Strategies to reduce electricity consumption on dairy farms - An economic and environmental assessment

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Abstract

The aim of this thesis was to assess how, and to what extent, do managerial and technology changes affect electricity consumption, associated costs and greenhouse gas (GHG) emissions of dairy farms. Dairy farms in Ireland are expected to expand in the future, due to policy incentives and the abolishment of European Union milk quotas in 2015, which will result in an increased use of resources such as land, water, and energy, and increased emissions to the environment. In order to develop strategies to reduce electricity consumption associated costs and GHG emissions, it was necessary to understand the consumption trends and the hot-spots of electricity consumption within the farm. Therefore, we performed a life cycle assessment by quantifying the energy use on 22 commercial Irish dairy farms, from cradle-to-farm-gate. This analysis demonstrated that a total of 31.7 MJ of energy was required to produce one kg of milk solids, of which 20% was direct and 80% was indirect energy use. Electricity consumption was found to represent 12% of total cradle-to-farm-gate energy use or 60% of direct energy, and was centered on milk harvesting. Following this analysis we devised two main groups of strategies, i.e. 'cost strategies' and 'energy strategies'. 'Cost strategies' consisted of measures that could save on-farm costs but no energy or related emissions, such as, moving to a new electricity tariff or decoupling large electricity users, such as water heating, from milking times and shifting them to off-peak periods when electricity price is lower. Examples of 'energy strategies' are; the use of variable speed vacuum pumps on the milking machine, pre-cooling of milk and solar thermal technologies to provide hot water for cleaning purposes. A mechanistic model of electricity consumption that simulates farm equipment on an hourly and monthly basis was developed to further evaluate the 'cost' and 'energy' strategies. We used this model to show that a Day & Night electricity tariff minimised annual electricity costs, while a Flat tariff would increase the electricity costs by between 16% and 34%, depending on farm size. We also discovered that milking earlier in the morning and later in the evening reduced the simulated annual electricity consumption and related GHG emissions by between 5% and 7%, depending on farm size. An analysis of 'energy strategies' was carried out which revealed that that the ideal blend of technologies to maximise farm profitability while also reducing electricity consumption and GHG emissions, consisted of a direct expansion milk tank with pre-cooling of milk with well water to 15°C, electrical water heating and standard vacuum pumps. An individual farmer can also choose to increase his or her use of renewable energy by adding solar thermal water heating with the trade-off of reduced profitability and negative return on investment figures. This analysis highlighted the need for an investment appraisal approach to technology investments on dairy farms.

Contents

Chapter 1

General Introduction

1.1 Background and scope

The agri-food sector is Ireland's largest indigenous industry and exporter; it accounts for 25% of manufacturing industry turnover (DAFM, 2013), exports over €9 billion annually and employs 8% of the total population (Board Bia, 2013). Dairy products and ingredients are the single largest contributor (29%) to this €9 billion of exports. The business environment for dairying is changing rapidly, which necessitates strategic planning and goal setting to position the farm business for profitable and environmentally sustainable milk production in the future (Bell, 2009). Two main developments that challenge future sustainable dairy production are described below.

First, the Irish Department of Agriculture Food and the Marine launched "Food Harvest 2020", a white paper for the development of the agricultural sector. This paper predicts a strong increase in international demand for high quality food products due to the expansion of developing Asian markets and the rapid increase in global population. The paper identifies potential for increasing total agricultural exports from Ireland by 42%, whereas milk production in Ireland is estimated to increase by over 50%, aided by the abolishment of EU milk quotas in 2015 (DAFM, 2010). The increased national production of milk is expected to arise from expansion on existing family farms in addition to an increased frequency of new farm conversions from alternative enterprises, such as sheep, suckler beef and tillage. If dairy farmers expand in line with this policy initiative, it will result in an increased consumption of resources, such as land, water, and energy. Furthermore, expansion of a dairy enterprise requires significant capital investment in more industrial milk harvesting equipment, such as milking systems, cooling systems and heating systems, and more automation, such as automatic wash systems, which may increase their electricity consumption per litre of milk produced.

Second, European Union members are obliged to achieve the overall goals of the 20-20 by 2020 initiative. This initiative 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). Additionally, the European Energy Services Directive 2006/32/EC was enacted to encourage 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 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 higher electricity price during peak periods of consumption and a lower price 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 electricity costs.

Pressure is increasing on the dairy industry in Western Europe, as a result of exposure to a globalizing market in which the developments in the price of milk are insufficient to keep pace with the increasing costs of production associated with rising energy costs (Oenema et al., 2011). The above described factors that are currently acting on dairy farming businesses will create an unprecedented level of uncertainty around electricity consumption and costs, and associated greenhouse gas emissions (GHG) on dairy farms. Providing farmers with strategies to reduce electricity consumption, costs and emissions will help turn the policy measures described above into an advantage for dairy farmers. Provisional studies in New Zealand by the New Zealand Centre for Advanced Engineering, for example, have suggested that implementation of the best management practices will produce an energy efficient dairy farm and that the energy consumption could decrease from 163 to 92 kWh/cow/year, representing a saving of about 44% (Morison, 2007).

Helping farmers to make informed business decisions in the domain of energy efficient and conventional technology will help to improve the profitability and environmental sustainability of the dairy sector.

1.2 Gaps in knowledge

Energy uses on dairy farms are generally characterised as being either direct or indirect (Wells, 2001). Direct energy uses are those where the energy is consumed on the farm. Examples are the use of electricity and fossil fuels (oil, diesel and petrol). Indirect energy uses are those where the direct energy use occurs outside the farm boundaries. The energy use, therefore, is then embodied in the products used on the farm. Examples are energy used during the manufacture and transport of fertilisers, concentrate feed or any substantial purchases brought in for farm maintenance, such as aggregate for road maintenance (Wells, 2001).

In order to develop strategies to reduce electricity consumption, associated costs and GHG emissions on dairy farms, a state-of-the-art assessment of direct and indirect energy use, and daily and seasonal consumption patterns of electricity are needed. Several studies have quantified the direct and indirect energy use (i.e. energy use up to the farm-gate or along the entire life cycle) of production of dairy milk (see review of De Vries and De Boer, 2010). Fewer authors have recorded detailed inventories of the electricity consumption on commercial dairy farms. Examples of studies where electricity is measured and expressed explicitly include studies of Wells (2001), Hartman and Sims (2006) and Basset-Mens et al. (2005). These studies are relevant to this thesis because the milk production fundamentals in New Zealand are similar to those in Ireland. In these studies, farms produced milk in temperate climates from grazed grass with low levels of supplementation. For Irish dairy production, however, such an analysis is missing. Moreover, previous studies did not report information regarding the daily and seasonal electricity consumption patterns on commercial dairy farms, or quantify the related costs under future electricity tariff systems; these data are critical for identifying strategies to reduce its use.

Another major knowledge gap comprises of the unknown consequences of investing in a specific dairy farm technology to achieve reductions in electricity consumption, associated costs and GHG emissions. Some whole-farm simulation models published to date contain a sub-model to calculate on-farm energy use. For example, DairyWise is an empirical model integrating all major subsystems of a dairy farm into a whole-farm model (Schils et al., 2007), FarmGHG is an empirical model of carbon and nitrogen flows on dairy farms (Olesen et al., 2006), FarmSim is another model of GHG emissions at the farm scale where on-farm energy use is computed (Saletes et al., 2004) and the Moorepark Dairy Systems Model computes energy costs based on historic consumption values (Shalloo et al., 2004). Although these models contain an energy calculation element for computing total on-farm GHG emissions or farm profitability, they are not suitable for assessing the impact of the strategies to reduce electricity consumption identified in this thesis. This is because they are either based on historic consumption trends, do not include sufficient technology parameterisation, do not account for the impact of ambient temperatures on technology performance, or do not place the electricity consumption in the correct hourly time horizon, making analysis of future electricity tariffs impossible. Up until now a detailed model to predict the electricity consumption and associated costs and GHG emissions of electricity consumption on dairy farms has not been reported. Moreover, despite the work of previous authors to bring net present value (NPV) calculations to support capital investment from the horticulture industry (Aramyan et al., 2007) to the dairy farm (Gebrezgabher et al., 2012), the simple payback method is generally used to support investment in new technologies on dairy farms. This method computes a payback figure (in years) by dividing the estimated annual monetary saving generated by an item of energy efficient technology by the purchase cost of that technology. Such a payback method was implemented by Houston et al. (2014) to calculate the return on investment for a number of technology innovations on small-scale dairy farms, including anaerobic digestion, wind turbines and upgraded lighting systems. This payback method, however, can be misleading because critical factors such as the value of money over time, increases in electricity price and the interest rate of borrowed capital from financial institutions are not taken into account, all of which can impact on the effective return on investment of a technology.

In addition to the uncertainty around electricity consumption trends at farm level, there is also a considerable gap in knowledge around how, and to what extent, the management and performance of specific items of dairy farm infrastructure affect electricity consumption, associated costs and GHG emissions of dairy farms. We focused on milk cooling systems as a case study for further investigation for the following reasons. First, milk cooling systems typically consume over 30% of total annual electricity consumption on dairy farms (Morison et al., 2007). Second, there seemed to be greatest scope for optimisation of electricity use of on-farm milk cooling systems, given its similarity to milk processing operations such as pasteurisation where a high degree of precise control is required (Negiz et al., 1996). Third, Vellinga et al. (2011) identified pre-cooling of milk as a cost effective GHG mitigation strategy. Fourth, the optimum system performance criteria of both conventional electrical and solar thermal water heaters are well understood (Alizadeh, 1999; Eames and Norton, 1998; Notton et al., 2014; Savicki et al., 2011). Similarly, the scope for improving the efficiency of motors by applying a variable speed drive system is well understood (Bose, 2006; Europump and Hydraulic Institute, 2005; Ricci et al., 2003; Saidur et al., 2012; Teitel et al., 2008; Xue et al., 2010). These variable speed drive systems were applied to milking machine vacuum pumps previously by Ludington et al. (2004) and Morison et al. (2007). They found a reduction in electricity consumption of milking systems between 56% and 65%. We acknowledge that further refinement of water heating systems and vacuum pump systems may be possible; however in this thesis we focused on milk cooling as a case study for technology improvement because it is an area that may benefit from optimal control.

1.3 Objective and research questions

The following objectives were set in order to answer the key research question: How, and to what extent do managerial and technology changes affect electricity consumption, associated costs and GHG emissions of dairy farms? An overview of the thesis structure can also be seen in table 1.

1. Establish the state-of-the-art of total energy usage on Irish dairy farms, with special focus on quantifying on-farm electricity consumption and identifying energy saving strategies that maximize electricity consumption in off-peak periods. To achieve this objective we assessed average daily and seasonal trends in electricity consumption on 22 Irish dairy farms, through detailed auditing of electricity consuming processes. In order to determine the potential of identified strategies to save energy we assessed total energy use along the production chain of Irish milk through a life cycle energy assessment of total energy use on 22 Irish dairy farms
2. Define, validate and demonstrate a mechanistic model for electricity consumption on dairy farms. In this study an electricity consumption model, capable of simulating electricity consumption for dairy farms on an hourly and monthly basis, was developed. The model was capable of simulating electricity consumption, associated costs and CO_2 emissions of the main electricity consuming systems within the farm gate (e.g. milk cooling, water heating and milking systems). The model was validated using empirical data from three commercial farms of different scales.
3. Investigate state-of-the-art in milk cooling technology to determine if electricity use could be reduced compared to the current modus operandi. We investigated milk cooling technologies because they represent the largest electricity consumer on dairy farms. A rapid milk cooling system utilising stored cold energy was developed which was capable of cooling milk instantly with low electricity consumption. The performance of this system was examined under different control regimes and compared on energy consumption and technical performance platforms.
4. Assess the impact of electricity price structure changes and variations in milking start time on dairy farm energy consumption and associated costs. This study used the mechanistic model to simulate the effect of five different electricity tariffs on the total annual electricity costs of three representative dairy farms within the Irish dairy industry. An analysis of the

predicted energy consumption, costs and GHG emissions while varying the milking start time was also carried out.

5. Implement appraisal of technology investment strategies on dairy farm electricity consumption and associated costs. This study used the mechanistic model for electricity consumption together with a farm profitability model to calculate the return on investment of six different combinations of technology investments on three representative dairy farms within the Irish dairy industry.

Table 1. Overview of the structure of the thesis.

Chapter	Characteristic	Scope
2	State-of-the-art in energy use	Total energy use was documented on 22 Irish dairy farms. Electricity use was described in detail.
3	Model development and validation	A model for the prediction of electricity use on dairy farms of differing scales was described, validated and demonstrated.
4	Technology development, milk cooling	Current state-of-the-art in milk cooling was examined and a new rapid milk cooling system with cold energy storage was developed and tested.
5	Model application, tariffs and management	The impact of five different electricity tariffs on electricity costs of dairy farms was assessed. The impact of farmer behavioural changes was assessed by quantifying the variations in total electricity costs and electricity consumption when milking start time was changed.
6	Model application, technologies and return on investment	The return on investment of six different farm technology investment strategies was computed using the model for electricity consumption on dairy farms together with a farm profitability model.

References

Alizadeh, S. 1999. An experimental and numerical study of thermal stratification in a horizontal cylindrical solar storage tank. Solar Energy 66(6): 409-421.

Aramyan, L. H., A. G. J. M. O. Lansink, and J. A. A. M. Verstegen. 2007. Factors underlying the investment decision in energy-saving systems in Dutch horticulture. Agricultural Systems 94(2):520-527.

Basset-Mens, C., S. Ledgard and A. Carran. 2005. First Life Cycle Assessment of Milk Production Systems for New Zealand Dairy Farm Systems, Paper presented to the Australia New Zealand Society for Ecological Economics Conference, Palmeston North, Massey University, pp 258-265.

Bell, R. 2009. Long-term strategic planning of dairy businesses. Pages 25–39 in Proc. 27th West Canadian Dairy Seminar (WCDS): Advances in Dairy Technology. Vol. 21. Red Deer, Alberta, Canada.

Board Bia. 2013. 2012 Annual Report and Accounts, Board Bia (the Irish food board), Dublin, Ireland. http://www.bordbia.ie/aboutus/reports/Current%20Annual%20Reports/Annual%20Report%202012.pdf. Accessed on April 17 2014.

Bose, B. K. 2006. Chapter 6 - Electrical Machines for Variable-Speed Drives. Pages 325-390 in Power Electronics And Motor Drives. B. K. Bose, ed. Academic Press, Burlington.

CER. 2011. Second Consultation on Possible National Rollout Scenarios for the Smart Metering Cost Benefit Analysis. Commission for Energy Regulation, Dublin Ireland. CER 10197.

DAFM. 2013. Fact sheet on Irish agriculture - October 2013. Department of Agriculture Food and the Marine, Dublin, Ireland. https://www.agriculture.gov.ie/media/migration/publications/2013/FactsheetonIrishAg171013.pdf. Accessed on April 17 2014.

DAFM. 2010. Food harvest 2020 – A vision for Irish agri-food and fisheries. Department of Agriculture Food and the Marine, Dublin Ireland.

DCENR. 2009. Maximising Ireland's Energy Efficiency. The National Energy Efficiency Action Plan 2009-2020. Department of Communications, Energy and Natural Resources, Dublin, Ireland.

De Vries, M. and I. J. M. De Boer. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. Livest. Sci. 128(1-3):1-11.

Eames, P. C. and B. Norton. 1998. The effect of tank geometry on thermally stratified sensible heat storage subject to low Reynolds number flows. International Journal of Heat and Mass Transfer 41(14): 2131-2142.

EC. 2008. 20 20 by 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - 20 20 by 2020 - Europe's climate change opportunity, European Commission, Brussels, Belgium.

Europump and International Hydraulic. 2005. Chapter Seven - Variable speed drives. Pages 59-66 in Variable Speed Pumping. Europump and Hydraulic. Institute, ed. Elsevier Science, Amsterdam.

EU. 2006. Directive 2006/32/EC of the European Parliment and of the council on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Official Journal of the European Union.

Gebrezgabher, S. A., M. P. M. Meuwissen, and A. G. J. M. Oude Lansink. 2012. Energy-neutral dairy chain in the Netherlands: An economic feasibility analysis. Biomass and Bioenergy 36(0):60-68.

Hartman, K. and R. Sims. 2006. Saving energy on the dairy farm makes good sense. Proceedings of the 4th Dairy3 Conference held at Hamilton New Zealand. Centre for Professional Development and Conferences, Massey University, Palmerston North, New Zealand, pp 11-22.

Houston, C., S. Gyamfi, and J. Whale. Evaluation of energy efficiency and renewable energy generation opportunities for small scale dairy farms: A case study in Prince Edward Island, Canada. Renewable Energy 67(0): 20-29

Ludington, D., E. Johnson, J. Kowalski, A. Magem, and R. Peterson. 2004. Dairy Farm Energy Efficiency Guide. Southern California Edison, USA. Report I.D. 429.

Morison, K., W. Gregory, and R. Hooper. 2007. Improving Dairy Shed Energy Efficiency, Technical Report. New Zealand Centre for Advanced Engineering (CAENZ). Christchurch, New Zealand.

Negiz, A., A. Cinar, J. E. Schlesser, P. Ramanauskas, D. J. Armstrong, and W. Stroup. 1996. Automated control of high temperature short time pasteurization. Food Control 7(6):309-315.

Notton, G., F. Motte, C. Cristofari, and J.-L. Canaletti. 2014. Performances and numerical optimization of a novel thermal solar collector for residential building. Renewable and Sustainable Energy Reviews 33(0):60-73.

Oenema, J., H. van Keulen, R. L. M. Schils, and H. F. M. Aarts. 2011. Participatory farm management adaptations to reduce environmental impact on commercial pilot dairy farms in the Netherlands. NJAS - Wageningen Journal of Life Sciences 58(1–2):39-48.

Olesen, J. E., K. Schelde, A. Weiske, M. R. Weisbjerg, W. A. H. Asman, and J. Djurhuus. 2006. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agriculture, Ecosystems and Environment 112(2-3):207-220.

Ricci, F. and H. Le-Huy. 2003. Modeling and simulation of FPGA-based variable-speed drives using Simulink. Mathematics and Computers in Simulation 63(3–5):183-195.

Saidur, R., S. Mekhilef, M. B. Ali, A. Safari, and H. A. Mohammed. 2012. Applications of variable speed drive (VSD) in electrical motors energy savings. Renewable and Sustainable Energy Reviews 16(1):543-550.

Saletes, S., J. Fiorelli, N. Vuichard, J. Cambou, J. E. Olesen, S. Hacala, M. Sutton, J. Fuhrer, and J. F. Soussana. 2004. Greenhouse gas balance of cattle breeding farms and assessment of mitigation options. In: Kaltschmitt, M., Weiske, A. (Eds.), Greenhouse Gas Emissions from Agriculture. Mitigation Options and Strategies. Institute for Energy and Environment, Leipzig, pp. 203–208.

Savicki, D. L., H. A. Vielmo, A. Krenzinger. 2011. Three-dimensional analysis and investigation of the thermal and hydrodynamic behaviors of cylindrical storage tanks. Renewable Energy 36(5): 1364-1373.

Schils, R. L. M., M. H. A. de Haan, J. G. A. Hemmer, A. van den Pol-van Dasselaar, J. A. de Boer, A. G. Evers, G. Holshof, J. C. van Middelkoop, and R. L. G. Zom. 2007. DairyWise, A Whole-Farm Dairy Model. Journal of Dairy Science 90(11):5334-5346.

Shalloo, L., P. Dillon, M. Rath, and M. Wallace. 2004. Description and validation of the Moorepark Dairy System Model. Journal of Dairy Science 87(6):1945-1959.

Teitel, M., A. Levi, Y. Zhao, M. Barak, E. Bar-lev, and D. Shmuel. 2008. Energy saving in agricultural buildings through fan motor control by variable frequency drives. Energy and Buildings 40(6):953-960.

Vellinga, T. V., M. H. A. de Haan, R. L. M. Schils, A. Evers, and A. van den Pol–van Dasselaar. 2011. Implementation of GHG mitigation on intensive dairy farms: Farmers' preferences and variation in cost effectiveness. Livestock Science 137(1–3):185-195.

