECD was designed to simulate the electricity consumption and related costs and CO_2 emissions of dairy farms. The MECD is a mechanistic mathematical representation of the electricity consumption that simulates farm equipment under the following headings; milk cooling system, water heating system, milking machine system, lighting systems, water pump systems and the winter housing facilities. The main inputs to the model are milk production, cow number and capacity of the milk cooling system, milking machine system, water heating system, lighting systems, water pump systems and the winter housing facilities as well as details of the management of the farm (e.g. season of calving, frequency of milking and milking start time). The energy consumption of each of the seven infrastructural systems described above was computed using the MECD in a 12 x 24 matrix structure that simulated a representative day for each month of the year (12 months x 24 hour). Electricity tariffs were compiled in an identical 12 x 24 matrix. Dairy farm electricity costs were then calculated by multiplying the electricity consumption matrix by the tariff matrix.

2.2 Model Inputs

The electricity consumption and related costs and CO_2 emissions of a dairy farm (DF) with 195 milking cows was simulated using the MECD. Background data from an energy study of these farms presented by Upton et al. (2013) was used to populate the MECD with data pertaining to the infrastructural configuration on the DF. The DF was a spring calving farm operating a grass-based milk production system with low supplementary feed input. Annual milk production was 774,089 L. A 24 unit herringbone milking plant with two stalls per milking unit was used to milk the herd which was fitted with an oil lubricated centrifugal vane vacuum pump without variable speed control. A standard pressurised cylinder water heating system was used to provide hot water for cleaning purposes. The farms morning milking time was set to 07:00 h and the evening milking time was set to 17:00 h.

2.3 Electricity Tariffs

Dairy farmers commonly use one of two currently available electricity tariffs, a Flat tariff or Day&Night tariff. These tariffs along with three tariff systems that may be used by electricity providers in the future, i.e. Time of Use (TOU) and Real Time Price (RTP) tariffs, are used in this analysis. To ensure tariffs were as comparable as possible, all tariffs were normalised to 2013.

2.3.1 Flat and Day&Night Tariffs. Electricity Tariffs. Reference Flat rate tariffs from 2013 were used, when electricity price was €0.20/kWh for all time periods throughout the year. Day&Night tariff electricity costs were €0.20/kWh from 09:00 to 00:00 h and €0.08/kW from 00:00 to 09:00 h. Electricity costs were sourced from an Irish comparison of energy prices from 2013 (SEAI, 2014).

2.3.2 Time of use Tariffs. We explored two TOU tariffs (TOU1 and TOU2) corresponding to the TOU tariffs applied to small and medium sized enterprises (SME) by the CER in their smart metering trial which commenced in 2010 (CER, 2011). To ensure normalisation of the tariffs to 2013 the day rates were inflated by 25%. This mimics the increase in day rate electricity price since 2010. The structure of these tariffs is presented in figure 1. Their structure was similar to that of the Day&Night tariff except that a third price band was introduced between 17:00 and 19:00 h. The mean electricity price of TOU1 was €0.18/kWh (range 0.14-0.28 €/kWh), the mean electricity price of TOU2 was €0.16/kWh (range 0.08-0.28 €/kWh), see figure 1.

2.3.3 RTP Tariffs. Real time pricing of electricity implies a dynamically varying electricity price from hour to hour, from day to day and from season to season. The price deviations are based on the national grid load/demand. Large industrial electricity users already avail of this dynamic pricing system. The single electricity market operators (SEMO) are responsible for managing the supply of electricity to the national grid and setting the generation price and wholesale price of electricity from hour to hour. The Single Electricity Market (SEM) is the wholesale electricity market operating in Ireland. As a gross mandatory pool market operating with dual currencies and in multiple jurisdictions the SEM represents the first market of its kind in the world (SEMO, 2013). Under the pool arrangements the sale and purchase of electricity occurs on a gross basis with all generators paying/suppliers receiving the same price for electricity sold via the pool in a given trading period. The system marginal electricity price (SMP) for 2013 was downloaded from the SEMO website and used as a basis for the RTP tariff. The SMP, however, does not reflect the price paid by the consumer, as other charges apply, such as transmission costs, balancing costs, distribution costs and retail margin. Costs for these additions were sourced from Deane, Fitzgerald, Malaguzzi-Valeri, Touhy and Walsh (2013). The RTP tariff, therefore, was computed as:

$$\mathrm{RTP(i,j) = SMP(i,j) + Tc + Bc + Dc + Rm} \qquad [1]$$

Where RTP(i,j) is the real time price of electricity in month i (1-12) and hour j (1-24) (€/kWh); Tc is transmission cost, taken as €0.008/kWh; Bc is balancing cost, taken as €0.003/kWh; Dc is distribution cost taken as €0.051/kWh and Rm is retail margin taken as €0.017. The mean electricity cost of the RTP was €0.16/kWh (range 0.14 - 0.30 €/kWh). This tariff varied from month to month and from hour to hour due to the dynamic nature of the SMP. Figure 2 shows the RTP variation by month and by hour.

2.4 Electricity related CO_2 emissions

It is common to use a static emission factor when computing the electricity related emissions arising from electricity consumption, static emission factors for electricity consumption in Ireland can be found in (SEAI, 2014). In reality CO_2 emissions are not equal across all hours of the day due to intermittent wind energy flowing onto the national electricity grid and fluctuations in the fuel mixes that are used by various electricity generating stations. To provide a more realistic picture of the electricity related CO_2 emissions we derived a dynamic CO_2 emission factor which varied by hour of the day and also by month. The CO_2 emission intensity for Irish electricity in 2013 was downloaded from the Eirgrid (the Irish electricity grid operator) website and formatted to a 12 x 24 matrix structure that simulated a representative day for each month of the year (12 months x 24 hour) (figure 3). Electricity related CO_2 emissions were calculated by multiplying the energy consumption matrix by the CO_2 matrix.

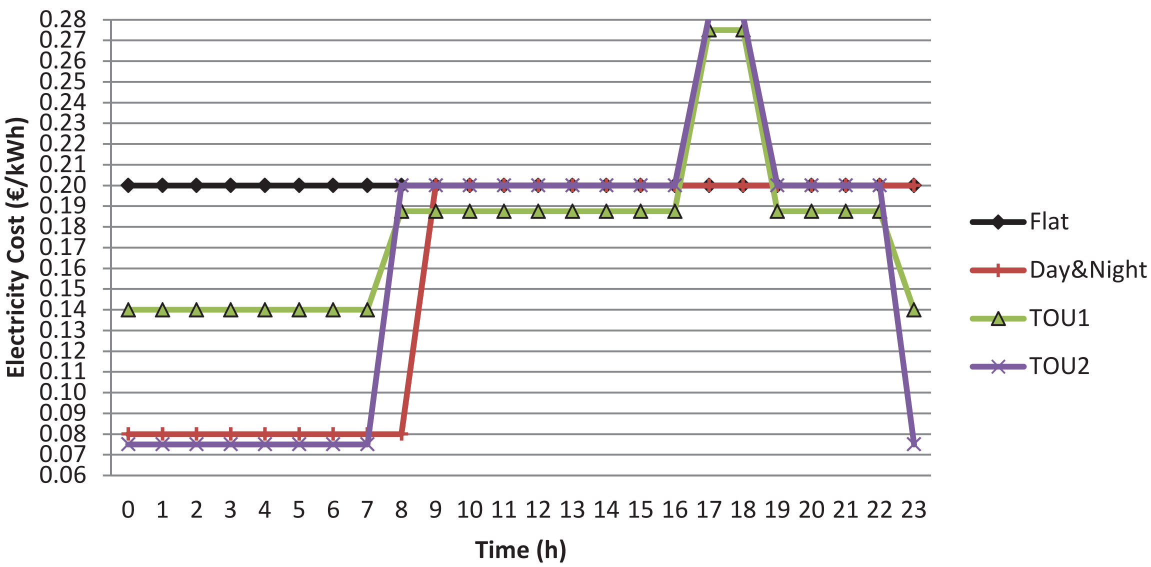

Figure 1. Graph of electricity costs (€/kWh) by hour of the day for 4 of the tariffs used in this analysis. Flat, Day&Night, Time Of Use1 (TOU1) and TOU2.