Wells, C. 2001. Total energy indicators of agricultural sustainability: Dairy farming case study. Technical Paper 2001/3 prepared for the New Zealand Ministry of Agriculture and Forestry, Wellington, New Zealand.

Xue, Z. and L. Shi. 2010. Modeling and Experimental Investigation of a Variable Speed Drive Water Source Heat Pump. Tsinghua Science & Technology 15(4):434-440.

Chapter 2

Energy Demand on Dairy Farms in Ireland

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Abstract

Reducing electricity consumption in Irish milk production is a topical issue for two reasons. First, the introduction of a dynamic electricity pricing system, with peak and off-peak prices, will be a reality for 80% of electricity consumers by 2020. The proposed pricing schedule intends to discourage energy consumption during peak periods (i.e. when electricity demand on the nation grid is high) and to incentivise energy consumption during off-peak periods. If farmers, for example, carry out their evening milking during the peak period, energy costs may increase, which would impact farm profitability. Second, electricity consumption is identified to contribute to about 25% of energy use along the life cycle of pasture-based milk. The objectives of this study, therefore, were to document electricity use per kg of milk sold and to identify strategies that reduce its overall use while maximizing its use in off-peak periods (currently from 00:00 to 09:00 h). We assessed, therefore, average daily and seasonal trends in electricity consumption on 22 Irish dairy farms, through detailed auditing of electricity consuming processes. In order to determine the potential of identified strategies to save energy, we also assessed total energy use of Irish milk which is the sum of the direct (i.e. energy use on-farm) and indirect energy use (i.e. energy needed to produce farm inputs). On average, a total of 31.73 MJ was required to produce one kg of milk solids, of which 20% was direct and 80% was indirect energy use. Electricity accounted for 60% of the direct energy use, and mainly resulted from milk cooling (31%), water heating (23%) and milking (20%). Analysis of trends in electricity consumption revealed that 62% of daily electricity was used at peak periods. Electricity use on Irish dairy farms, therefore, is substantial and centred around milk harvesting. To improve the competitiveness of milk production in a dynamic electricity pricing environment, therefore, management changes and technologies are required that decouple energy use during milking processes from peak periods.

1 Introduction

The removal of the milk quota system in the European Union (EU) in 2015 is likely to increase milk production per farm and to decrease milk price (Bouamra-Mechemache et al., 2008; Lips et al., 2005). In Ireland, for example, milk production has the potential to increase by 50% by 2020 (DAFM, 2010) if farmers respond to national policy frameworks and are encouraged by the abolition of EU milk quotas in 2015, whereas milk price is expected to decrease by 33% (Lips et al., 2005). Milk production systems in Ireland, therefore, will continue to focus on cost control and maximising the amount of milk that is produced from grazed grass. The potential of Irish soils to grow grass throughout the year and success in utilizing grass are key factors affecting output and profitability of dairy production systems (Shalloo et al., 2004).

Efficient use of energy is one way to improve the cost competitiveness of the Irish dairy sector. At this moment, electricity costs on Irish farms are around 1.5% of cost price of milk sold (Upton et al., 2011), but they are expected to increase because of introduction of dynamic electricity pricing. Besides a potential cost reduction, reducing electricity consumption has an environmental benefit, because electricity consumption has been shown to represent 25% of total energy use on pasture-based dairy farms in New Zealand (Wells, 2001). Hence understanding electricity consumption trends will have the potential to reduce overall energy use and reduce production costs.

The new Irish electricity grid infrastructure is proposed by the Commission for Energy Regulation (CER) and 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. The peak period is typically from 17:00 to 19:00 h. If dairy farmers carry out their evening milking during these peak periods they will be exposed to increases in energy costs. This dynamic pricing structure, however, could also present opportunities to reduce overall energy costs if equipment is managed intelligently to optimise energy use in off-peak periods (currently from 00:00 to 09:00 h). By 2020, about 80% of all electricity consumers are expected to be connected to the smart grid (CER, 2011). The electricity demand on the national grid not only varies during the day (i.e. peak in evening), but also across seasons (i.e. peak in winter) (Eirgrid, 2012). To use energy cost-effectively, therefore, dairy farmers need insight into the variation in electricity consumption during the day, and across the year. To our knowledge, no research has been published that studied on-farm daily and seasonal electricity consumption profiles while providing detailed equipment electricity consumption information. This information, however, is required to identify strategies that reduce energy costs and that use electricity efficiently, i.e. aiming at a reduction of electricity use per kg of milk sold while maximizing its use in off-peak periods.

The main objective of this study, therefore, was to document electricity use per kg of milk sold from the farm and to identify strategies that can reduce its overall use while maximizing its use in off-peak periods. We assessed average daily and seasonal trends in electricity consumption on 22 Irish dairy farms, through detailed auditing of electricity consuming processes. In order to determine the potential of identified strategies to save energy, our second objective was to assess total energy use along the production chain of Irish milk. We therefore, performed a life cycle energy assessment of total energy use on 22 Irish dairy farms.

2 Materials and Methods

Data Collection

We selected 22 commercial dairy farms from a database of advisory clients within Teagasc, which are referred to as study farms. Selection criteria included availability of financial information, data on herd size and the ability and willingness of the farmer to collect and maintain accurate data. All data were collected for 2011. All inputs and outputs necessary to compile the life cycle energy assessment were recorded using a combination of manual recording and wireless data transfer. General farm data were collected using a survey, including farm area worked and detailed information on farm infrastructure (e.g. type and size of milking equipment, milk cooling equipment, manure handling equipment, machinery and winter housing facilities).

Monthly questionnaires were completed by each farmer. Data collected were: quantity and type of fertilizer used, quantity of diesel or fuel oil consumed, area of land worked by contractors, amount and type of concentrate feed purchased, forage/ manure/ slurry imported or exported from the farm, quantity and type of farm chemicals used and a stock take of all animals on the farm. In order to assess actual consumption of, for example, fertilizer or feed, opening and closing balances were obtained at the beginning and end of the monitoring period. In addition to thse data, milk production and composition information was gathered from the milk processors.

Electricity consumption was recorded using a wireless monitoring system supplied by Carlo Gavazzi (Carlo Gavazzi Automation SpA, Via Milano 13, I-20020 Lainate, Italy). Energy analysers of type EM24 DIN together with Digi connect wireless WAN cellular routers were used to measure and transport the electricity consumption data. Powersoft logging and recording software (Carlo Gavazzi Automation SpA) was used to record cumulative energy use in kiloWatt hours (kWh) every 15 minutes for each electricity consuming process behind the farm gate. Domestic electricity use was measured separately and subtracted for the dairy farm measurements.

Data Processing

Raw data from electricity monitoring were exported to spreadsheets, and subsequently used to compute trends in electricity consumption of individual farms. To determine electricity costs of individual farms, we combined data on electricity use with day and night tariffs (day tariff was 0.18 €/kWh; night tariff was 0.08 €/kWh from 00:00 to 09:00 h).

Furthermore, data obtained from questionnaires, dairy processors and the wireless electricity monitoring system were used to perform a life cycle energy assessment.

Life Cycle Energy Assessment

We performed a single-issue life cycle assessment (LCA) by quantifying the total energy use according to ISO (2006). The four stages of an LCA are: goal and scope, inventory analysis, impact assessment and interpretation of results (ISO, 2006).

Goal and Scope Definition. LCA relates in this case, energy use to a functional unit, which is the main function of a production system expressed in quantitative terms. The main function of our system is production of milk. To allow a comparison of our results with those presented in the literature (Basset-Mens et al., 2009; Cederberg and Flysjö, 2004; Hartman et al., 2006; O'Brien et al., 2012; Thomassen et al., 2009; Wells, 2001; Williams et al., 2006) we used multiple functional units: kg energy corrected milk (ECM); (Sjaunja et al., 1990; Yan et al., 2011)), kg fat-and-protein corrected milk (FPCM; (CVB, 2000)); kg milk solids (MS), liters of milk and kg of milk.

The system boundary was defined from cradle-to-farm-gate, which implies that energy use is quantified for all processes involved up to the moment that milk leaves the farm gate, including production and transport of concentrates, roughage, seeds, herbicides and chemical fertilizer. Such a cradle-to-farm gate LCA, therefore, resembles quantification of the direct (i.e. energy use on-farm) and indirect energy use (i.e. energy needed to produce farm inputs) of milk (De Boer, 2003).

Besides milk, our production system also yields meat from culled cows and calves. In such a multiple-output situation, the energy use of the system has to be allocated to these various outputs. We used economic allocation implying that the energy use was allocated to the various outputs based on their relative economic value (i.e. 88.3 % to milk and 11.7% to culled cows and calves).

Life Cycle Inventory. In the second stage, the inventory analysis, energy used in each production process is collected. For each product consumed by a dairy farm, an energy conversion factor is determined including the amount of energy related to the production and transport of each unit of this product. The energy conversion factors for chemical fertilizers, herbicides, and ingredients of purchased concentrates were based on the international LCA database Ecoinvent (2010). All applicable data quantities were converted to a common unit for international comparisons. For energy, this unit is the mega-joule (MJ) or giga-joule (GJ).

For the composition of concentrate feed used on each farm a standard 16% crude protein feed was chosen. Feed formulation was obtained from a number of feed suppliers (supplementary Table A). Yan et al. (2013) used the same methodology for feed composition analysis. The energy content per tonne of dry matter (DM), (MJ/T DM), of the standard concentrate was calculated using Ecoinvent (2010) and feed conversion tables from Nutrient Requirements for Dairy Cattle (NRC, 2001). Conversion factors for liquid fuels and factors about efficiency of electricity generation were taken from Howley et al. (2009), which provided local data for the distribution efficiency of the Irish electricity supply network.

Hours worked in the field for each contractor operation including ploughing, manure spreading and fertilizer spreading was recorded and a corresponding fuel usage was applied according to Witney (1996). Fuel used in transport of feed, fertilizer and forage to the farm have been included by incorporating the distance travelled from suppliers to the farm. With knowledge of the weight of material transported, conversion factors from Bone et al. (1996) were applied to find liters of fuel consumed in transportation. Lubricants including gear oil and transmission oil were also included. Production of medicines and machinery were excluded due to their small overall impact (Cederberg, 1998).

Other energy inputs in this study consisted of seeds used for reseeding grassland which contained a mixture of grass seed and clover seed. Purchased forage consisting of silage, hay, straw and whole crop wheat was also included. Herbicides and minerals mainly pre-calver minerals have been included. Forages were converted to tonnes of DM using tables from Nutrient Requirements for dairy cattle (NRC, 2001). All quantities were converted to MJ using the database Ecoinvent (2010).

Impact Assessment & Interpretation of Results. The impact assessment stage is where we process the data collected in the life cycle inventory phase. Raw data were processed to compute total energy use from cradle-to-farm-gate of milk production on a sample of Irish dairy farms using the common unit of energy, the MJ.

3 Results

General Farm Characteristics

Figure 1 shows the average lactation profile for the study farms relative to the average Irish dairy farm lactation profile. The study farms represent 0.14% of the specialised dairy farm population and supplied 0.24% of national milk in 2011. Table 1 shows the details of the study farms in terms of scale and production. The study farms operated grass-based milk production systems with spring calving herds. The seasonality of this production system in terms of milk output is visible in Figure 1. The average fat content of the milk supplied was 4.23% (with a standard deviation (SD) of 0.16%), whereas the average protein content was 3.60% (SD of 0.11%). In 2011, the national average fat content was 3.97% (SD of 0.23%) and protein content 3.39% (SD 0.15%; (CSO, 2012).

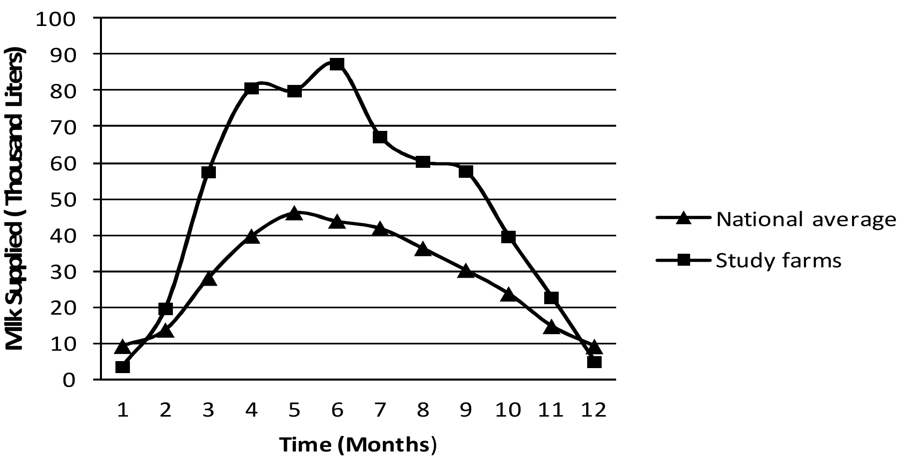

Figure 1; Mean milk production profile of the 22 study farms relative to the national average lactation profile for specialised dairy farms (CSO, 2012).

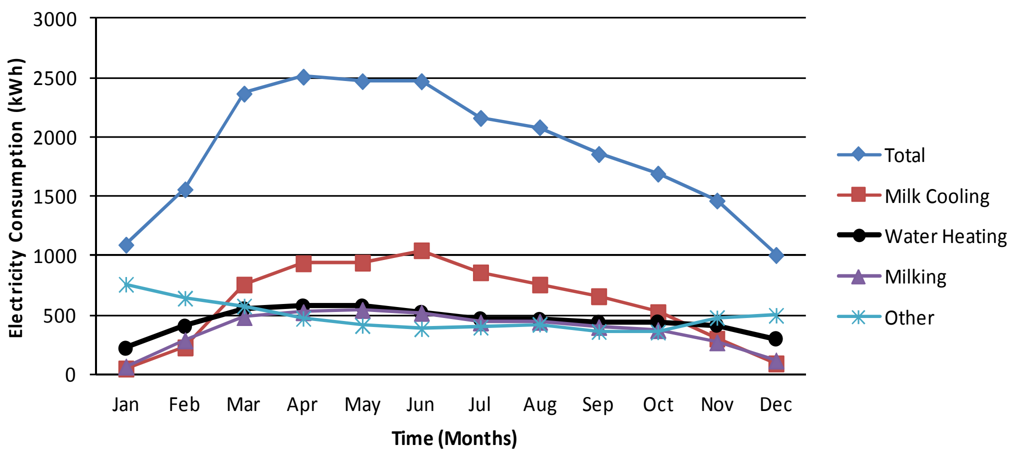

Figure 2; Monthly electrical energy consumption (kWh) for 22 farms over 12 months for all major energy consuming processes.

Table 1; Average production parameters for study farms compared to national average figures (CSO, 2012; Hennessy et al., 2011; Lalor et al., 2010).

Parameter	Min	Mean	Max	National Average
Farm Area (ha)	43	76	142	57
Number of Cows (Herd Size)	47	118	290	66
Stocking Density (LU/ha)[1]	1.68	2.27	3.45	1.77
Milk Production ('000 Liters/annum)	255	559	1329	316
Milk Production (Tonnes MS/annum)[2]	21	44	109	24
Nitrogen Application Rate (kg N/ha/annum)[3]	86	194	278	86
Kg of Concentrate Fed per 100 kg Milk Produced	0.49	1.19	2.06	NA[4]

[1] LU/ha = Livestock Units per hectare

[2] MS = Milk Solids

[3] N = Fertilizer Nitrogen

[4] NA = Not available

Energy Analysis

Table 2 presents total energy used, expressed per functional unit (diverse units), and the contribution of different processes along the life cycle per kg of milk solids (MS). Total energy use averaged 31.73 MJ/kg MS, ranging from 15.28 to 49.00 MJ/ kg MS. About 57% of this energy use was accounted for by the application of chemical fertilizers (range 40-80%). Other significant energy consuming processes included production and transport of purchased concentrate feed 21% (range 8-36%), electricity 12% (range 8-21%), and liquid fuels such as diesel, petrol and kerosene 8% (range 1-15%). Other items such as seeds and herbicides represented a small portion of total energy use 2% (range 0-15%).

Fertilizer application. There were large differences in the chemical fertilizer application rates in this study (Table 1). Mean energy input by chemical fertilizer was 17.96 MJ/kg MS (range 10.54-30.71 MJ/kg MS)

Concentrate Feed. The average farm fed 1.19 kg of concentrate per 100 kg of milk produced, (range 0.49-2.06 kg of concentrate / 100 kg of milk).

Fuel, Lubricants and Other Energy Inputs. Fuel used on the farm accounted for 66% of total fuel energy input and amounted to 1.68 MJ/kg MS. These inputs were specifically diesel (97.5% of on farm fuel use), gear oil and transmission oil (1.3%) and kerosene (1.2%). Fuel used by contractors accounted for 31.7% of fuel use and transport of feed, fertilizers and forage to the farm accounted for just 2.3% of fuel use. Other energy inputs amounted to 0.77 MJ/kg MS (range 0-5.08 MJ/kg MS).

Electrical Energy Inputs. The major processes of electricity consumption were: milk cooling (31%), water heating (23%), milking (20%), pumping water (5%), lighting (3%), other miscellaneous consumption such as winter housing systems, air compressors and backing gates consumed 18% of the electrical energy. All farms were non-irrigated. Electricity used in the dairy milking shed accounted for almost 80% of the total electrical energy used. Table 3 presents a more detailed analysis of the electricity consumption results.

Altogether 42.34 Wh (Watt-hours) of electricity was used per liter of milk produced (range 23.03-76.29 Wh/L). In total 62% of all electrical energy used by the farms in this study was on the higher cost day tariff. Costs are presented in Table 3. The average cost of electricity on the study farms in 2011 was €0.0051 per liter of milk produced (€/L) (range 0.0026-0.0087 €/L).

Milking Machine. All farms engaged herringbone milking plants with two stalls per milking unit and were fitted with oil lubricated centrifugal vane vacuum pumps without variable speed control. Milking parlour size varied from 8 to 24 milking units, the average number of cows per milking unit was 9. The milking machine consumed 20% of total electrical energy. This consists of the vacuum pumps and the milk pump. Electrical energy consumption of the milking machine was 8.44 Wh/L of milk harvested with a range from 4.38 to 13.78 Wh/L.

Milk Cooling. On all but one farm milk was cooled in the first instance by a pre-cooling system, consisting of a plate heat exchanger (PHE) followed by final chilling in a direct expansion (DX) milk cooling tank. Four farms used an ice builder (IB) milk cooling system. We observed that the IB systems delivered an energy efficiency of 19.22 Wh/L (range 16.00 – 21.77 Wh/L), while the DX systems achieved 11.19 Wh/L (range 6.38 – 15.89 Wh/L). The IB systems ran on day tariff for 30% of their operating times, whereas the DX systems used 70% day tariff electricity.

Water Heating. Of the 22 farms in this study, 20 farms used electrical powered water heating systems; all were pressurised cylinder type. The remaining farms use oil fired boilers to heat their water for milking plant washing. Diesel and kerosene used for this purpose were included in the fuel energy analysis section. Over 45% of water heating was carried out on the day tariff even though all farms had night tariff available for this purpose. Water heating consumed 9.83 Wh/L of milk sent to the dairy processor (range 3.30-14.30 Wh/L).

Other Electrical Inputs. Other miscellaneous equipment consumption across all farms was 7.54 Wh/l with a range of 2.02 Wh/L to 19.23 Wh/L. Figure 2 shows that 'other' electrical energy consumption increases from November to February corresponding to periods where farm animals are housed indoors resulting in electrical consumption by motorised manure scrapers and lights.

Electricity Consumption Trend Analysis

Daily Electricity Consumption Trends. The profile of electrical energy consumption trends from day to day followed a sinusoidal pattern (Figure 3), large peaks in consumption were a result of the morning and evening milkings. Figure 3 shows the average electrical demand of the study farms for the 14th and 15th of June 2011. These days were chosen as representative days during peak milk production to illustrate the nature of the electricity consumption profile. Consumption peaks were present from 7:00 to 12:00 h and again from 16:30 to 19:30 h, these peaks can be attributed to the twice a day milking routine used by the study farmers.