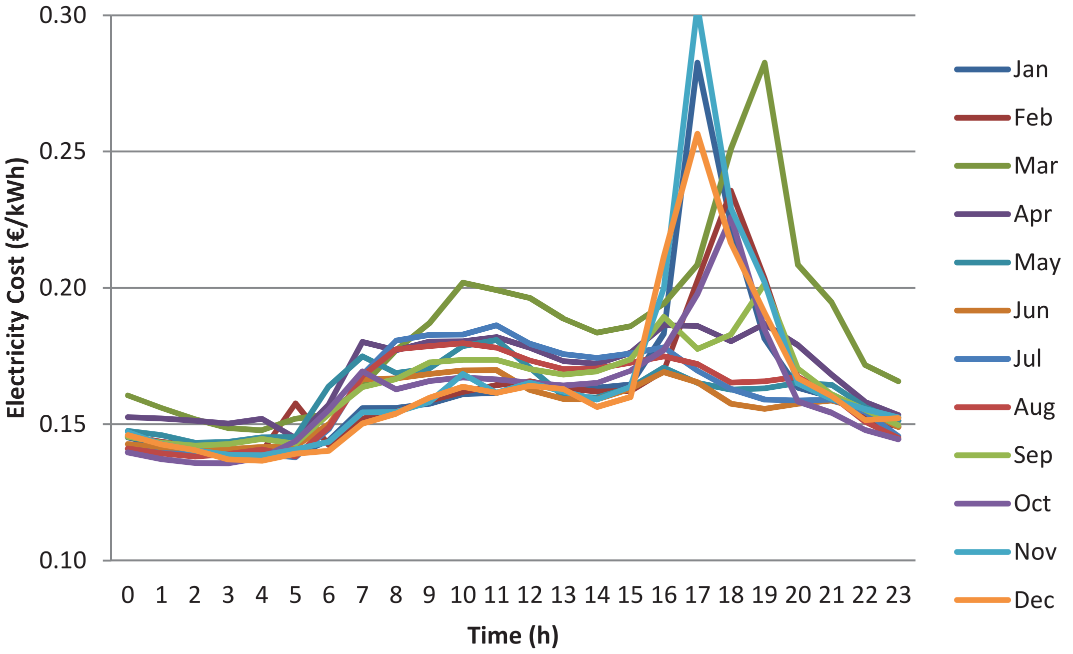

Figure 2. Graph of electricity costs (€/kWh) by hour for an average day in each month of the year (2013) for the Real Time Pricing (RTP) Tariff used in this analysis.