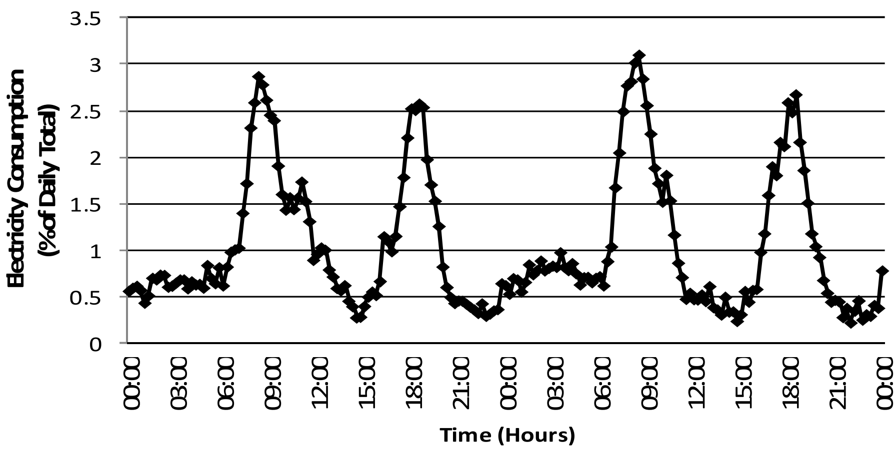

Figure 3; Average percentage of daily electricity consumption for 22 commercial farms in Ireland from 14th – 15th June 2011, data points at 15 minute intervals.

Seasonal Electricity Consumption Trends. The seasonal effect of electricity consumption follows the milk production curve due to the fact that over 80% of consumption is by equipment associated with milk harvesting. Consequently, 20% of electrical energy consumption is independent of the amount of milk produced. Figure 2 shows the seasonality of kWh consumption by month. It is evident that electricity consumption by milk cooling equipment, water heating plant and the milking machine pumps are linked to milk production as they follow the milk production curve (Figure 1). Consumption of other items is decoupled from milk production and rises from November to February.

Table 2; Total energy consumption (mean & standard deviation, min, and max) per energy input category, expressed in various units, for 22 study farms in 2011.

		GJ/Farm[2]	MJ/kg MS[3]	MJ/L	MJ/kg Milk	MJ/kg ECM[4]	MJ/ kg FPCM[5]	% of Total
Fertilizer	Mean	789.92	17.96	1.41	1.37	1.34	1.34	57%
	(SD)[1]	(315.24)	(6.25)	(0.50)	(0.48)	(0.47)	(0.47)	(11%)
	Min	226.78	10.54	0.87	0.85	0.81	0.81	40%
	Max	1428.95	30.71	2.44	2.37	2.30	2.3	80%
Concentrates	Mean	288.14	6.55	0.52	0.50	0.49	0.49	21%
	(SD)	(96.50)	(2.57)	(0.19)	(0.19)	(0.19)	(0.19)	(7%)
	Min	138.18	2.17	0.18	0.17	0.16	0.16	8%
	Max	504.31	11.87	0.95	0.92	0.89	0.89	36%
Electricity	Mean	172.19	3.91	0.31	0.30	0.29	0.29	12%
	(SD)	(73.83)	(1.06)	(0.08)	(0.08)	(0.08)	(0.08)	(3%)
	Min	67.68	2.25	0.18	0.18	0.17	0.17	8%
	Max	395.58	6.75	0.53	0.53	0.50	0.50	21%
Fuel	Mean	111.62	2.54	0.20	0.19	0.19	0.19	8%
	(SD)	(65.29)	(1.32)	(0.10)	(0.10)	(0.10)	(0.10)	(3%)
	Min	3.55	0.04	0.00	0.00	0.00	0.00	1%
	Max	291.40	6.18	0.48	0.46	0.46	0.46	15%
Other	Mean	33.83	0.77	0.06	0.06	0.06	0.06	2%
	(SD)	(62.27)	(1.11)	(0.09)	(0.08)	(0.08)	(0.08)	(3%)
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0%
	Max	297.57	5.08	0.39	0.39	0.39	0.39	15%
Total	Mean	1395.71	31.73	2.50	2.42	2.37	2.36	100%
	(SD)	(414.38)	(7.72)	(0.61)	(0.59)	(0.58)	(0.58)	-
	Min	484.14	15.28	1.25	1.21	1.15	1.15	-
	Max	1973.47	49.00	3.90	3.79	3.67	3.67	-

[1] SD = Standard Deviation

[2] GJ = Giga Joules

[3] MJ = Mega Joules, MS = Milk Solids

[4] ECM = Energy Corrected Milk

[5] FPCM = Fat and Protein Corrected Milk

Table 3; Breakdown of electricity consumption per liter of milk produced including cost of electrical energy consumed and tariff distribution profile by percentage of day rate tariff usage.

	Electricity Consumed (Wh/L) [1]	Cost of electricity (€/L) [2]	% day tariff [3]
Milk Cooling	13.02	0.0016	60%
Water Heating	9.83	0.0011	45%
Milking	8.44	0.0011	71%
Lighting	1.37	0.0002	89%
Other	7.54	0.0010	69%
Water Pumping	2.13	0.0003	38%
Total	42.34	0.0051	62%

[1] Wh/L = Watt hours / Liter

[2] €/L = Euro per Liter

[3] Percentage of electricity consumed from 09:00 to 12:00 h

4 Discussion

General Farm Characteristics

It is evident that the study farms had a much higher milk output than the national average farm, and therefore, were not representative for Irish dairy farms in 2011. Study farms represent the larger than average modern dairy farm, with a higher stocking density per ha (i.e. more intensive). Milk output and hence herd size will increase in future if farmers respond to the potential for expansion in milk production identified in the Food Harvest 2020 report (DAFM, 2010). Results of this study and hence the conclusions drawn, therefore are relevant for larger and more intensive dairy farms.

Comparisons with Other Studies

Table 4 presents total energy use per unit of milk production from selected international studies. These countries represent a variety of milk production systems and climatic conditions, hence the large differences across studies. Comparisons were made to assess how results of this study fit within the range in the literature.

Based on data of 150 dairy farms in New Zealand, Wells (2001) computed an average total energy use of 24.60 MJ/kg MS, of which 38% was related to fertilizers, 21% to liquid fuels, 20% to electricity and 21% to other items. Basset-Mens et al. (2009) computed a total energy use for a national average New Zealand farm of 1.51 MJ/kg of milk. This Irish study assessed an average total energy use of 31.73 MJ/kg MS or 2.42 MJ/kg milk. The higher average values in this study are explained mainly by a higher input of chemical nitrogen (N) fertilizer per ha, of on average 198 kg N/ha per year. Farms studied by Wells applied 85 kg of N/ha per year, whereas Basset-Mens et al. (2009) assumed a value of 114 kg N/ha per year.

Based on data of 8 dairy farms, Cederberg and Flysjö (2004) reported 2.7 MJ per kg ECM, of which 50-60% was required for cultivation and transportation of purchased feed. Based on data of 119 farms, Thomassen et al. (2009) reported 5.3 MJ per kg FPCM, of which 56% was required for cultivation and transport of purchased feed.

This study reported only 2.37 MJ/kg ECM or 2.36 MJ per kg FPCM, which is in line with results of O'Brien et al. (2012) who found that energy use per kg FPCM was lower in grass-based (2.3 MJ/kg FPCM) than in confinement systems (3.9 MJ/kg FPCM).

Electricity consumption analysis

Electricity use is a significant consumer of energy and accounts for 12% of total energy use, and 60% of the direct energy use. This study has quantified the breakdown of electricity usage by component, within day and between season's usage as well as comparing the usage of electricity on night and day tariffs on a subset of commercial dairy farms. In effect, 80% of the electricity use is related to heating water, cooling milk and running the milking machine. These fundamental operations are common across all milk production systems, not just grass-based systems. Hence, efficiency figures and recommendations described in relation to these operations should be applicable to other global milk producers. This information will contribute to the energy efficiency and cost reduction agenda at farm level.

Daily Electricity Consumption Trends. Figure 4 shows the demand on the national grid for the same two days that are presented in Figure 3 (Eirgrid, 2012). The cyclical nature of the load on the national grid is visible.

The peak in electricity consumption on the study farms occurred during the time intervals when demand on the grid was highest. In a dynamic electricity pricing environment these times would correspond with periods of higher electricity costs. Peak demand on the grid occurred between 17:00 and 18:00 h. This peak demand was 78% higher than the lowest demand interval which occurred between 05:00 and 06:00 h. Consequently the lowest cost electricity would be available at this time.

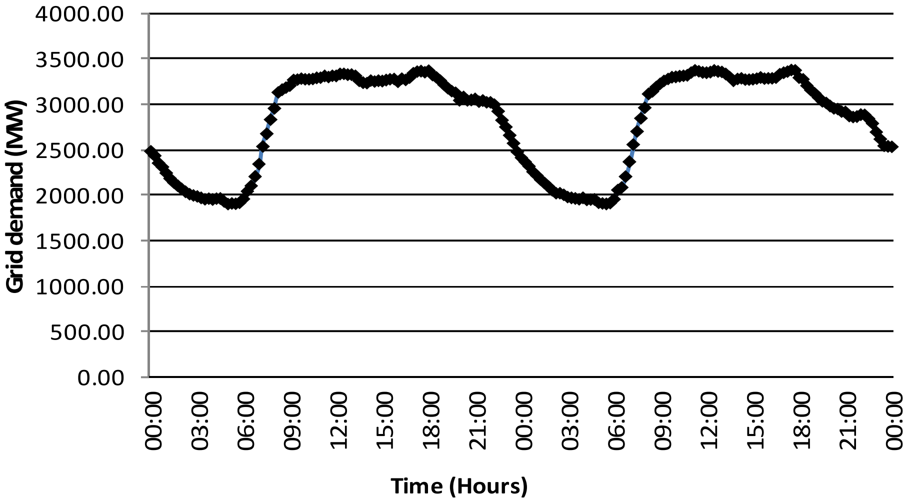

Figure 4; Demand on the Irish electricity grid in mega Watts from 14th – 15th June, data points at 15 minute intervals.

Seasonal Electricity Consumption Trends. The demand on the national grid also experiences a seasonal effect. Figure 5 shows the demand on the national grid, in mega Watts (MW) from January 2010 to December 2011 inclusive (Eirgrid, 2012). Peak demand occurred in December 2010 with weakest demand in July 2011. The peak was 30% higher than the trough. In a truly dynamic electricity pricing scenario this seasonal effect would result in a higher electricity price in winter months versus summer months. The Irish milk production system produces milk from grazed grass which requires a spring calving pattern resulting in higher energy use during the summer months (Figure 2). This may present an opportunity to farmers with spring calving herds to optimise calving patterns to reduce electricity consumption during winter months when electricity prices are likely to be higher.

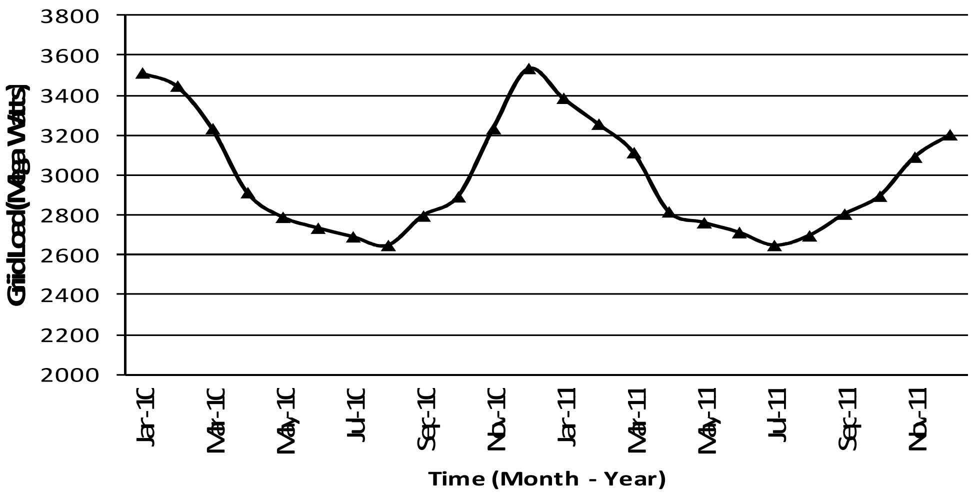

Figure 5; Demand on the Irish electricity grid in mega Watts from Jan 2010 to Dec 2011.

Options for Reducing Electricity Consumption and Electricity Costs

Electricity consumption analysis of both daily and yearly consumption patterns show that dairy farmers could be exposed to higher electricity prices if a pricing structure is implemented that varies tariffs according to the load on the national grid. The results of this study pertaining to electricity consumption trends and their relationship to the demand profile on the national grid may be of relevance to dairy industries internationally. Estonia, Finland, France, Ireland, Italy, Malta, The Netherlands, Norway, Portugal, Spain, Sweden and the United Kingdom are all classified as "Dynamic Movers" in relation to the implementation of smart grid infrastructure. These countries have a clear path towards a full rollout of smart metering. Either the mandatory rollout is already decided, or there are major pilot projects that are paving the way for a subsequent decision (Hierzinger et al., 2012). Other countries such as Australia and New Zealand have recognised smart metering as a method of improving resource use efficiency and have carried out some early stage feasibility studies and cost benefit analysis calculations (Energy Fed NZ, 2010, DRET, 2008). Many of these countries have well established milk production industries that may be able to use smart grid infrastructure to their advantage by taking note of some of the findings of this study.

Further research is required to quantify the financial impact of possible smart grid roll out on commercial farms based on differing smart metering approaches, however a three pronged approach to maximise the efficiency of energy usage in the context of smart metering will be required. Firstly, decoupling large energy users such as milk cooling and water heating from milking times and shifting them to off peak periods will be required. Milk cooling has the largest electrical energy consumption (31% of total electricity consumption) on Irish dairy farms. Over 60% of milk cooling electricity consumption currently occurs on the more expensive day rate tariff. Using a milk cooling system that decouples the cooling load from these peak tariffs would be useful in mitigating the impact of a smart metering electricity pricing scenario, because cold energy could be generated when electricity is cheap. IB system in this study used more electricity per liter of milk cooled than the alternative DX systems, however IB systems can be an effective tool to decouple the milk cooling load from milking times by shifting the load to off peak periods but only if they are set up and managed correctly (MDC, 1995). This practice together with optimised use of a PHE with ground water would reduce energy use and energy costs associated with milk cooling. This strategy of shifting the load to the off peak rates would reduce on-farm energy costs both in a day/night and a dynamic electricity pricing scenario.

Secondly, in the longer term, a farmer must decide whether they should alter their calving pattern and thus the seasonality of milk supply to avoid producing milk when the demand and ultimately the price will be at peak (December and January). In a spring calving grass based system the electricity demand should be the lowest at this point as most cows are not lactating. Further research is required to investigate the impact of calving pattern (including spring versus autumn calving) on the energy demand and energy costs of milk production in various dynamic electricity pricing scenarios.

Thirdly, efficiency gains and lower energy costs can be realised through application of energy efficient technology. For example there may be scope to reduce the electricity consumed by vacuum pumps through the application of variable speed drive (VSD) technology. However, adoption at farm level is low. Similarly there are no studies available quantifying the use of solar thermal water heating systems or solar photo voltaic cells, or micro wind turbines in the Irish dairy environment. Some of these systems have been shown to be an effective solution on French and New Zealand dairy farms (IDL, 2009) (Morison et al., 2007). However given the difference in climate, due to changes in latitude, country specific data is required.

Future Analysis of Electricity Consumption

This study has shown that there is a requirement for a model to be developed around electricity usage on dairy farms. This model should be integrated with a whole farm model similar to those that currently exist (the Moorepark Dairy Systems Model) (Shalloo et al., 2004). Options around calving pattern (autumn vs. spring), milking frequency, and the integration of smart metering could be evaluated on, energy consumption and energy costs across a range of herd sizes and production systems.

5 Conclusion

This study presents novel data regarding daily and seasonal electricity consumption trends from 22 commercial dairy farms in Ireland. On average, a total of 31.73 MJ was required to produce one kg of milk solids, of which 20% was direct and 80% was indirect energy use. Electricity accounted for 60% of the direct energy use and appeared centred around milking. Over 60% of daily electricity was used at peak periods. To improve the competitiveness of milk production in a dynamic electricity pricing environment, therefore, management changes and technologies are required that decouple energy use during milking processes from peak periods. Combining technology that decouples energy use from milking times with energy efficient technology therefore, can improve the economic and environmental competitiveness of the milk production sector.

Table 4; Compared energy consumption, in mega joules (MJ), assessment of milk production of selected studies, gathered by functional unit.

Study	Study case	Country [1]	FU [2]	Subset	Total Energy	Direct Energy	Indirect Energy
Wells (2001)	150 commercial farms	NZ	kg MS	Average	24.60	10.80	13.80
Wells (2001)	150 commercial farms	NZ	kg MS	Irrigated	33.60	17.80	15.80
Wells (2001)	150 commercial farms	NZ	kg MS	Non-Irrigated	21.60	8.90	12.70
Hartman et al (2006)	62 dairy farms	NZ	kg MS	Total	47.00	24.40	22.60
This study	22 dairy farms	IRE	kg MS	Total	31.73	6.45	25.28
Basset-Mens et al (2009)	Average Dairy Farm	NZ	kg Milk	Total	1.51	NA [3]	NA
This study	22 dairy farms	IRE	kg Milk	Total	2.42	0.49	1.93
Thomassen et al (2009)	119 dairy farms	NL	kg FPCM	Total	5.30	0.80	4.50
O'Brien et al (2012)	1 research farm	IRE	kg FPCM	Total	2.30	NA	NA
This study	22 dairy farms	IRE	kg FPCM	Total	2.36	0.48	1.88
Cederberg and Flysjö (2004)	8 farms production <7500 kg ECM/ha	S	kg ECM	Total	2.70	NA	NA
This study	22 dairy farms	IRE	kg ECM	Total	2.37	0.48	1.89
Williams et al (2006)	Non-organic	UK	Liter of milk	Total	2.52	NA	NA
This study	22 dairy farms	IRE	Liter of milk	Total	2.50	0.51	1.99

[1] NZ = New Zealand, IRE = Ireland, NL = The Netherlands, S = Sweden, UK = United Kingdom

[2] FU = Functional unit, MS = Milk Solids, FPCM = fat and protein corrected milk, ECM = energy corrected milk

[3] NA = Not available

References

Basset-Mens, C., S. Ledgard, and M. Boyes. 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecol. Econ. 68(6):1615-1625.

Bone, I., M. Galvin, I. Moncrieff, T. Brennand, P. Cenek, C. Perrins, K. Jones, P. Winder, and M. Hunt. 1996. Transport (Part3). Pages 339-351 in: Energy Efficiency: A guide to current and emerging technologies, Volume 1, Buildings and Transportation. Centre for Advanced Engineering, University of Canterbury, Christchurch.

Bouamra-Mechemache, Z., R. Jongeneel, and V. Requillart. 2008. Impact of a gradual increase in milk quotas on the EU dairy sector. Eur. Rev. Agric. Econ. 35(4):461-491.

Cederberg, C. 1998. Life cycle assessment of milk production – a comparison of conventional and organic farming SIK, Report No. 643. The Swedish Institute for Food and Biotechnology, Goteborg, Sweden, pp. 1–86.

Cederberg, C. and A. Flysjö. 2004. Life cycle inventory of 23 dairy farms in southwestern Sweden. SIK Report Nr 728. The Swedisch Institute for Food and Biotechnology, Göteborg, Sweden.

CER. 2011. Second Consultation on Possible National Rollout Scenarios for the Smart Metering Cost Benefit Analysis, Commission for Energy Regulation, Ireland.

CSO. 2012. Central Statistics Office, Statbank database, accessed 01-08-2012, Link http://www.cso.ie/px/pxeirestat/statire/SelectTable/Omrade0.asp?PLanguage=0.

CVB. 2000. Tabellenboek Veevoeding 2000: Voedernormen Landbouwhuisdieren en Voederwaarde Veevoeders. Centraal Veevoeder Bureau, Lelystad, The Netherlands.

DAFM. 2010. Food harvest 2020 – A vision for Irish agri-food and fisheries. Department of Agriculture Food and the Marine, Ireland.

De Boer, I. J. M. 2003. Environmental impact assessment of conventional and organic milk production. Livest. Prod. Sci. 80(1-2):69-77.

DRET. 2008. Cost-benefit analysis of options for a national smart meter roll-out: Phase Two—Regional and detailed analyses regulatory impact statement. Department of Resources Energy and Tourism (DRET), Canberra, Australia.

Ecoinvent. 2010. Ecoinvent 2.0 database. Swiss centre for life cycle inventories, Dübendorf. <http://ecoinvent.ch> (accessed 30.05.2012).

Eirgrid. 2012. System demand tables 2011, Accessed 15-10-2012, Link; http://www.eirgrid.com/operations/systemperformancedata/systemdemand/.

Energy Fed NZ. 2010. Developing our energy potential, New Zealand Energy Efficiency and Conservation Strategy. Energy Federation of New Zealand.

Hartman, K. and R. Sims. 2006. Saving energy on the dairy farm makes good sense. Proceedings of the 4th Dairy3 Conference held at Hamilton New Zealand. Centre for Professional Development and Conferences, Massey University, Palmerston North, New Zealand.

Hennessy, T., B. Moran, A. Kinsella, and G. Quinlan. 2011. National Farm Survey 2010. Agricultural Economics & Farm Surveys Department, Teagasc Athenry Co. Galway, Ireland. Available from: http://www.teagasc.ie/publications/2011/1016/NFS10.pdf (Viewed on February 15, 2012).

Hierzinger R., Albu M., van Elburg H, Scott A.J., Lazicki A., Penttinen L., Puente F., and Saele H. 2012. European Smart Metering Landscape Report, SmartRegions Deliverable 2.1. Accessed May 24 2013. http://www.energyagency.at/fileadmin/dam/pdf/projekte/klimapolitik/SmartRegionsLandscapeReport2012.pdf

Howley, M., B. O'Gallachoir, and E. Dennehy. 2009. Energy in Ireland 1990–2008. Energy policy statistical support unit. Sustainable Energy Authority of Ireland.

IDL. 2009. Les consommations d'énergie en bâtiment d'élevage laitier. Repères de consommations et pistes d'économies. Institut de l'élevage.

ISO. 2006. Environmental Management, The ISO 14000 Family of International Standards ISO Standard Collection. Geneve, Switzerland.

Lalor, S. T. J., B. S. Coulter, G. Quinlan, and L. Connolly. 2010. A survey of fertilizer use in Ireland from 2004-2008 for grassland and arable crops. Teagasc Johnstown Castle Environment Research Centre, Wexford, Ireland.

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):1-16.

MDC. 1995. Bulk milk tanking cooling efficiency, Milk Development Council UK.

Morison, K., W. Gregory, and R. Hooper. 2007. Improving Dairy Shed Energy Efficiency, Technical Report, New Zealand Centre for Advanced Engineering, University of Canterbury Campus, Private Bag 4800, Christchurch 8140 New Zealand.

NRC. 2001. Nutrient Requirements of Dairy Cattle: Seventh Revised Edition. Subcommittee on Dairy Cattle Nutrition, Committee on Animal Nutrition, National Research Council.

O'Brien, D., L. Shalloo, J. Patton, F. Buckley, C. Grainger, and M. Wallace. 2012. A life cycle assessment of seasonal grass-based and confinement dairy farms. Agric. Syst. 107:33-46.

Shalloo, L., P. Dillon, M. Rath, and M. Wallace. 2004. Description and validation of the Moorepark Dairy System Model. J. Dairy Sci. 87(6):1945-1959.

Sjaunja, L. O., L. Baevre, L. Junkkarinen, J. Pedersen, and J. Setala. 1990. A Nordic proposal for an energy corrected milk (ECM) formula. In 27th session of the International Commission for Breeding and Productivity of Milk Animals, Paris.

Thomassen, M. A., M. A. Dolman, K. J. van Calker, and I. J. M. de Boer. 2009. Relating life cycle assessment indicators to gross value added for Dutch dairy farms. Ecol. Econ. 68(8-9):2278-2284.

Upton, J., M. Murphy, and P. French. 2011. Lessons Learned from Teagasc Energy Audits. Proceedings of the Teagasc National Dairy Conference:101-106. Teagasc, Ireland.

Wells, C. 2001. Total energy indicators of agricultural sustainability: Dairy farming case study. Technical Paper 2001/3 prepared for the New Zealand Ministry of Agriculture and Fisheries, Wellington, New Zealand.

Williams, A. G., E. Audsley, and D.L.Sandars. 2006. Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Main Report Defra Research Project ISO205, Bedford: Cranfield University and Defra.

Witney, B. 1996. Choosing and using farm machines, Land Technology. Land Technology.

Yan, M. J., J. Humphreys, and N. M. Holden. 2011. An evaluation of life cycle assessment of European milk production. J. Environ. Manage. 92(3):372-379.

Yan, M. J., J. Humphreys, and N. M. Holden. 2013. The carbon footprint of pasture-based milk production: Can white clover make a difference? J. Dairy Sci. 96(2):857-865.

Supplementary Material

Table A. Relative share of various feed ingredients (including country of origin) and energy conversion factor used in the concentrate feed. (Source: Irish Feed miller, 2011).

Component - Origin	Relative Share of Ingredients	MJ / T DM
Barley - Ireland	3%	3150
Wheat - Ireland	3%	3380
Maize Grain Europe	5%	4498
Soya (bean) hulls – Argentina/USA	16%	70
Palm Kernal – Indonesia/Malaysia	4%	3905
Rapeseed – Canada	15%	10940
Citrus Pulp – Brazil/USA	17%	1603
Maize Gluten - USA	8%	12676
Molasses – Pakistan	6%	3800
Distillers grains	17%	16488
Vegetable oil	3%	10668
Minerals	3%	5000
Total	100%	7031

Chapter 3

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, i) 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, ii) validated the MECD using empirical data of one year on commercial spring calving, grass-based dairy farms with 45, 88 and 195 milking cows and iii) demonstrated the functionality of the model by applying two electricity tariffs to the electricity consumption data and examining the effect on total dairy farm electricity costs. The MECD was developed using a mechanistic modelling 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 – 38% by moving from a day and night tariff to a flat tariff.

1 Introduction

Grass-based production of one liter 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 Mega Joules (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 09:00 to 00:00 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 years for European farmers (Eurostat, 2013). Moreover, European dairy farmers are approaching a period of change driven by the removal of the milk quota regime. Without a quota regime, 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 17:00 to 19:00 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 present opportunities to reduce overall energy costs if equipment is managed intelligently to optimise energy consumption in off-peak periods (currently from 00:00 to 09:00 h) (Upton et al., 2013). Evaluation of the potential impact of electricity pricing tariff changes on dairy farm electricity costs requires the development of a specific electricity consumption model.

Similarly, changing one technology in favour of another (e.g. the addition of a water cooled plate heat exchanger to pre-cool milk) or one management strategy over another (e.g. milking once or twice a 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 about farm electricity consumption gathered through a physical auditing process. Finally, we demonstrated an application of the model by evaluating the impact of two electricity pricing tariffs on total dairy farm electricity costs.

2 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 the 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, vacuum pump size etc.) and management practices (e.g. grazing season length), and calculated the electricity consumed by each of the 7 infrastructural systems for 24 hours of a day 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:

$$Q_{mc}(i,j) = \frac{C_m \times \Delta T(i,j) \times M_m(i,j)}{COP(i,j) \times 3600} \qquad [1]$$

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

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

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)), $\Delta T(i,j)$ = difference in temperature between the milk entering the storage tank ($T_{bulk}(i,j)$) and the milk tank set point (T_{final}) (°C). $T_{bulk}(i,j)$ 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). $M_m(i,j)$ 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), COP(i,j) was the milk cooling system coefficient of performance, dimensionless (-). A sub-model was developed to compute the cooling systems 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 vapour compression refrigeration cycle performance of an individual cooling system but rather provide a dynamic element to the COP value of a generalised Direct Expansion (DX) or Ice Bank (IB) cooling system. T_{evap} = evaporator temperature of the refrigeration system (assumed to be 268 Kelvin (K) for DX and 265 K for IB). T_{amb} (K) = hourly ambient temperatures for 2011 from Met Eireann (Irish meteorical service), the farms used in the validation of this model were within a 20 mile radius of this weather station. *a* = adjustment factor to account for inefficiencies in real world systems (assumed 0.10 for this analysis). This approach yielded a range in COPs for a DX system of 1.2 to 4.1 and 1.1 to 2.7 for an IB system.

The start time of the cooling system coincided with the time of milking (which was a model input). The duration of cooling was computed with knowledge of the necessary cooling consumption (equation 1) as well as the installed capacity of the cooling system (equation 4).

$$t_m(i,j) = Q_{mc}(i,j)/C_{cap} \qquad [4]$$

Where $t_m(i,j)$ was the time taken to cool the milk (hours), and C_{cap} was the capacity of the milk cooling compressors (kW). However, on any given day Q_{mc} can vary due to the ambient temperature effect on the COP, which in turn varies t_m. To combat this issue an approximation of the COP (average COP value across all times and seasons), was used as a first iteration. This allowed the electricity consumption to be placed in the relevant time horizon, which in turn allowed the final appropriate COP value to be assigned to the cooling consumption on an hourly basis.

Water Heating. The electricity consumed to heat water on a dairy farm was described by equation 5.

$$Q_{wh}(i, j) = \frac{C_w \times \Delta T(i, j) \times M_w(i, j)}{\varepsilon \times 3600} \qquad [5]$$

Where $\Delta T(i, j) = T_{hot} - T_{cold}(i, j)$ [6]

And $Q_{wh}(i,j)$ = predicted energy consumption for heating cleaning water in month i (1-12) and hour j (1-24) (kWh), C_w = specific heat capacity of water (kJ/kg.°C), $\Delta T(i,j)$ = difference in temperature between the water entering the storage tank ($T_{cold}(i,j)$) and the water heater set point (T_{hot}) (°C). Borehole water temperatures from Goodman et al. (2004) were used to determine T_{cold}. Guidelines for hot water temperatures and recommended water volumes per milking cluster were taken from the Teagasc Milk Quality Handbook (O'Brien, 2008), and used for T_{hot}. The mass of water to be heated was represented by $M_w(i,j)$ (kg). ε was the efficiency of the heating system (-) taken at 0.90 from Upton et al. (2010). The time taken to heat the water was computed using equation 7.

$$t_w(i, j) = Q_{wh}(i, j) / P_{wh} \qquad [7]$$

Where $t_w(i,j)$ was the time taken to heat the water (hours) which was used to determine the specific hours the water heating system was used, and P_{wh} was the installed capacity of the water heating system (kW). Water heating commenced at 00:00 h to coincide with night rate electricity tariffs if the heating system was controlled with a timer, otherwise heating commenced after each milking.

Milking Machine. Electricity consumption of the milking machine was described by the formula:

$$Q_{mm} = (Roundup(N_{cows} / N_{cluster}) \times t_{row} + t_{wash}) \times Pp \qquad [8]$$

Where Q_{mm} = predicted electricity consumed by the milking machine for one milking (kWh), N_{cows} = number of cows milked, $N_{cluster}$ = number of milking clusters in the milking parlour. t_{row} was the cycle time needed to milk $N_{cluster}$ of cows, (hours) and Pp was the installed capacity of the milking machine pumps (kW). t_{wash} was the time required to wash the milking machine clusters and pipes with cleaning fluid after milking. Where Roundup indicates that the number of cycles needed was rounded to the first integer above the outcome of $N_{cows}/N_{cluster}$.

Lighting. Electricity is consumed by lighting on a dairy farm in three main areas, 1) during milking, 2) in the housing facilities, and 3) lighting outdoor areas. Electricity consumed by lighting was then described by equation [9];

$$Q_l(i, j) = N_{lm} \times Q_{lm} \times T_{lm}(i, j) + N_{hf} \times Q_{lhf} \times T_{lhf}(i, j) + N_{lod} \times Q_{lod} \times T_{lod}(i, j) \qquad [9]$$

Where $Q_l(i,j)$ = predicted electricity consumed by lighting for month i and hour j (kWh), N_{lm} = number of light fittings in the milking facility, Q_{lm} = installed capacity per light unit in the milking facility (kWh), this is calculated using a lookup table of light types. $T_{lm}(i,j)$ = operating time of lights in the milking facility (hours), which was assumed to be equal to milking time (i.e. $Roundup(N_{cows}/N_{cluster}) \times t_{row} + t_{wash}$). Similarly for the remaining variables where hf = housing facility and od = outdoor area. $T_{lhf}(i,j)$ and $T_{lod}(i,j)$ were specified as inputs to the model and describe the operating times of the lights in the housing facilities and the outdoor areas during the months when animals are housed indoors.

Water pump & wash pump. The predicted electricity consumed by the water pumps in month i and hour j, $Q_{wp}(i,j)$ (kWh), was described by the equation;

$$Q_{wp}(i,j) = [(V_{mc}(i,j) + V_{dc}(i,j) + V_w(i,j)) / P_c] \times P_{wp} \qquad [10]$$

Where $V_{mc}(i,j)$ = volume of water consumed by the milking cows (L) which was pumped to water troughs for drinking, $V_{dc}(i,j)$ = volume of water consumed by the dry cows (L). V_{mc} and V_{dc} were taken from Beede (1992), $V_w(i,j)$ = water used for washing and cleaning (L), which was calculated using a combination of data from Beede (1992) and De Boer et al. (2013). P_c = total pump capacity (L/hour) and P_{wp} = total pump power (kW) which are model inputs.

Winter housing. The predicted electricity consumption of the automatic scraping systems in month i and hour j, $Q_{as}(i,j)$, (kWh), was described by the equation;

$$Q_{as}(i,j) = S_{st} \times S_f(i,j) \times S_p \times (D_{in} - D_{out}) \qquad [11]$$

Where S_{st} = scraper sweep time (hours), S_f = scraping events in month i and hour j (-), S_p = scraper power (kW), D_{in} = housing date of animals (Mo), D_{out} = turnout date of animals (Mo). The months of housing and turnout are converted to integers for the purposed of equation 11.

Cost & CO_2 Calculations

The 7 electricity consumption matrices described above were summed for month i and hour j to give the total dairy farm consumption matrix (M_t). Based on the users model inputs, a 12 × 24 matrix was populated for electricity tariffs. Tariffs were compiled from electricity suppliers of the farmers. CO_2 emission factors for electricity production were taken from Howley (2011) and used to populate a 12 x 24 matrix. These matrices were multiplied by M_t to yield the cost matrix (M_c) and emission matrix (M_e).

Model Validation

To validate the performance of the model, the energy consumption of three Irish farms were simulated and compared to actual farm data: a small farm (SF) with 45 milking cows; a medium farm (MF) with 88 milking cows, and a large farm (LF) with 195 cows. Farms chosen were spring calving herds operating grass-based milk production systems with low supplementary feed input. Actual data from these farms were based on Upton et al. (2013), which yielded detailed electricity consumption data for all major infrastructural systems for all months in 2011, such as milking equipment, milk cooling, manure handling equipment, water pumps and winter housing facilities. Details of the farms scale and production levels are presented in Table 1.

Table 1; Mean values of characteristics for three farms, SF (small farm), MF (medium farm) and LF (large farm).

Farm Characteristics	SF	MF	LF
Farm Area (ha)	48	70	110
Dairy herd Size	45	88	195
Stocking Density (LU/ha)[1]	1.68	1.90	2.43
Milk Production (Liters/annum)	255,278	499,898	774,089
Milk Production (kg MS/annum)[2]	21,429	39,286	62,199
Production intensity (Kg MS/ha)	446	561	565
Milk Solids per cow (kg MS/cow)	476	446	319

[1] LU/ha = Livestock Units per hectare. Where one livestock unit is equivalent to one adult dairy cow.

[2] MS = Milk Solids

Evaluating model bias and precision

The following parameters were computed to evaluate model bias and precision.

Mean square prediction error (MSPE). The MSPE is defined by equation 12 (Bibby and Toutenburg, 1977).

$$MSPE = (A_m - P_m)^2 + S_P{}^2(1-b)^2 + S_A{}^2(1-r^2) \qquad [12]$$

The MSPE is comprised of the mean bias, line bias and random variation. Where A_m and P_m are the means of the actual and predicted electricity consumption data, $S_A{}^2$ and $S_P{}^2$ are the variances of the actual and predicted electricity consumption data, b is the slope of the linear regression of actual on predicted and r is the correlation coefficient of actual and predicted. A mean bias (A_m-P_m) different from zero indicates that predicted values are respectively consistently higher or lower than the actual values. A low line bias, which is the deviation of the slope of the regression of actual on predicted from unity (1-b), indicates that the model will under predict at low actual values and over predict at high actual values, or vice versa. The results of mean bias, line bias and random variation were calculated as a proportional contribution to each of the three components to the total MSPE. The proportional contribution of the mean bias, line bias and random variation was calculated as the mean bias, line bias and random variation divided by the MSPE. The relative contribution of the random variation around the regression line ($1-r^2$) is high if the MECD is predicting electricity consumption with a high level of accuracy. This random variation is due to electricity consumption variation due to farmer and equipment operating behaviour.

The Root Mean Square Error (RMSE). The RMSE (Bibby and Toutenburg, 1977) was calculated as:

$$RMSE = \sqrt{MSPE} \quad [13]$$

The RMSE provides information on the accuracy of the simulation by comparing term by term the actual and predicted data.

Relative Prediction Error (RPE). The RPE (Rook et al., 1990) was calculated as:

$$RPE = \left(\frac{RMSE}{Am} \right) \times 100 \quad [14]$$

Where A_m is the mean value of the actual data. The RPE is an expression of the RMSE as a percentage of the actual data. According to Fuentes-Pila et al. (1996) a RPE lower than 10% indicates a satisfactory prediction, between 10% and 20% a relatively acceptable prediction, and an RPE greater than 20% suggests a poor model prediction**.**

On-Farm Data used for model validation

In 2011, actual milk production was 255,278 L for SF, 499,898 L for MF and 774,089 L for LF, whereas actual electricity consumption was 8,791 kWh for SF, 21,099 kWh for MF and 33,262 kWh for LF. Table 2 shows the actual electricity consumption (kWh) for each of the 7 main infrastructural systems on each of the three farm sizes. On average, milk cooling made up 40% of total electricity consumption across all three farms (range 26 – 49%), water heating 28% (range 24 – 34%), milking machine 18% (range 17 – 24%), wash pump 0.3% (range 0 – 0.7%), water pump 8% (range 1 – 9%), automatic scrapers 4% (range 0 – 8%) and lighting 3% (range 1 – 5%).
The actual electricity consumption and electricity costs per liter of milk were lowest for the SF, i.e. 34 Wh/L and €0.0043/L, with 62% of electricity consumed on the day rate electricity tariff (from 09:00 to 00:00 h). Electricity consumption values were 42 Wh/L for MF and 43 Wh/L for LF, whereas electricity costs were €0.0058/L for MF and €0.0051 €/L for LF, with 75% and 68% of the electricity being consumed on the day tariff respectively.

Table 2; Empirical electricity consumption of each infrastructural component, total consumption and costs for a small farm (SF), a medium farm (MF) and a large farm (LF) as measured in 2011 (Upton et al. 2013).