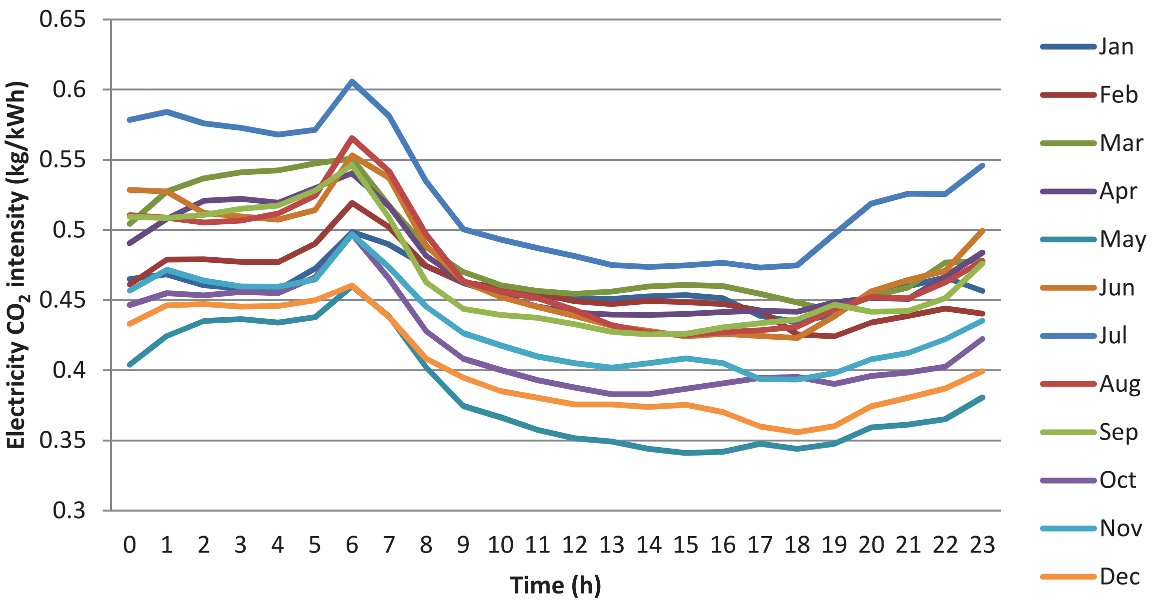

Figure 3. Graph of electricity CO_2 intensity (kgCO_2/kWh) by hour for an average day in each month of the year (2013)

2.5 Technology Scenario Description

Milk cooling is the largest consumer of electricity on dairy farms and the practice of pre-cooling milk in a plate heat exchanger (PHE) with ground water was identified as a technology which may reduce electricity costs on dairy farms (Upton et al., 2013). We simulated the annual electricity consumption, related costs and CO_2 emissions of four technology scenarios.

i. Milk was cooled with a direct expansion (DX) milk cooling system. DX refers to a system where the evaporator plates are incorporated in the lower portion of the storage tank which is in direct contact with the milk. Liquid refrigerant expands inside the evaporator taking heat out of the milk. This was termed the Base scenario.

ii. A DX milk cooling system was used in conjunction with a water cooled PHE which chilled milk to 15°C before entry to the milk storage tank. The PHE had the effect of reducing the thermal energy of the milk entering the storage tank thereby reducing the quantity of electricity consumed by the cooling system. The cost of pumping extra water through the pre-cooler was included in the calculations.

iii. Milk was cooled using an Ice Bank (IB) cooling system. IB cooling systems consist of an insulated water tank that houses a copper tube evaporator array. Ice builds up around the copper tubes in a cylindrical formation. Water is circulated through the cooling device (pre-cooler or bulk tank) and back to the IB in a closed loop (Murphy, Upton, O'Mahony , 2013). IB cooling systems are less efficient in terms of electricity consumed per litre of milk cooled, but when combined with precision technologies they can generate enough ice at night to meet the entire milk cooling demand the next day (MDC, 1995). This system can take advantage of significantly cheaper night rate electricity by shifting the cooling load to off peak rates (currently 00:00 to 09:00 h).

iv. An IB milk cooling system was used in conjunction with a water cooled PHE which chilled milk to 15°C before entry to the milk storage tank. The outputs of the MECD of total annual electricity consumption and related costs and CO_2 emissions were computed for each technology scenario.

3. Results and Discussion

Data pertaining to the variations in electricity consumption, related costs and CO_2 emissions for four technology scenarios on five electricity tariffs are presented in table 1.

3.1 Effect of technology scenarios on electricity consumption, related costs and CO_2 emissions

The simulated electricity consumption of the DF was 32,607 kWh when the milk was cooled via a DX milk cooling system without pre-cooling of milk in a PHE (scenario i). With this configuration milk cooling made up 48% of total annual electricity consumption, water heating 24%, milking machine 19%, water pump 8% and lighting 2%. This farm did not use automatic scrapers for manure handling. The simulated specific electricity consumption was 42 Wh/L. Annual electricity related emissions in the base scenario were 14,992 kg. With the addition of a PHE to the DX milk cooling system (scenario ii) annual electricity consumption dropped to 23,660 kWh (28% reduction) which saved 3,973 kg CO_2. The specific electricity consumption dropped to 31 Wh/L under scenario ii.

The simulated electricity consumption of the DF was 34,777 kWh when the milk was cooled via an IB milk cooling system without pre-cooling of milk in a PHE (scenario iii). With this configuration milk cooling made up 51% of total annual electricity consumption, water heating 23%, milking machine 18%, water pump 7% and lighting 1%. The simulated specific electricity consumption was 45 Wh/L. Annual electricity related emissions under scenario iii were 16,588 kg. With the addition of a PHE to the IB milk cooling system (scenario iv) annual electricity consumption dropped to 24,181 kWh (30% reduction) which saved 5,044 kg CO_2. The specific electricity consumption dropped to 31 Wh/L under scenario iv.

These results are important because they highlight the effect of DX and IB cooling on electricity consumption and related CO_2 emissions. One might expect that an IB would result in lower CO_2 emissions because the cold energy was generated on off-peak electricity (from 00:00 to 09:00 h) thereby benefitting from similarly reduced CO_2 emissions however figure 3 shows that off-peak prices actually coincide with higher CO_2 emissions than day time emissions. This is reflected in the fact that the CO_2 emission factor for scenario i was 0.46 $kgCO_2$/kWh whereas the emission factor under scenario iii was 0.48 $kgCO_2$/kWh. These findings agree with those of Finn, O'Connell and Fitzpatrick (2013) who cited morning ramping and priority dispatch of peat generation as possible reasons for relatively high off-peak CO_2 emission factors.

Morning ramping of electricity generation follows the period of lowest demand. Carbon emissions from generation are greatest during warm-up from a cold state to an available state. Therefore warming of thermal plants in preparation for morning ramping contributes significantly to high CO_2 emission factors during periods of low electricity demand on the national grid. Priority dispatch of peat generation implies that peat (an indigenous fuel resource) powered electricity plants operate constantly to provide a level of base generation. Burning peat fuel produces a relatively high level of CO_2 per kWh of electricity produced (Denny and O'Malley 2006). Therefore as cleaner fuels (such as natural gas) are added to the electricity generation mix throughout the day the overall CO_2 intensity reduces.

3.2 Effect of tariff structure on electricity costs

3.2.1 Scenario i, DX cooling without PHE. When milk was cooled with a DX milk cooling system without a PHE the annual electricity costs varied from €4,571 on the Day&Night tariff to €6,534 on the Flat tariff implying an increase in costs of approximately 43% given the Day&Night tariff. If the DF were operating on TOU1 in 2013 a 30% (€1,392) increase in total electricity costs would have been realised. Similarly costs would have increased by 20% (€907) on TOU2 and 20% (€893) on RTP tariffs.

3.2.2 Scenario ii, DX cooling with PHE. When a PHE was added to the DX milk cooling system the annual electricity costs varied from €2,857 on the Day&Night tariff to €4,732 on the Flat tariff implying an increase in costs of approximately 66% given the Day&Night tariff. If the DF were operating on TOU1 in 2013 a 51% (€1,453) increase in total electricity costs would have been realised. Similarly costs would have increased by 34% (€967) on TOU2 and 38% (€1,096) on RTP tariffs.

3.2.3 Scenario iii, IB cooling without PHE. When milk was cooled with a DX milk cooling system without a PHE the annual electricity costs varied from €3,793 on the Day&Night tariff to €6,955 on the Flat tariff implying an increase in costs of approximately 83% given the Day&Night tariff. If the DF were operating on TOU1 in 2013 a 51% (€1,953) increase in total electricity costs would have been realised. Similarly costs would have increased by 21% (€802) on TOU2 and 47% (€1,780) on RTP tariffs.