Parameter	SF	MF	LF
Milk cooling (kWh)	3473	5450	16288
Water heating (kWh)	2336	7175	7992
Milking machine (kWh)	2150	3673	5714
Wash pump (kWh)	NA[1]	149	NA
Water pump (kWh)	87	1994	2785
Auto scrapers (kWh)	563	1653	NA
Lighting (kWh)	183	983	483
Electricity consumption (Wh/Liter)	34	42	43
Total Electricity consumption (kWh)	8791	21099	33262
Electricity costs (€/Liter)	0.0043	0.0058	0.0051
Annual electricity costs (€)	1097	2900	3942

[1]NA = Not applicable

Model demonstration

To demonstrate the functionality of the model two existing tariff matrices were applied to the total dairy farm consumption matrix (M_t). First the farms electricity costs were computed using the farm electricity tariffs from 2011. This took the form of a day and night tariff matrix, where the price of electricity changed from day to night rate at 00:00 h and from night to day rate at 09:00 h (as applied in Ireland in 2013), and a flat rate tariff of €0.18/kWh, which corresponds to the rate for a medium duty consumer (with consumption of approx. 15,000 kWh of electricity per annum) in 2013. This demonstrates the models ability to react to changes in electricity pricing structure. The model also has the ability to evaluate changes in technology applied to each of the 7 infrastructural systems on a dairy farm as well as the ability to evaluate managerial changes, such as once a day milking. However it is outside the scope of this paper to demonstrate all of the functionality of the model.

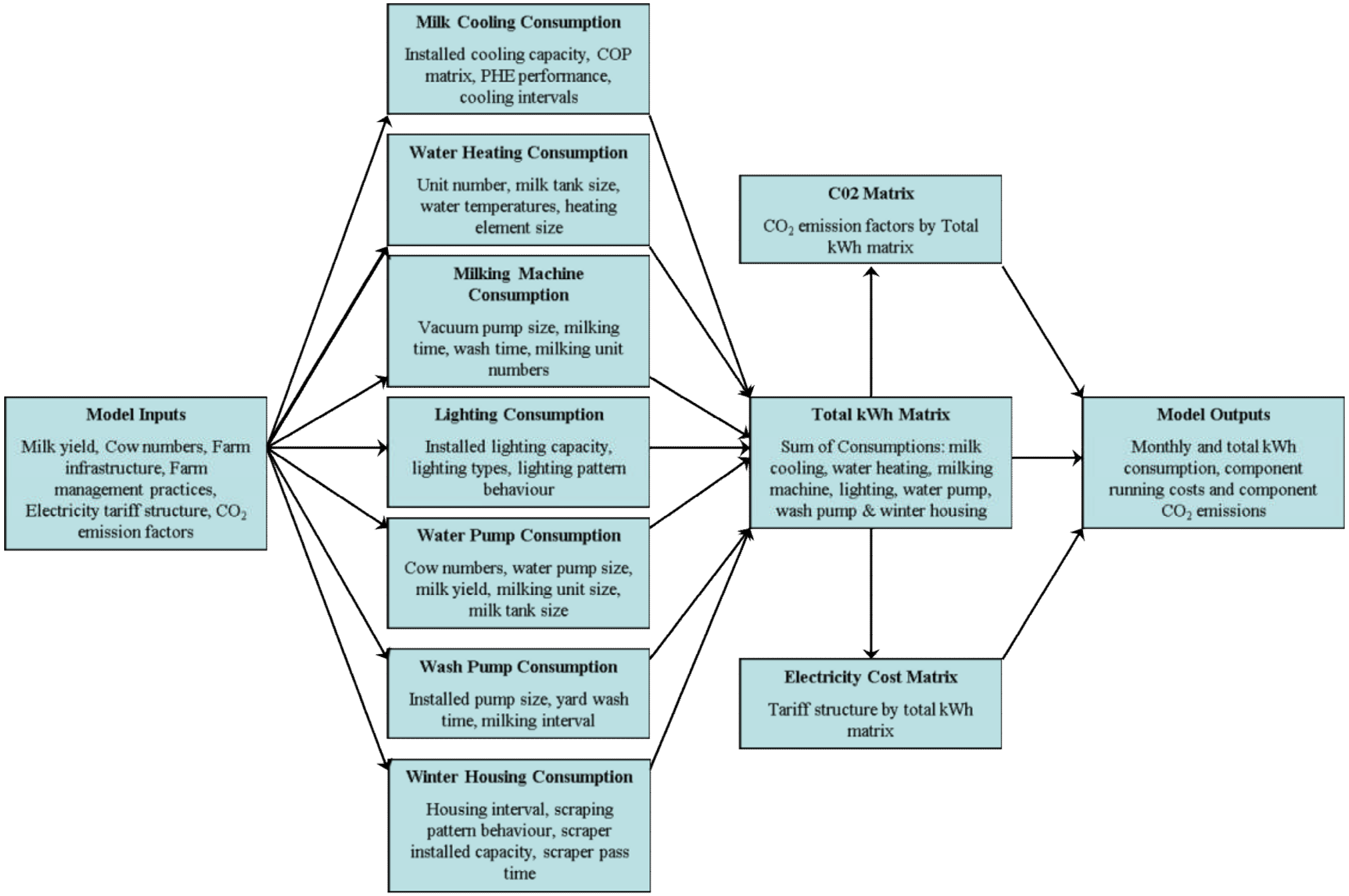

Figure 1; Schematic of milk production electricity consumption model showing the 4 primary sections, illustrated from left to right; i) inputs, ii) consumption matrix calculations for the 7 main infrastructural systems iii) consumption summing and tariff application iv) outputs.

3 Results

Model Predictions

Small farm (SF). The model predicted a total electricity consumption of 8,498 kWh, total electricity costs of €1,108, and electricity related emissions of 4,633 kg of CO_2 (Table 3). Predictions were made for 5 of the 7 infrastructural systems on a monthly basis (Table 3). This farm did not use a wash pump for cleaning purposes. Moreover, the water supply of the SF was sourced, for the majority of the year, from a gravity fed borehole which did not require pumping. During periods of dry weather or especially high water demand, a secondary pumped supply was used which consumed only 87 kWh of electricity in 2011 (1% of the overall electricity consumption). Therefore no prediction was made for this water pumps electricity consumption due to the sporadic nature of its operation. The model underpredicted the total electricity consumption of the SF by 293 kWh (3.3%) and overpredicted the electricity costs by €11.50 (1%). The MSPE of the total electricity consumption prediction was 5,233 kWh^2. The proportion of variation made up by the mean bias, line bias and random variation were 0.11, 0.01 and 0.88 (see table 6), whereas the RMSE was 72.3 kWh and the RPE was 9.9%. Further details relating to the quality of predictions for the SF are presented in Table 6.

Medium Farm (MF). The model predicted a total electricity consumption of 20,779 kWh, total electricity cost of €2,896 and electricity related emissions of 11,329 kg CO_2. Predictions were made for all of the 7 infrastructural systems on a monthly basis (Table 4). The model underpredicted the total electricity consumption of the MF by 320 kWh (1.5%), and underpredicted the total electricity costs by €4.10 (0.1%). The MSPE of the total electricity consumption prediction for the MF was 7,127 kWh^2, the proportion of variation made up by the mean bias, line bias and random variation were 0.10, 0.02 and 0.88, the RMSE was 84.4 kWh and the RPE was 4.8%. Further details relating to the quality of predictions for the MF are presented in Table 6.

Large Farm (LF). The model predicted a total electricity consumption of 32,326 kWh, total cost of €3,922 and total electricity related emissions of 15,147 kg CO_2. The LF did not use a standalone wash pump, instead the main water pump was used for washing purposes. The LF did not use automated scrapers in the winter facility.

The model underpredicted the total electricity consumption by 936 kWh (2.8%) and underpredicted total electricity costs by €20.40 (0.5%). Further details of the model predictions of the LF are shown in Table 5. The MSPE of the total electricity consumption prediction for the LF was 47,997 kWh^2, the proportion of variation made up by the mean bias, line bias and random variation were 0.13, 0.00 and 0.87 (table 6), the RMSE was 219.1 kWh and the RPE was 7.9%. Further details relating to the quality of predictions for the LF are presented in Table 6.

Model bias and precision

Table 6 shows the MSPE, RMSE and RPE for the 7 infrastructural systems along with the actual and predicted electricity consumption values. The model was most accurate on the MF prediction, delivering an RPE of 4.8% (RMSE 84.4 kWh) for total electricity consumption. About 88% of the variation was accounted for by the random variation. The RPE for total electricity consumption were 9.9% for SF (RMSE 72.3 kWh) and 7.9% for LF (RMSE 219.1 kWh). The random variation accounted for a large portion of the MSPE, i.e. 0.88 for SF and 0.87 for LF. The models prediction of milk cooling consumptions, water heating consumptions and milking machine consumptions all yielded RPEs of less than 20%. These consumptions made up 86% of total electricity consumption across all three farms which made them the most important items to predict accurately. Automatic scraper consumptions, lighting consumptions and water pump consumptions proved more difficult to predict. RPE values varied between 20% and 30% for water pump predictions, between 42% and 58% for automatic scraper consumptions and between 18% and 113% for lighting consumptions. However these consumptions, when totalled, made up 14% of the total electricity consumption of the three farms.

Model Demonstration

Results of the demonstration of the model are presented in Table 7. For this analysis M_t was multiplied by 2 different electricity price matrices to compute two different cost matrices. This approach yielded a model prediction for total farm electricity costs of €1,108 for SF, €2,896 for MF and €3,922 for LF. Secondly, applying a flat rate tariff of €0.18/kWh demonstrated the effect on total electricity costs if farms were to use a flat rate electricity tariff instead of the day and night rate tariff. Total electricity costs then increased to €1,530 for SF, €3,844 for MF and €5,046 for LF.

Table 3; Model predictions for monthly and annual total kilowatt hour (kWh) consumption, electricity costs in Euros (€) and electricity related CO_2 emissions for the 7 main infrastructural components for the small farm (SF).

Model Outputs SF	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Milk cooling (kWh)	0	172	380	406	419	400	396	372	340	277	161	0	3322
Water heating (kWh)	0	256	283	274	275	266	251	228	221	208	183	0	2444
Milking machine (kWh)	0	175	262	221	228	221	228	228	221	228	122	0	2131
Wash pump (kWh)	NA[1]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Water pump (kWh)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Auto scrapers (kWh)	145	131	0	0	0	0	0	0	0	0	0	145	422
Lighting (kWh)	36	39	9	8	8	8	8	8	8	8	4	36	179
Total electricity consumption (kWh)	181	772	934	908	930	894	883	836	789	721	469	181	8498
Electricity per Liter (Wh/L)	0	69	26	24	28	27	28	32	35	39	80	0	33
Total electricity costs (€)	26	100	130	127	121	115	111	107	98	89	57	26	1108
kg CO_2 (Electricity)	99	421	509	495	507	487	481	456	430	393	256	99	4633

[1] NA = Not applicable

Table 4; Model predictions for monthly and annual total kilowatt hour (kWh) consumption, electricity costs in Euros (€) and electricity related CO_2 emissions for the 7 main infrastructural components for the medium farm (MF).

Model Outputs MF	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Milk cooling (kWh)	51	308	623	866	672	592	532	485	436	373	294	121	5353
Water heating (kWh)	591	563	624	603	624	619	640	640	635	640	549	567	7294
Milking machine (kWh)	216	282	360	349	360	349	360	360	349	312	209	120	3628
Wash pump (kWh)	12	11	12	12	12	12	12	12	12	12	12	12	145
Water pump (kWh)	101	109	184	192	185	222	153	145	159	118	128	136	1832
Auto scrapers (kWh)	315	284	315	0	0	0	0	0	0	0	305	315	1533
Lighting (kWh)	66	82	103	91	94	91	94	94	91	82	64	41	994
Total electricity consumption (kWh)	1352	1640	2221	2113	1947	1885	1792	1737	1682	1538	1560	1312	20779
Electricity consumption per Liter (Wh/L)	129	63	38	34	32	26	37	38	33	49	66	106	42
Total electricity costs (€)	173	232	328	330	278	267	244	235	225	200	217	167	2896
kg CO_2 (Electricity)	737	894	1211	1152	1062	1028	977	947	917	838	850	715	11329

Table 5; Model predictions for monthly and annual total kilowatt hour (kWh) consumption, electricity costs in Euros (€) and electricity related CO_2 emissions for the 7 main infrastructural components for the large farm (LF).

Model Outputs LF	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Milk cooling (kWh)	56	682	1121	1739	2275	1870	2034	1779	1739	1102	398	101	14898
Water heating (kWh)	669	633	709	675	701	699	717	717	699	717	683	685	8303
Milking machine (kWh)	570	515	570	552	570	552	570	570	552	510	320	271	6124
Wash pump (kWh)	NA[1]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Water pump (kWh)	7	116	280	325	377	305	282	241	221	174	106	20	2452
Auto scrapers (kWh)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lighting (kWh)	77	70	41	40	41	40	41	41	40	37	23	0	493
Total electricity consumption (kWh)	1379	2016	2722	3331	3965	3466	3645	3348	3251	2540	1530	1132	32326
Electricity consumption per Liter (Wh/L)	589	55	31	32	33	36	41	44	47	46	46	182	42
Total electricity costs (€)	148	243	337	430	494	433	457	415	400	295	160	112	3922
kg CO_2 (Electricity)	553	910	1272	1615	1953	1681	1773	1611	1564	1171	630	413	15147

[1] NA = Not applicable

Table 6; Mean square prediction error (MSPE), root mean squared error (RMSE) and relative prediction error (RPE) for the 7 main infrastructural components in the electricity consumption prediction model as well as the prediction of total electricity consumption for the 3 modelled farms 1) small farm (SF), 2) medium farm (MF), and 3) large farm (LF).

	Actual (A)	Predicted (P)	Bias (P-A)	MSPE	Proportion of MSPE			RMSE	RPE
					Mean Bias	Line Bias	Random Variation		
Unit	**kWh**	**kWh**	**kWh**	**$(kWh)^2$**	**-**	**-**	**-**	**kWh**	**(%)**
SF									
Milk cooling	3473	3322	-151	745	0.21	0.35	0.44	27.3	9.4%
Water heating	2336	2444	108	1096	0.07	0.02	0.90	33.1	17.0%
Milking machine	2150	2131	-18	601	0.00	0.23	0.77	24.5	13.7%
Wash pump	NA	NA	NA	NA	NA	NA	NA	NA	NA
Water pump	87	NA	NA	NA	NA	NA	NA	NA	NA
Auto scrapers	563	422	-141	393	0.35	0.06	0.59	19.8	42.2%
Lighting	183	179	-4	294	0.00	0.20	0.80	17.1	112.6%
Total electricity consumption	8791	8498	-293	5233	0.11	0.01	0.88	72.3	9.9%
MF									
Milk cooling	5450	5353	-97	939	0.07	0.01	0.92	30.6	6.7%
Water heating	7175	7294	119	702	0.14	0.18	0.68	26.5	4.4%
Milking machine	3673	3628	-45	839	0.02	0.00	0.98	29.0	9.5%
Wash pump	149	145	-4	4	0.02	0.03	0.94	2.0	16.3%
Water pump	1994	1832	-162	1110	0.16	0.74	0.10	33.3	20.1%
Auto scrapers	1653	1533	-120	6284	0.02	0.10	0.88	79.3	57.6%
Lighting	983	994	11	227	0.00	0.17	0.83	15.1	18.4%
Total electricity consumption	21099	20779	-320	7127	0.10	0.02	0.88	84.4	4.8%

LF									
Milk cooling	16288	14898	-1391	63934	0.21	0.30	0.49	252.9	18.6%
Water heating	7992	8303	311	11652	0.06	0.04	0.90	107.9	16.2%
Milking machine	5714	6124	411	4450	0.26	0.46	0.28	66.7	14.0%
Wash pump	NA	NA	NA	NA	NA	NA	NA	NA	NA
Water pump	2785	2452	-333	4818	0.16	0.05	0.79	69.4	29.9%
Auto scrapers	NA	NA	NA	NA	NA	NA	NA	NA	NA
Lighting	483	493	10	55	0.01	0.00	0.99	7.4	18.4%
Total electricity consumption	33262	32326	-936	47997	0.13	0.00	0.87	219.1	7.9%

[1] NA = Not applicable

Table 7; Total electricity costs (€) and electricity costs per liter of milk produced (€/L) for a small farm (SF), a medium farm (MF), and a large farm (LF) for two tariff schemes. 1) A flat rate tariff of €0.18/kWh was used, which corresponds to the flat rate for a medium duty consumer in 2013. 2) Day & Night rate where the price of electricity changed from day to night rate at 12 midnight and from night rate to day rate at 9am (as applied in Ireland). Day and Night Tariffs were compiled from electricity suppliers of the farms. Average Day rate was €0.18/kWh, average night rate was €0.09/kWh.

Model Demonstration	SF		MF		LF	
	Flat	Day & Night	Flat	Day & Night	Flat	Day & Night
Total electricity costs (€)	1530	1108	3844	2896	5046	3922
Electricity cost per Liter milk (€/L)	0.0060	0.0043	0.0077	0.0058	0.0065	0.0051

4 Discussion

Model Structure

Many models have been developed to simulate a range of important impacts of innovations at farm level. Examples are biophysical and economic impacts on dairy farms (Baudracco et al., 2013; Shalloo et al. 2004), greenhouse gas impacts at beef and dairy production systems (Foley et al., 2011; O'Brien et al., 2010) and pasture production impacts in grazing systems (O'Neill et al., 2013). At this time, none of these models contains a dedicated electricity consumption sub-model, probably because its financial impact was deemed insignificant when energy prices were low and environmental efficiency was not deemed important. However, to evaluate the impact of rising energy prices, or changes to pricing structure, or implementation of technical and managerial innovations on farm profitability and to estimate the environmental effects a dedicated electricity model is required. Similarly if the MECD was integrated with a whole farm modelling system, such as Shalloo et al. (2004), the impact of scenarios such as once a day milking vs. twice a day milking on energy efficiency and energy costs could be examined along with other management strategies such as spring vs. autumn calving or changes in breeding practices by the farmer (e.g. crossbreeding with jersey cows which may produce lower milk volumes but similar milk solids per animal).

The mechanistic modelling approach taken in this paper is similar to that taken by Henze et al. (1997), who used a mechanistic approach to describe the operating performance of an ice building system. Other modelling techniques exist, such as pattern recognition regression modelling, which are widely accepted as a technology offering an alternative way to tackle complex and ill-defined problems (Kalogirou, 1999). However, regression models are a generalisation tool and are not useful in the analysis of innovations in an existing system. For example, it would be possible to forecast electricity use at farm level given a forecasted milk yield using a regression model. Many tools exist for the purpose of forecasting milk yields such as those described by Grzesiak et al., (2006), Olori et al., (1999) and Quinn et al., (2005). However a regression based electricity prediction model would only be valid if the infrastructure installed on the farm remained static because these models are trained to predict the future based on historic performance. For these reasons a mechanistic approach was taken in this study.

Model Validation

RPE values of less than 10% (9.9%, 4.8% and 7.9% for the SF, MF and LF) suggest that the MECD described in this paper can be classified as providing an acceptable prediction accuracy for total electricity consumption (Fuentes-Pila et al., 1996). This level of accuracy is satisfactory for the intended use of this model as a decision support tool for dairy farmers because the practical significance of the errors are low, i.e. prediction errors of total annual electricity costs amounted to approximately €11.50 for SF, €4.10 for MF and €20.40 for LF. Moreover, the random variation accounts for >87% of the MSPE of the total electricity consumption predictions indicating that the majority of errors in prediction are due to chance or random causes. This is preferred to having a large portion of errors accounted for by mean or line bias which would indicate consistent steady state errors or inadequacies in the structure of the model respectively. The sub-predictions of the 7 infrastructural systems generated mixed accuracy levels. The milk cooling consumption prediction RPE values were 9.4% for SF, 6.7% for MF and 18.6% for LF, which also can be classified as satisfactory prediction accuracy (i.e. < 20% RPE). The water heating consumptions were predicted with RPE values of 17.0% for SF, 4.4% for MF and 16.2% for LF, this can be classified as satisfactory prediction accuracy. Similar satisfactory prediction accuracy was achieved for the milking machine consumptions, since the RPE values were 13.7% for SF, 9.5% for MF and 14.0% for LF.

Some poor prediction accuracies were achieved for the water pump consumptions, automatic scraper consumptions and lighting consumptions (details in Table 6). These components together, however, made up only 14% of the total electricity used across the three farms, hence the poor RPE values achieved (especially for automatic scrapers) only slightly influenced the overall model accuracy. However, if this model was to be applied to a confinement dairy system where cows were housed indoors all year round and where the scrapers and lights made up a higher proportion of the total electricity consumption, then the overall accuracy may decline in a more significant fashion.

Sources of variation

Variations in prediction accuracy were found with this modelling approach. Here we will explain how some of the variations might have arisen.

Milk cooling. The milk cooling consumption (Q_{mc}) for a given volume of milk is driven largely by the COP of the cooling system (equation 3). It is very common for modellers to assume a COP based on manufacturers performance data (O'Dwyer et al. 2012; Henze et al. 1997; Halvgaard et al. 2012; Ying-Yi et al. 2012). In the MECD we accounted for the variation in ambient temperatures. It is possible, however, that the weather data used, which were sourced from a weather station approximately 20 miles away from the farms, did not present the ambient temperature of the air at the cooling compressor on the farms. The largest effect on milk cooling energy predictions, however, were expected to be due to variations in effectiveness of the milk pre-cooling system throughout the year. If ground water temperatures varied dramatically throughout the year this would impact on prediction accuracies.

Water Heating. Water heating electricity consumption (Q_{wh}) is governed by hot water consumption, initial water temperature and final hot water temperature. Many farmer related sources of variation and equipment related variations exist in this system. The frequency of washing of the milking machine with hot water is a fixed model input, i.e. it remains constant throughout the year. This may not reflect the true washing frequency, which may vary from season to season, causing prediction errors.

Milking machine. The electricity consumed by the milking machine is influenced primarily by the time spent milking, which is influenced by size of the herd (N_{cows}), size of the milking machine ($N_{clusters}$) and the operator row time (RT). RT can be approximated according to whether the farmer fully or partially prepares the cows teats before milking as described by O'Brien et al. (2012). However the model only uses one value throughout the year for RT. It is likely that a farmer would adjust RT throughout the year according to weather conditions and stage of lactation. This would introduce errors in the prediction of Q_{mm}.

Lighting. The model requires input on the types (e.g. T8 fluorescent, T5 fluorescent, sodium, halogen and metal halide) and numbers of fittings located in the milking facility, outdoor areas and winter housing facility. The model assumes that lighting in the milking facility is turned on during milking. A lighting behaviour chart is a required model input and this allows the run times of the housing facilities lights and outdoor area lights to be quantified. Naturally the behaviour of the farmer with regard to lighting will not follow these patterns in reality resulting in prediction errors.

Water pumping. The quantity of electricity consumed by the water pumps is influenced by the quantity of water consumed by the milking facility during and after milking, the water consumed by the dairy cows and the maintenance water for stock during the year. Drinking water consumed by the dairy herd will vary from day to day and season to season which will not be picked up by the model resulting in prediction errors of this metric.

Winter facilities. Electricity is consumed in the winter housing facilities by automatic manure handling equipment. An automatic scraper behaviour chart is a required model input and this allows the run times of the scraping equipment to be quantified. However if the scrapers run more or less frequently in reality then variation will be introduced.

Model Applications

Farmers are presented with a plethora of alternative technologies and strategies when upgrading infrastructure (especially around milk harvesting technology). The MECD has been developed with an adaptable infrastructure approach in mind allowing for alternative technologies and managerial changes to be evaluated. Moreover, the MECD could be used to optimise the decision making process for new technologies at farm level. Similarly, the effect of milking speed on electricity costs could be evaluate arising from variations in milking parlour size, milking routine among farmers or variations in cow type.

Countries such as Estonia, Finland, France, Ireland, Italy, Malta, The Netherlands, Norway, Portugal, Spain, Sweden and the United Kingdom are all classified as “Dynamic Movers” in relation to the implementation of smart grid infrastructure. Within these countries either the mandatory rollout is already decided, or there are major pilot projects underway to evaluate the feasibility of smart grids (Hierzinger et al., 2012). Countries such as Australia and New Zealand have recognised smart metering as a method of improving resource use efficiency and have carried out some early stage feasibility studies and cost benefit analysis calculations (Energy Federation of New Zealand, 2010, DRET, 2008). These developments heighten the importance of energy efficiency and moreover increase the need for further analysis around the impact of smart grids on dairy farming, especially in countries where milk production is a substantial or expanding industry. The MECD could be used to account for time of use tariffs or dynamic pricing tariffs which would provide guidelines to farmers on how best to use these new pricing structures to their advantage.

5 Conclusion

A model was built that simulated the total yearly electricity consumption, electricity consumption of the 7 main infrastructural systems, total electricity costs and total electricity related CO_2 emissions. This model was validated by comparing the simulated results against actual farm data, using empirical data of farms of varying scale. The model delivered an acceptable RPE of <10% for total electricity consumption with over 87% of the mean square prediction error of total electricity consumption being accounted for by random variation. These levels of accuracy make the model suitable for application as an advice tool for farmers to improve their energy efficiency and reduce milk production costs. The usefulness of the model was demonstrated through an electricity tariff change (i.e. from day and night rate to flat rate), which showed that total electricity costs would increase by over 30% if farmers were to use a flat rate tariff instead of a day and night tariff. This methodology could be used to assess the impact of various time of use tariffs or even a dynamic pricing system on total electricity costs in the future.

References

Baudracco, J., N. Lopez-Villalobos, C. W. Holmes, E. A. Comeron, K. A. Macdonald, and T. N. Barry. 2013. e-Dairy: a dynamic and stochastic whole-farm model that predicts biophysical and economic performance of grazing dairy systems. Animal 7(5):870-878.

Beede, D. K. 1992. Water for Dairy Cattle in Large Dairy Herd Management H. H. Van Horn and C. J. Wilcox, Eds., American Dairy Science Association, Savoy, IL.

Bibby J. and H. Toutenburg. 1977. Prediction and improved estimation in linear models. Wiley, New York.

CER. 2011. Second Consultation on Possible National Rollout Scenarios for the Smart Metering Cost Benefit Analysis CER10197. Commission for Energy Regulation, Dublin, Ireland.

De Boer, I. J. M., I. E. Hoving, T. V. Vellinga, G. W. J. Van de Ven, P. A. Leffelaar, and P. J. Gerber. 2013. Assessing environmental impacts associated with freshwater consumption along the life cycle of animal products: the case of Dutch milk production in Noord-Brabant. Int. J. Life Cycle Assess. 18(1):193-203.

DRET. 2008. Cost-benefit analysis of options for a national smart meter roll-out: Phase Two—Regional and detailed analyses regulatory impact statement. Department of Resources Energy and Tourism (DRET), Canberra, Australia.

Energy Federation of New Zealand. 2010. Developing our energy potential, New Zealand Energy Efficiency and Conservation Strategy. Energy Federation of New Zealand, Wellington, New Zealand.

Eurostat. 2013. Eurostat energy price tables, accessed 09-10-2013, http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database.

Foley, P. A., P. Crosson, D. K. Lovett, T. M. Boland, F. P. O'Mara, and D. A. Kenny. 2011. Whole-farm systems modelling of greenhouse gas emissions from pastoral suckler beef cow production systems. Agriculture Ecosystems & Environment 142(3-4):222-230.

Fuentes-Pila, J., M. A. DeLorenzo, D. K. Beede, C. R. Staples, and J. B. Holter. 1996. Evaluation of equations based on animal factors to predict intake of lactating Holstein cows. Journal of Dairy Science 79(9):1562-1571.

Goodman, R., G. Jones, J. Kelly, E. Slowey, and N. O'Neill. 2004. Geothermal Energy Resource Map of Ireland. Sustainable Energy Ireland, Ireland

Grzesiak, W., P. Blaszczyk, and R. Lacroix. 2006. Methods of predicting milk yield in dairy cows - Predictive capabilities of Wood's lactation curve and artificial neural networks (ANNs). Computers and Electronics in Agriculture 54(2):69-83.

Halvgaard, R., N. K. Poulsen, H. Madsen, and J. B. Jorgensen. 2012. Economic Model Predictive Control for building climate control in a Smart Grid. In Proceedings of the Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES, San Diego, California, USA.

Henze, G. P., R. H. Dodier, and M. Krarti. 1997. Development of a Predictive Optimal Controller for Thermal Energy Storage Systems. HVAC&R Research 3(3):233-264.

Henze, G. P. and M. Krarti. 1998. Ice storage system controls for the reduction of operating cost and energy use. Journal of Solar Energy Engineering-Transactions of the Asme 120(4):275-281.

Hierzinger R., M. Albu, H. van Elburg, A. J. Scott, A. Lazicki, L. Penttinen, F. Puente, and H. Sale. 2012. European Smart Metering Landscape Report, SmartRegions Deliverable 2.1. Accessed May 24, 2013. http://www.energyagency.at/fileadmin/dam/pdf/projekte/klimapolitik/SmartRegionsLandscapeReport2012.pdf.

Howley, M., E. Dennehy, M. Holland B. O'Gallachoir 2011. Energy in Ireland 1990–2010. Energy policy statistical support unit. Sustainable Energy Ireland, Dublin, Ireland.

Kalogirou, S. A. 1999. Applications of artificial neural networks in energy systems - A review. Energy Conversion and Management 40(10):1073-1087.

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):1-16.

O'Brien, B. 2008. Teagasc Milk Quality Handbook, Practical Steps to Improve Milk Quality. Teagasc, Fermoy, Ireland.

O'Brien, B., J. Jago, J. P. Edwards, N. Lopez-Villalobos, and F. McCoy. 2012. Milking parlour size, pre-milking routine and stage of lactation affect efficiency of milking in single-operator herringbone parlours. Journal of Dairy Research 79(2):216-223.

O'Brien, D., L. Shalloo, C. Grainger, F. Buckley, B. Horan, and M. Wallace. 2010. The influence of strain of Holstein-Friesian cow and feeding system on greenhouse gas emissions from pastoral dairy farms. J. Dairy Sci. 93(7):3390-3402.

O'Callaghan, E. and D. Harrington. 2000. Effect of Liner Design on Milking Characteristics. Irish Journal of Agricultural and Food Research 39(3):383-399.

O'Dwyer, C., R. Duignan, and M. O'Malley. 2012. Modeling demand response in the residential sector for the provision of reserves. In Proceedings of 2012 IEEE PES General Meeting, San Diego, California, USA.

O' Neill, B., E. Lewis, M. O. Donovan, L. Shalloo, N. Galvin, F. J. Mulligan, T. M. Boland, and R. Delagarde. 2013. Predicting grass dry matter intake, milk yield and milk fat and protein yield of spring calving grazing dairy cows during the grazing season. Animal 7(8):1379-1389.

Olori, V. E., S. Brotherstone, W. G. Hill, and B. J. McGuirk. 1999. Fit of standard models of the lactation curve to weekly records of milk production of cows in a single herd. Livestock Production Science 58(1):55-63.

Quinn, N., L. Killen, and F. Buckley. 2005. Empirical algebraic modelling of lactation curves using Irish data. Irish Journal of Agricultural and Food Research 44(1):1-13.

Rook, A. J., M. S. Dhanoa, and M. Gill. 1990. Prediction of the voluntary intake of grass silages by beef cattle. Precision of alternative prediction models Animal Production 50:455-466.

Shalloo, L., P. Dillon, M. Rath, and M. Wallace. 2004. Description and validation of the Moorepark Dairy System Model. J. Dairy Sci. 87(6):1945-1959.

Upton, J., J. Humphreys, P.W.G. Groot Koerkamp, P. French, P. Dillon, and I.J.M. De Boer. 2013. Energy demand on dairy farms in Ireland. Journal of Dairy Science 96(10):6489-6498.

Upton, J., M. Murphy, P. French, and P. Dillon. 2010. Energy Use on Dairy Farms Pages 87-97 in Proceedings of Teagasc National Dairy Conference. Teagasc, Mullingar, Ireland.

Ying-Yi, H., L. Jie-Kai, W. Ching-Ping, and C. Chi-Cheng. 2012. Multi-Objective Air-Conditioning Control Considering Fuzzy Parameters Using Immune Clonal Selection Programming. Smart Grid, IEEE Transactions on 3(4):1603-1610.

Chapter 4

Rapid milk cooling control with varying water and energy consumption

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Abstract

A control system for rapid milk cooling plant connected to a variable flow milking machine is presented. The plant consisted of a pre-cooler in the first stage that utilised ground water as a cooling medium and an ice bank that provides ice chilled water for the second cooling stage. The control system comprised of two proportional integral derivative controllers applied to each cooling stage in tandem. The set point of the first controller was the desired milk pre-cooling temperature while the set point of the second controller was the desired final milk temperature. Eight different precooling set points (13°C - 20°C) were tested for feedback and feedback-feedforward controller configurations. Selection of low temperature pre-cooling set points resulted in larger volumes of ground water being consumed in the first stage per unit milk in comparison to the selection of higher temperature set points (three times higher). However, low pre-cooling temperatures resulted in less ice storage utilisation and therefore less power consumption. Introduction of a feedforward loop to the controllers reduced the disturbance from the varying milk flow and by doing so reduced the final milk temperature deviation from the set point. Optimum water utilisation rates were calculated for varying water cost at the current price of electricity. These points represent the ideal combination of ground water and power consumption per unit milk to produce the most financially efficient means of cooling. Potential cost reductions of up to 34.5% through the selection of the ideal water rates were discovered.

Nomenclature

Abbreviations	
COP	coefficient of performance
FB	feedback
FB-FF	feedback-feedforward
FF	feedforward
GW	ground water
IB	ice bank
ICW	ice chilled water
PHE	plate heat exchanger
PID	proportional integral derivative
VSD	variable speed drive
WC	water chiller
Symbols	
d	disturbance (min^{-1})
e	error (°C)
G_d	transfer function between the output milk
G_p	transfer function between the output and
K_b	feedback controller
K_f	feedforward controller
k_D	derivative term (s)
k_I	integral term ($1s^{-1}$)
k_P	proportional term
q	feedforward controller output (mA)
r	set point (°C)
u	manipulating variable (mA)
u_{max}	maximum manipulating variable limit (mA)
u_{min}	minimum manipulating variable limit (mA)
w	controller output (mA)
y	milk output temperature (°C)

1 Introduction

Dairy production is an energy intensive process with milk cooling being the largest contributor to electricity use on Irish dairies (Upton, Murphy, French, & Dillon, 2010). The amount of energy needed for cooling depends primarily on the efficiency of the refrigeration system and the temperature differential in the milk between the start and finish of the cooling process. The most common method of reducing the cost of milk cooling is to employ a two stage process comprising of a pre-cooling unit and a main refrigeration system. Plate heat exchangers (PHE) are the most commonly utilised pre-coolers. PHEs use tepid ground water (GW) to reduce the milk temperature. The amount of GW available for pre-cooling usage depends on a number of factors such as; herd size, number of milking clusters, farm infrastructure, well depth and climate conditions. Effective utilisation of GW in the pre-cooling process has a significant influence on milk temperature. However, there is also a financial cost associated with the use of GW. Most dairy farms have a borehole where water is pumped from the ground, in certain cases the water is partly or wholly supplied by a district scheme where it is charged per volume (m^3). GW used for pre-cooling is typically re-used for parlour wash down, as pre-heated water for cluster rinsing and can be used as animal drinking water (depending on temperature and storage time). Audits on milk cooling equipment carried out by the Teagasc Moorepark Animal and Grassland Research Innovation Centre (AGRIC) in 2010 revealed poor levels of PHE pre-cooling on dairy farms. In each case, insufficient water flow rate was found to be the underlying cause of the PHEs ineffectiveness, a cognate study in the UK found similar problems regarding GW utilisation in PHE pre-cooling (Milk Development Council, 1995). Due to the varying costs per unit of water between dairy farms, a standard GW to milk pre-cooling ratio cannot be applied in every situation. A method of controlling water utilisation in pre-cooling could yield substantial benefits for costs and energy reduction in milk refrigeration.

Modern milking machines operate by extracting milk from a cow's udder using a cluster of suction cups. The suction is generated using sinusoidal negative pressure. The milk from each cluster is collected in a receiver jar from where it is then pumped to the pre-cooler or directly to the refrigeration system. The milk flow profile contains peaks and troughs at irregular intervals. Modern milking machine receiver jars contain level sensors that measure the height of the milk level and control the speed of the milk pump via an analogue signal to a variable speed drive (VSD). This method reduces the variation in milk flow, reducing peak the flow rate and enabling more effective pre-cooling. Despite the improvement of the situation with a VSD, a simple on/off controller for the GW flow still results in sub-optimal pre-cooling as the rate of cooling cannot be controlled. To facilitate the control of pre-cooling levels, an automatic system that is capable of manipulating the GW flow is needed.

Chilled water can be used in the second stage of a dual stage PHE to instantly cool milk; it can also be used to gradually cool the milk in a bulk tank. Gradual cooling is less energy intensive than instant cooling as the pumping demand for the chilled water (CW) is lower. Water can be chilled using a water chiller (WC), which usually consists of an insulated water tank with an evaporator and a holding vessel of equal volume. The water is chilled to approximately 1°C at off peak hours (on the electricity grid) and the milk is cooled to below 4°C. Used chilled water cannot be re-circulated to the insulated tank as this may lead to a rise in the total chilled water temperature to above 4°C, so the water is directed to the holding vessel. Another method of chilling water is by circulation through an ice bank (IB). IBs 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 (PHE or bulk tank) and back to the IB in a closed loop. WCs operate with higher coefficients of performance (COP) than IBs due to the lower evaporating temperature required for producing ice, but IBs are much more compact due to the high energy density of ice and are cheaper to purchase and install.

During the milk cooling period some microorganisms may multiply (Holm, Jepsen, Larsen, & Jespersen, 2004), especially fast growing psychrotrophic bacteria that re-produce in the temperature range of 4°C to 7°C. Rapidly cooling the milk to below 4°C prevents further psychrotrophic bacteria growth. However, systems that effectively pre-cool and then gradually refrigerate the milk below 4°C within the regulated time (in Ireland 30 min from the end of milking) greatly reduce the possibility of significant bacterial growth. One major advantage of instant cooling is that the milk is always ready for collection and transport to the processing plant. Not only is this useful in situations where direct collection occurs, but is also helpful where uncertain collection schedules exist. Having a rapid cooling system gives the farm manager freedom to set milking routines without having to strictly conform to the collection schedule of the milk processor.

Because the milk flow from modern milking machines is variable, rapid milk cooling is technically difficult. One strategy to combat this situation would be to operate the cooling plant at full capacity by running the GW and CW pumps at maximum speed; this insures that the cooling system can deal with the peak flow rates from the milking machine. However, running the GW pump at full power consumes excessively large volumes of water. Also, constantly operating the CW pump at full speed throughout the cooling circuit leads to increased thermal losses and pump running costs.

The aim of this study was to demonstrate by proof of principle that a control system that can optimise both the milk pre-cooling process with GW and the rapid cooling of milk below 4°C with CW for milk and assess the cooling costs, energy use, and variable GW availability in milking systems with variable flow milk pumps. Such a system would allow farm mangers to utilise their water supply more effectively and also give a greater degree of control over energy and water consumption for milk cooling.

2 Materials and Methods

Cooling Apparatus

The milk refrigeration system chosen for this study was a dual stage PHE with the GW pre-cooling taking place in the first stage and the main CW cooling in the second stage. An IB was selected, as chilled water is required for instant cooling. However, either a WC or IB system could be selected for this application. A full scale test rig was designed and built (Figure 1) consisting of a dual stage PHE and an IB. The dual stage PHE had both a GW and ice chilled water (ICW) in a single pass arrangement with 25 channels each. The corrugated plates were gasket sealed with a chevron angle of 65°. Two VSD pumps controlled the flow rates of the GW and ICW. The IB was an external melt ice on coil thermal storage unit with an inline coil array.

Class A PT100 temperature resistance thermometers and type K thermocouples were used to measure in-flow milk and water temperatures. Ultra sonic flow meters measured milk, GW and ICW flow. Temperature and flow measurements were taken in-pipe immediately before entering and immediately after exiting the PHE for GW, ICW and milk. Temperature and flow rates were recorded every 0.5 s. Power meters (Type EM24 DIN energy analyser, Fluke 123 scope meter, Fluke 902 HVAC clamp meter and Powersoft logging software) recorded the electricity consumption of each individual electrical device. LabVIEW 2010 software was used for control and data logging. All laboratory equipment was calibrated to ISO17025 standards. Instrumentation was supplied by Radionics Ireland and National Instruments.