3.2.3 Scenario iv, IB cooling with PHE. When a PHE was added to the IB milk cooling system the annual electricity costs varied from €2,527 on the Day&Night tariff to €4,836 on the Flat tariff implying an increase in costs of approximately 91% given the Day&Night tariff. If the DF were operating on TOU1 in 2013 a 60% (€1,527) increase in total electricity costs would have been realised. Similarly costs would have increased by 26% (€657) on TOU2 and 53% (€1,327) on RTP tariffs.

Table 1: Total annual electricity consumption (kWh), related costs (€) and related CO_2 emissions (kg) from four technology scenarios on an Irish dairy farm with 195 dairy cows for five electricity tariffs.

		Direct Expansion (DX) Cooling					Ice Bank (IB) Cooling				
	Tariff	Day&Night	TOU1[a]	TOU2[b]	RTP	Flat	Day&Night	TOU1	TOU2	RTP	Flat
No PHE[c]	Annual Electricity (kWh)	32,670	32,670	32,670	32,670	32,670	34,777	34,777	34,777	34,777	34,777
	Annual Cost (€)	4,571	5,964	5,478	5,464	6,534	3,793	5,746	4,595	5,573	6,955
	Annual CO_2 (kg)	14,992	14,992	14,992	14,992	14,992	16,588	16,588	16,588	16,588	16,588
PHE	Annual Electricity (kWh)	23,660	23,660	23,660	23,660	23,660	24,181	24,181	24,181	24,181	24,181
	Annual Cost (€)	2,857	4,310	3,824	3,953	4,732	2,527	4,054	3,185	3,855	4,836
	Annual CO_2 (kg)	11,019	11,019	11,019	11,019	11,019	11,544	11,544	11,544	11,544	11,544

[a] TOU = time of use
[b] RTP = real time pricing
[c] PHE = plate heat exchanger

3.3 Implications of the results for dairy farmers

The analysis presented here showed that dairy farm energy costs are influenced by the tariff that the farm subscribes to and that electricity costs, consumption and CO_2 emissions vary depending on the milk cooling system utilised. Further analysis of various future electricity tariffs showed that the Day&Night electricity tariff was optimal from an annual electricity cost viewpoint, while a Flat tariff would increase the electricity costs of the DF by between 43% and 91% depending on the milk cooling system utilised on the farm. Likewise an investigation of an RTP tariff, where electricity costs are influenced by the demand on the national electricity grid, showed that annual electricity costs would increase by between 20% and 53% depending on the milk cooling system utilised.

The data presented in this paper described the energy prices and farming infrastructure related to the Irish dairy production environment, consequently the impacts of various pricing structures and milk cooling scenarios would likely differ from region to region. However the MECD utilised in this analysis is very flexible and could be calibrated to account for confinement dairy systems, automatic milking systems, regional electricity prices and regional technology performance.

4. Conclusions

This study presented novel data regarding the simulated variations in total annual electricity consumption, related costs and CO_2 emissions for five different electricity tariffs (Flat, Day&Night, TOU1, TOU2 and RTP). Costs were lowest on the Day&Night Tariff and highest on the Flat Tariff (between 43% and 91% higher than Day&Night). An analysis of simulated electricity costs while varying milk cooling system configuration showed that lowest electricity consumption and related CO_2 emissions resulted from a direct expansion milk cooling system with pre-cooling of milk, however lowest electricity costs resulted from simulating an ice bank milk cooling system with pre-cooling of milk. Highest electricity consumption and related emissions resulted from an IB milk cooling system without pre-cooling. The methodology presented here for determining the optimum combinations of electricity tariffs and technology configurations will help dairy farmers and advisors to choose the least cost option for a given farm.

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