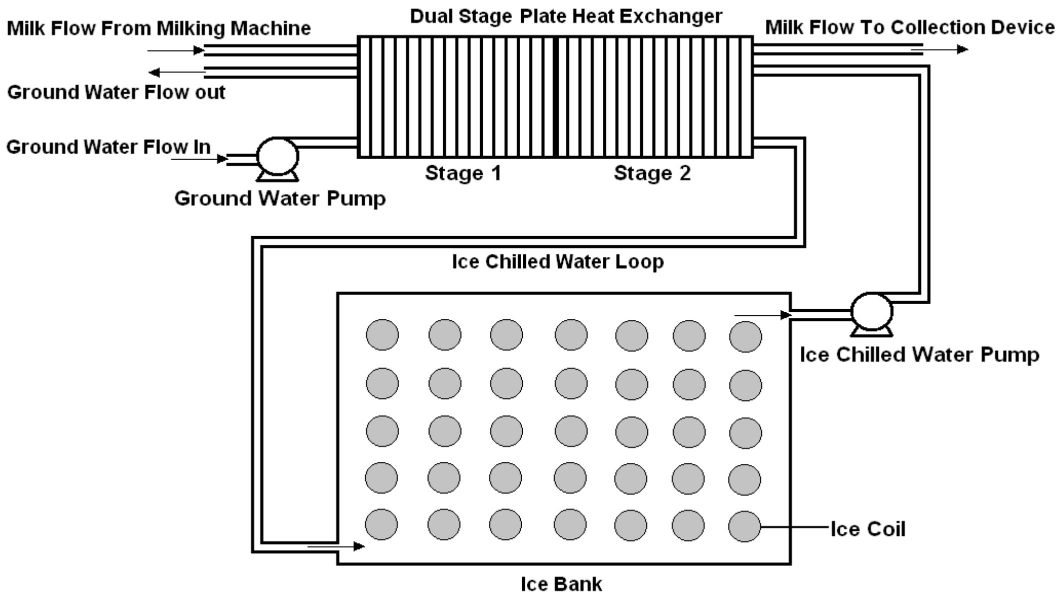

Figure 1; Schematic of the dual plate heat exchanger (PHE) used for instant milk cooling with ground water (GW) used for pre-cooling in the first stage and ice chilled water (ICW) used in the second stage (arrows indicate flow direction).

Milk Cooling Energy and Cost Model

An energy balance model was used to calculate and optimise the electrical energy consumption and monetary cost of cooling the milk with the apparatus used in this study. The ice mass depletion per unit of milk was calculated based on the specific heat capacity of milk and the specific heat of fusion of ice. The electricity consumption of the system to produce the ice depends on the system COP. The COP of refrigeration units with air cooled condensers are greatly affected by variations in ambient temperature (Yu & Chan, 2005; Zaman & Hussain, 2011). The average ambient air temperature at the Moorepark Met Eireann metrological observation station from 00:00 to 08:00 h over the entire year of 2011 was used as on operating parameter. The COP was calculated by interpolation of empirical test data. The mean annual COP was found to be 2.6 at an average ambient temperature of 8.3°C and an average pre-evaporating refrigerant temperature of -8.1°C. Air agitation, GW and ICW pumping energy use was also factored into the model. Several assumptions were made. 1. No thermal leakage occurred in the PHE. 2. The IB and piping was perfectly insulated. 3. The IB was fully charged before milk cooling and was fully discharged during cooling. 4. No stand-off losses occurred in the IB. 5. Total ice mass was generated during the night. The specific heat and density difference between milk and water were taken into account using the same method as Stinson, Studman, and Warburton

(1987). Day and night rate electricity tariffs were set at €0.183/kWh and €0.097/kWh, respectively. Putting an exact financial cost on GW usage on Irish dairies is very difficult; most farms have a deep well from where the GW is sourced and any excess is returned down a borehole. In this scenario the only cost involved is in pumping GW from the well. In exceptional cases water is purchased from the local grid. If the GW used in the PHE is recycled and used for cleaning purposes this water can be considered as being of no extra cost to cooling. For these reasons GW costs ranging from €0.00 m^{-3} to €0.20 m^{-3} were selected for the financial analysis.

Process

Milk exits a cow's udder at 37°C and it is cooled below 4°C to prevent bacterial growth. In the cooling apparatus described above, the milk is cooled using GW and ICW in the first and second stages of the PHE, respectively. GW is pumped from an underground well or reservoir and stored in a holding vessel after usage for parlour wash down and other purposes. The ICW is circulated in a continuous loop between the IB and PHE. The ice is generated during off peak electricity periods. A certain ice mass is produced to ensure the cooling demand is met. The cooling load depends on the milk volume and temperature. The ice building is controlled by an ice mass sensor. By limiting the ice charge to the required level, surplus ice production is eliminated, thus preventing excessively low evaporating temperatures and therefore increasing the efficiency of the refrigeration unit (Chaichana, Charters, & Aye, 2001). The ice building is also assisted by an air agitation system; the introduction of air to the water surrounding the ice causes agitation which increases the heat transfer between the ice surface and the water. Studies on cold storage have shown air agitation to be very beneficial in the ice production process, increasing growth rates by 20 - 45% (Mohamed, 2005).

Controller

The milk temperature leaving the dual stage PHE is varied by manipulating the flow rates of GW and ICW. This is achieved by controlling the speed of the pumps using VSDs. Proportional integral derivative (PID) controllers are the most commonly utilised controllers in the process industry (Astrom & Hagglund, 2001). The popularity of PID control is due to its successful application over a wide range of control problems. The input to the VSD or the output of the PID controller is the combination of the proportional gain, integral action and derivative action, which is expressed as (equation of the ideal PID controller in the Laplace domain):

$$w(s) = [k_P + k_I/s + k_D]e(s) \quad (1)$$

Where $w(s)$ is the controller output, $e(s)$ is the error between the set point and the manipulating variable, k_P is the proportional term, k_I is the integral term and k_D is the derivative term. An increase in the proportion gain results in a faster rise time, a larger overshoot and a small increase in settling time. Increasing the integral action removes steady state error and increases settling time and overshoot. The derivative term reduces the overshoot and settling time and improves the stability of the system (closed-loop response) (Heong, Chong, & Yun, 2005). In order to apply the correct proportional derivative and integral values the controllers were heuristically tuned using the Zeigler-Nichols ultimate gain method (Ziegler & Nichols, 1942).

The varying flow rate of incoming milk creates a disturbance in the control loop. Since the variation in milk flow is quite unstable, a basic feedback (FB) loop would not be capable of rejecting this disturbance from the system. The disturbance is measured using a flow meter before it influences the system. It is then possible to eliminate the effects of the disturbances before they create control errors. The feedforward (FF) controller compensates for variation in milk flow approximately, before it has a chance to influence process dynamics. The FF and FB loops can be integrated into a single control circuit. When the disturbance is measurable, the implementation of a combined feedback-feedforward (FB-FF) controller is advisable (Adam & Marchetti, 2004). Figure 2 shows a block diagram of a combined FB-FF control system where $K_b(s)$ is the FB controller, $K_f(s)$ is the FF controller, $G_d(s)$ is the transfer function between the output $y(s)$ (milk temperature after the first or second stage of the PHE) and the disturbance $d(s)$ (incoming milk flow rate), $G_p(s)$ is the transfer function between the output and manipulated variable $u(s)$ (input for the GW or ICW VSD pump), $r(s)$ is the set point temperature of the milk after stage one or two of the PHE, $e(s)$ is the error signal, $w(s)$ is the FB controller output and $q(s)$ is the FF controller output.

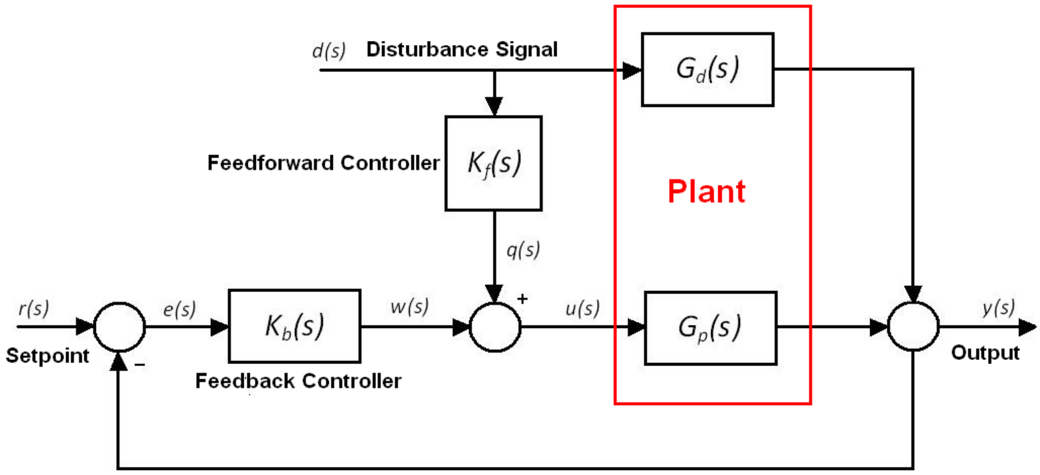

Figure 2; Feedback – feedforward control system block diagram where $K_b(s)$ is the feedback controller, $K_f(s)$ is the feedforward controller, $G_d(s)$ is the transfer function between the output y(s), the disturbance is d(s), $G_p(s)$ is the transfer function between the output and the manipulated variable u(s), r(s) is the set point temperature of the milk after stage one or two of the PHE, e(s) is the error signal, w(s) is the feedback controller output and q(s) is the feedforward controller output.

In the above system the role of the FF controller is to negate the undesirable effect of the disturbance signal. In this control system the ideal FF controller is defined by:

$$K_f(s) = G_d(s) / G_p(s) \quad (2)$$

The input to the plant has an upper and lower operational limit, any input outside this range will be processed just the same as the nearest corresponding limit and will lead to saturation of input *u(s)* resulting in impeded controller response. In the FB loop the controller $K_b(s)$ operates within the same fixed range as the plant in order to generate a maximum and minimum output *w(s)* that is always within the maximum manipulating variable limit $u_{max}(s)$ and the minimum manipulating variable limit $u_{min}(s)$. In the absence of an FF loop *w(s) = u(s)*. However, when the FF loop is introduced, its output *q(s)* is combined with *w(s)*, *u(s)* is liable to deviate outside the range of $u_{max}(s)$ and $u_{min}(s)$ resulting in controller output saturation. To insure this does not occur in the control loop the fixed output range of $K_b(s)$ (PID controller) is dynamically shifted in the opposite direction and magnitude of the FF vector *q(s)*, while the set point *r(s)* remains constant. This guarantees that:

$$w(s) + q(s) \leq u_{max}(s) \quad (3)$$

$$w(s) + q(s) \geq u_{min}(s) \quad (4)$$

This method of dynamically regulating the combined output of the FF and FB loops eliminates the possibility of saturation in the control loop. The operation of the FB controller is not inhibited whilst the influence of the disturbance rejection ability of the FF controller remains, resulting in a highly responsive control system capable of handling frequent disturbances.

Test Procedure

Testing was carried out under controlled laboratory conditions designed to emulate “real world” settings. Water was chosen as a substitute for milk due to its similar thermodynamic properties. The milking clusters were placed upright in basins with a continuous feed of 37°C water. The experiment simulated the operation of a 16 cluster milking machine with one receiver jar, a level sensing probe and a VSD milk pump. The milking machine pumped milk through the PHE and into a bulk tank for storage. During this process the controller manipulated the flow rate of GW to achieve a desired set-point for pre-cooing and the flow rate of ICW to insure instant cooling to the constant set-point of 3.5°C. Both the GW and ICW VSD pumps were controlled by two independent controllers identical to those described above. Both controllers had the same FF input signal. The set point of the ICW controller determines the final temperature of the milk and was kept constant at 3.5°C. This ensured instant cooling of the milk for each test. The set point of the GW controller determined the pre-cooling temperature of the milk. Change of the pre-cooling temperature set point affected the GW usage for pre-cooling and the ice consumption for instant cooling in the second stage, which in turn altered the energy costs. Eight pre-cooling set points (S1-S8) were tested (13°C to 20°C, with 1.0°C increments) for two control schemes, 1) using only the FB loop, and 2) using both the FB and FF control loops. GW temperature was kept constant at 10°C for all tests. The same test procedure, including the operation of the milking machine, was carried out 5 times for the 16 (8 temperature set-points × two control schemes) control settings, giving 80 tests in total. The mean milk flow rate for all tests was 34.05 l min^{-1} with a standard deviation of 0.59 l min^{-1}. The mean milk peak flow was 53.31 l min^{-1} with a standard deviation of 0.94 l min^{-1}.

Analysis of results

To compare the performance of the system for the 16 control settings, the following indicators were calculated: 1) The minimum and maximum temperature of the outgoing milk. 2) Bulk milk temperature was weighted relative to the milk flow rate and was the final temperature of the whole mass of milk. 3) The root of the mean squared error (RMSE) (Eq. 5) of the control systems ability to maintain the final milk temperature at the desired set point.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(\varepsilon_i)^2}{N}} \quad (5)$$

Where for the ith record, ε is the residual error term and N is the total number of records. RMSE squares the residual errors before averaging, thus a quadratic weighting is applied to the error value. In this way large residual errors have a relatively high weight in the RMSE. 4) The mean GW to milk flow, and 5) The mean ICW to milk flow. The indicators were based on the measurement of the related variables that were measured every 0.5 s.

3 Results and Discussion

System Performance

Table 1 shows the performance indicators of the PHE control system with FF control (indicated as FB-FF) and without FF control (indicated as FB) for eight pre-cooling settings (S1-S8). The addition of the FF loop had a substantial impact on the stability of the temperature of the outgoing milk. The mean minimum milk temperature below the set point reduced from 1.0°C for the FB controller to 0.57°C for the FB-FF controller (43% reduction). The FB controller achieved a mean bulk temperature of 3.64 °C (0.14 °C above target) while the FB-FF controller's mean bulk temperature was 3.54°C (0.04°C above target). The mean maximum milk temperature above the set point reduced from 2.1°C for the FB controller to 0.81°C for the FB-FF controller (61% reduction). The mean RMSE for the FB controller was 0.18°C while the RMSE for the FB controller was 0.5°C (2.8 times higher). The final milk output temperature deviated from the set point (3.5°C) much less for the FF-FB controller (between 2.8°C and 4.3°C) in comparison to the FB controller (between 2.5°C and 5.5°C). The main difference between settings was the GW and ICW ratios; as the GW consumption reduced the level of pre-cooling also reduced leading to an increase in ICW utilisation. Figure 3 and Figure 4 represent the operating characteristics of the

FB and FB-FF controller for S1, respectively. The dynamic control of GW and ICW flow rates in response to the variation in milk flow is also shown. Figure 5 shows the operating characteristics of the FB-FF controller for S8. The GW flow rate per unit milk was considerably lower for S8 (Figure 5) compared to S1 (Figure 4). The GW to milk ratio was 1.98 for S8 FB-FB and 5.90 for S1 FF-FB (3 times higher). This reduction in GW resulted in higher ICW usage and therefore more ice consumption per unit of milk. From the results it is clear that the FF-FB controller is capable of precisely and rapidly cooling incoming milk from a variable flow milking machine using different combinations of GW and ice. The most economic mixture of both systems should be selected depending on the costs of electricity and GW.

Table 1; Results of the performance indicators for the feedback (FB) controller and feedback-feedforward (FB-FF) controller for eight controller settings (S1-S8).

Control setting	Min milk temp (°C)	Bulk milk temp (°C)	Max milk temp (°C)	RMSE[a] (°C)	GW Milk Ratio[b]	ICW Milk Ratio[c]
S1FB-FF[d]	2.8	3.5	4.3	0.19	5.90	3.34
S1 FB[e]	2.5	3.6	5.5	0.49	5.98	3.41
S2 FB-FF	3.2	3.5	3.9	0.15	4.44	3.85
S2 FB	2.5	3.5	5.3	0.40	4.54	3.86
S3 FB-FF	2.9	3.5	4.1	0.18	3.36	4.14
S3 FB	2.6	3.6	5.1	0.39	3.38	4.34
S4 FB-FF	3.0	3.5	4.3	0.19	2.92	4.49
S4 FB	2.5	3.7	6.0	0.52	2.97	4.62
S5 FB-FF	2.9	3.5	4.3	0.19	2.68	4.66
S5 FB	2.2	3.6	5.8	0.52	2.69	4.79
S6 FB-FF	3.0	3.6	4.6	0.19	2.46	4.83
S6 FB	2.5	3.7	5.8	0.59	2.51	4.92
S7 FB-FF	2.9	3.6	4.5	0.17	2.19	4.99
S7 FB	2.5	3.7	5.9	0.52	2.21	5.03
S8 FB-FF	2.7	3.6	4.5	0.19	1.98	5.11
S8 FB	2.5	3.7	5.8	0.58	2.02	5.19

[a] Root mean squared error; [b] Ground water to milk flow ratio (); [c] Ice chilled water to milk flow ratio (); [d] Feedback-Feedforward; [e] Feedback

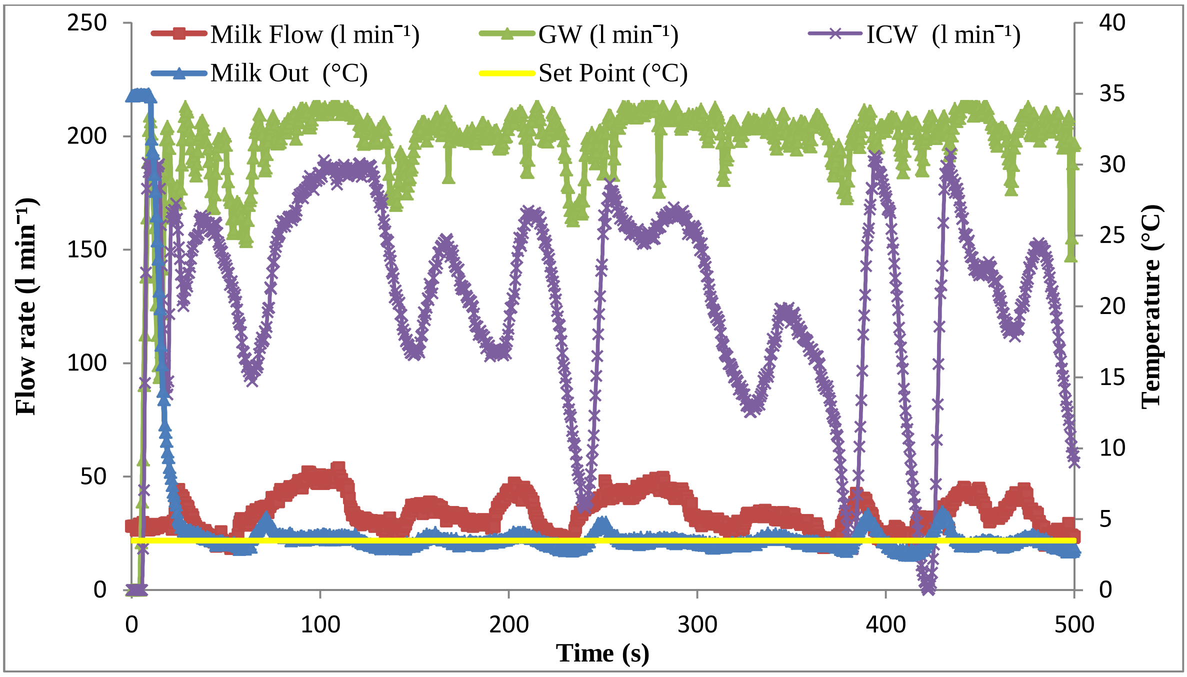

Figure 3; Operating characteristics for feedback (FB) only controller S1. Flow rates (l min^{-1}) of milk (red), ground water (GW) (green) and ice chilled water (ICW) (purple) on left axis. Temperature (^{o}C) of outgoing milk (blue) and set-point (yellow) on right axis.

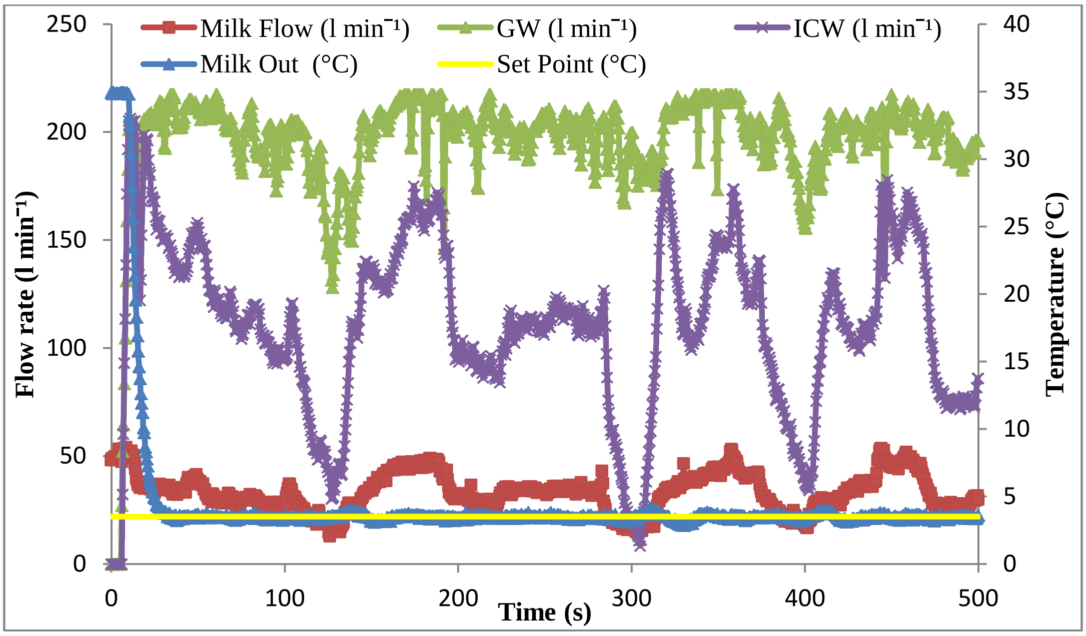

Figure 4; Operating characteristics for feedback-feedforward (FB-FF) controller S1. Flow rates (l min^{-1}) of milk (red), ground water (GW) (green) and ice chilled water (ICW) (purple) on left axis. Temperature (^{o}C) of outgoing milk (blue) and set-point (yellow) on right axis.

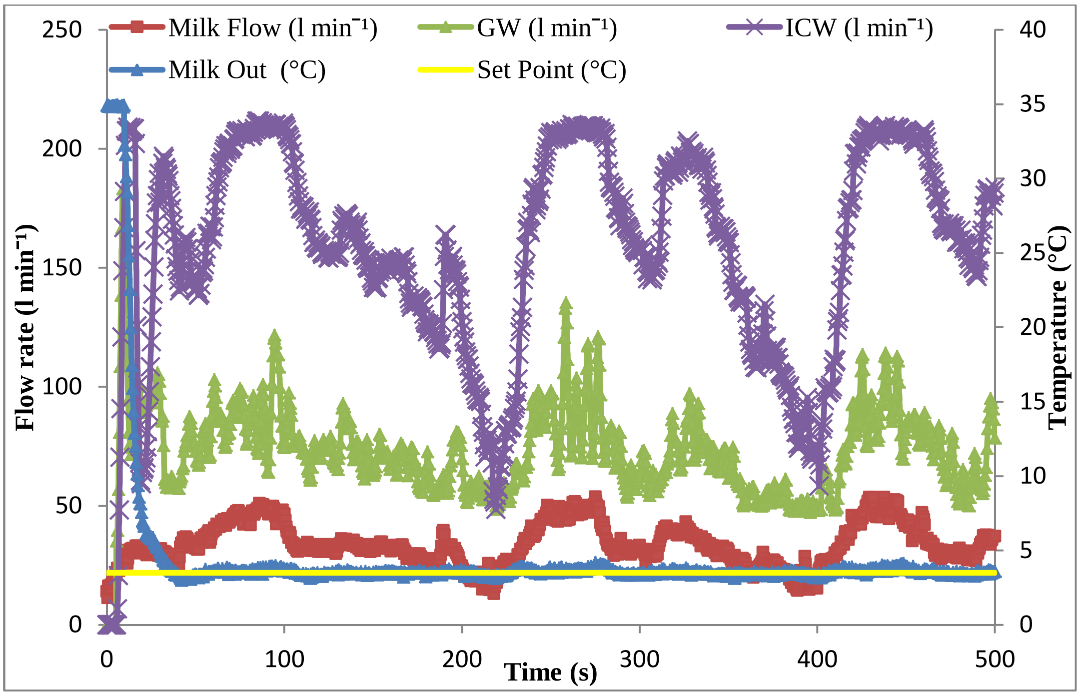

Figure 5; Operating characteristics for feedback-feedforward (FB-FF) controller S8. Flow rates (l min-1) of milk (red), ground water (GW) (green) and ice chilled water (ICW) (purple) on left axis. Temperature (°C) of outgoing milk (blue) and set-point (yellow) on right axis.

Energy Consumption and Cooling Cost

The results in Figure 6 were produced by the milk cooling and cost model described above and represent the cooling energy consumption per litre of milk with varying GW to milk ratios. The amount of cooling energy required reduced as the GW to milk ratio increased. However, the influence of the GW on the energy consumption became increasingly less substantial as the ratio increases. This is largely due to the decrease in PHE effectiveness per additional litre of water since the temperature differential between the pre-cooled milk and the GW reduces and the energy consumption of the water pump increases as the water flow increases.

Figure 7 shows the cost of cooling milk with varying GW to milk ratios. The cost of cooling per litre of milk fluctuates as the GW to milk ratio increases. There is an optimum GW to milk ratio for each fixed water cost that yields the minimum cooling cost. These points can be seen as the optimum combination of cooling power (ice storage) and GW consumption for specific water and electricity costs. The economic optimum water to milk ratio varies greatly with water cost. Where water is supplied without cost the optimum solution is to keep increasing the water flow rate until the added cooling effect of the water is cancelled out by the increasing pumping cost. However, in practice producing GW at no cost is unlikely as some working infrastructure and capital financing is required. Applying even a very small monetary cost to the GW (€0.05m^{-3}) has a profound effect on the optimum economic water ratio. As the water cost increases this optimum ratio continues to reduce.

Optimisation Potential

Between 2010 and 2012 Teagasc AGRIC conducted energy audits on 25 commercial dairy farms in Ireland. The average IB milk cooling energy consumption and cost were 0.013kWh l^{-1} and €0.0016 l^{-1} (excluding water cost), respectively. In each case either insufficient levels of pre-cooling or no pre-cooling were observed. Audits carried out specifically on pre-cooling found that 80% of PHEs had a GW to milk ratio of 1:1 or less. In similar energy audits completed in 1995 in the UK, average IB milk cooling energy consumption was found to be 0.0222 kWh/l with the average PHE GW to milk ratio 1:1 (Milk Development Council, 1995). A study in New Zealand found that increasing the GW to milk ratio considerably increased pre-cooling levels (Morrison, Gregory & Hopper, 2007). Figure 7 gives a clear representation of possible savings which could be achieved on a typical dairy farm if a control system was introduced to optimize the usage of GW. If it is assumed that the current dairy farm modus operandi for PHE pre-cooling is a GW to milk ratio of 1:1, then potential for system optimisation clearly exists. For a water cost of €0.05 m^{-3} a GW to milk ratio of 1:1 results in a milk cooling cost of €0.00115 l^{-1}, however a cooling cost of €0.00076 l^{-1} (34.5% less) can be achieved through correct water utilisation (Figure 7). Similarly savings of 17.9%, 9.6% and 0.5% can also be made for set water costs of €0.1 m^{-3}, €0.15 m^{-3} and €0.2 m^{-3}, respectively. Only operational costs are included in this study, the initial investment and depreciation costs of a VSD and a PID controller are not included.

Optimisation of GW usage is not only advantageous for instant milk cooling but for all milk cooling systems that employ pre-cooling with GW. The controller described above controls GW based on desired pre-cooling temperature. The control system's ability to instantly cool milk by balancing GW and ice consumption enables the selection of the optimum economic GW to milk ratio. Farmers can adjust the setting of the controller based on specific farm conditions, electricity cost and water cost/availability, this capability could also help farmers to negotiate any future spikes in energy costs or shortages in water supply. The controller setting can be adjusted manually using heuristic knowledge or can be automatically updated based on milk production, wash down water usage, electricity cost, and GW cost. With seasonally varying herd sizes and milk production levels, the optimum controller set point could be dynamically updated throughout the season.

Changes in controller setting could also be used to facilitate herd size expansion without increasing plant capital cost. Increased usage of GW will allow for the cooling of more milk without an increase in IB capacity, this attribute could help farmers cope with large increases in milk production in the near future.

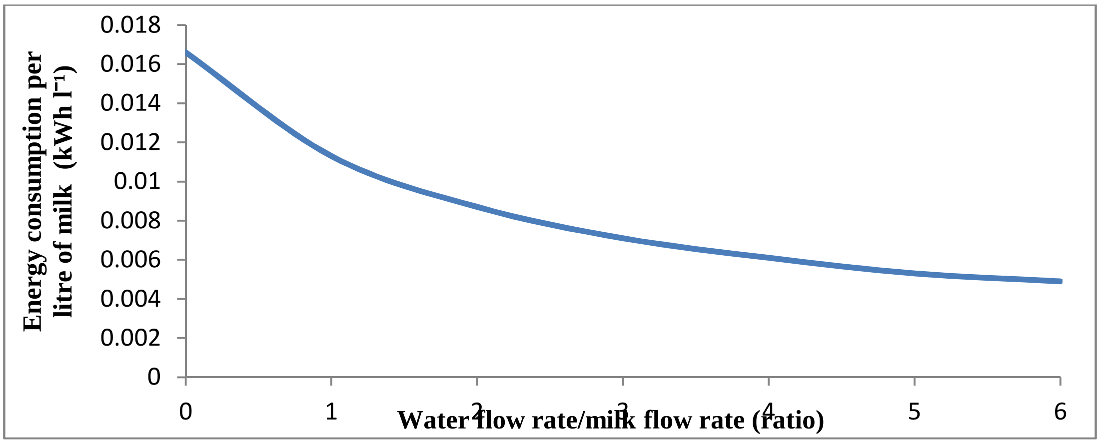

Figure 6; Energy consumption per litre of milk (kWh l^{-1}) with varying ground water ratios.

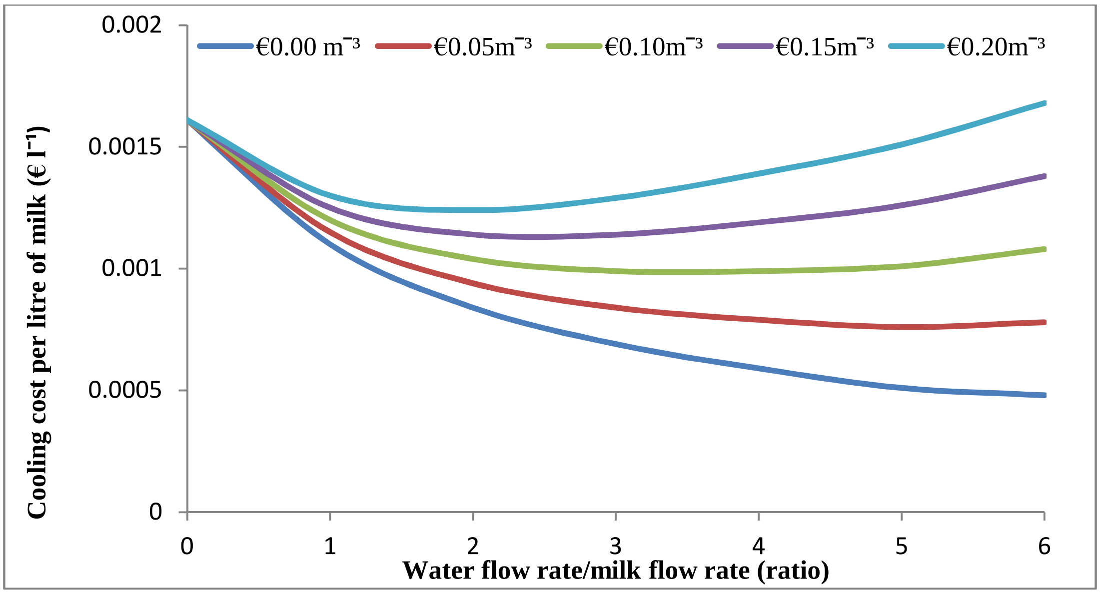

Figure 7; Milk cooling cost per litre of milk (€ l^{-1}) with varying water to milk ratios for five different ground water prices €0.00 m^{-3} (blue), €0.05 m^{-3} (red), €0.10 m^{-3} (green), €0.15 m^{-3} (purple), €0.20 m^{-3} (cyan).

4 Conclusion

A rapid milk cooling system was designed, built and tested for a variable flow milking machine and tested under various configurations. The system was capable of rapidly cooling a dynamic milk flow over a wide range of operating conditions. The introduction of a control system allows for potentially substantial energy and cost savings. The introduction of a FF loop to the controller significantly increased the accuracy of the output temperature; this is particularly useful for direct milk collection and non-agitated storage. However, for bulk storage with mechanical agitation a FF loop is not vital as the bulk temperature is only slightly above target (0.2°C maximum).

The system has the ability to operate under varying GW supply and pricing scenarios allowing the user to select either low cooling costs and high water usage, or low water usage and higher cooling costs. This is because the ice water usage will autonomously increase or decrease to achieve the desired instant cooling temperature allowing for the optimisation of pre-cooling for a given water or electricity cost. The same GW optimisation scheme can be applied to conventional cooling systems.

Future development of the system will involve a mathematical tool that automatically selects the optimum controller setting based on specific on site conditions using information from other on-farm databases.

References

Adam, E. J., & Marchetti, J. L. (2004). Designing and tuning robust feedforward controllers. Computers & Chemical Engineering 28(9), 1899-1911.

Astrom, K. J., & Hagglund, T. (2001). The future of PID control. Control Engineering Practice 9(11), 1163-1175.

Chaichana, C., Charters, W., & Aye, L. (2001). An ice thermal storage computer model. Applied Thermal Engineering 21(17), 1769-1778.

Heong, K. A., Chong G., and Yun, L. (2005). PID control system analysis, design, and technology. IEEE Transactions on Control Systems Technology 13(4), 559-576.

Holm, C., Jepsen, L., Larsen, M., Jespersen, L. (2004). Predominant Microflora of Downgraded Danish Bulk Tank Milk. Journal of Dairy Science 87(5), 1151-1157.

Milk Development Council (1995). Bulk milk tanking cooling efficiency, Milk Development Council Report, UK.

Mohamed, M. (2009). Solidification of phase change material on vertical cylindrical surface in holdup air bubbles. International Journal of Refrigeration 28(3), 403-411.

Morison, K., W. Gregory, and R. Hooper. 2007. Improving Dairy Shed Energy Efficiency, Technical Report. New Zealand Centre for Advanced Engineering (CAENZ). Christchurch, New Zealand.

Stinson, G. E., Studman, C. J., & Warburton, D. J. (1987). A dairy refrigeration heat recovery unit and its effects on refrigeration operation. Journal of Agricultural Engineering Research 36(4), 275-285.

Upton, J., Murphy, M., French, P. & Dillon P. (2010). Energy consumption on dairy farms. In Proceedings of the Teagasc National Dairy Conference (pp 87-97), Mullingar, Ireland.

Yu, F. W., & Chan, K. T. (2005). Experimental determination of the energy efficiency of an air-cooled chiller under part load conditions. Energy 30(10), 1747-1758.

Zaman, R. I., & Hussain A. K. M. I. (2011). Optimization of small window type air conditioner. In Proceedings of the IEEE 3rd International Conference on Communication Software and Networks (ICCSN) 27-29 May 2011, 598-601,

Ziegler, J. B., & Nichols, N. B. (1942). Optimum Settings for Automatic Controllers. Transactions of the ASME 64(11), 759–768.

Chapter 5

Assessing the Impact of Changes in the Electricity Price Structure on Dairy Farm Energy Costs

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Abstract

This study aims to provide information on the changes in electricity consumption and costs on dairy farms, through the simulation of various electricity tariffs that may exist in the future and how these tariffs interact with changes in farm management (i.e. shifting the milking operation to an earlier or later time of the day). A previously developed model capable of simulating electricity consumption and costs on dairy farms (MECD) was used to simulate 5 different electricity tariffs (Flat, Day&Night, Time of Use Tariff 1 (TOU1), TOU2 and Real Time Pricing (RTP)) on three representative Irish dairy farms: a small farm (SF), a medium farm (MF) and a large farm (LF). The Flat tariff consisted of 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 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 was a mechanistic mathematical representation of the electricity consumption that simulated 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 effect of milking start time was simulated to determine the effect on electricity consumption and costs at farm level. The earliest AM milking start time and the latest PM milking start time resulted in the lowest energy consumption. The difference between the lowest and highest electricity consumption within a farm was 7% for SF, 5% for MF and 5% for LF. This difference was accounted for by the variation in the milk cooling system coefficient of performance. There was greatest scope to reduce total annual electricity costs by adjusting milking start times on TOU2 (39%, 34% and 33% of total annual electricity costs on the SF, MF and LF) and least scope for reductions using this method on the Flat tariff (7%, 5% and 7% of total annual electricity costs). The potential for reduction of annual electricity consumption and related costs per litre of milk produced by adjusting milking times was higher for the LF than the SF or MF across all electricity tariffs. It is anticipated that these results and the use of the MECD will help support the decision-making process at farm level around increasing energy efficiency and electricity cost forecasts in future electricity pricing tariff structures.

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 viability. First, the electricity price for European farmers increased by 32% in the last 5 years (Eurostat, 2013), due to increases in global energy prices. Second, 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). Increased milk production may lead to increases in electricity costs per litre of milk harvested, because increased mechanisation and more industrial milk harvesting equipment is required to manage larger dairy herds. And third, European wide directives encourage the use of smart metering as a means of driving demand side energy efficiency, which might increase dairy farm electricity costs if not anticipated by the farmer. All of these components will combine to create an unprecedented level of uncertainty around electricity costs on dairy farms.

The European Energy Services 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 was transposed into Irish law. Also in 2009 the Irish Government adopted the National Energy Efficiency Action Plan 2009-2020 (NEEAP) in order to help 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). Compared with traditional electricity pricing systems, dynamic pricing systems may entail more uncertainty for end-users with respect to the frequency and timing of high peak prices (Ericson, 2011), however exposing electricity users to hourly real time prices is known as the most efficient tool that can urge consumers to consume more wisely and efficiently (Samadi et al., 2010).

The effect of both time of use (TOU) and real time pricing (RTP) tariffs on the residential sector (Allcott, 2011; Di Giorgio et al., 2014; Ericson, 2011; Finn et al., 2013; Herter et al., 2010; Rastegar et al., 2012; Torriti, 2012) and the commercial building sector (Avci et al., 2013; Finn et al., 2014; Lam et al., 2008; Mathieu et al., 2011; Wang et al., 2013) has been well documented. Up until now similar analysis has not been reported in relation to the agricultural sector. Furthermore, the smart metering trial conducted in Ireland by the commission for energy regulation (CER) in 2010 to deliver the evidence for the energy efficiency potential of smart metering (CER, 2011b) did not include agricultural premises in the SME sector, instead it focussed on retail, service, office, entertainment and manufacturing enterprises. The trial carried out by the CER focused on various TOU tariffs, however such rates do not necessarily lead to overall conservation at the electricity grid level (Woo et al., 2014). Another alternative is the RTP system, which can be implemented by capitalising on developments in advanced metering infrastructures (Ferreira et al., 2012; Joskow, 2012; King et al., 2012; Valenzuela et al., 2012).

RTP tariffs imply a dynamic electricity price 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 (Upton et al., 2013). 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 electricity costs. A dynamic pricing structure, however, could also present opportunities to reduce overall electricity costs if the farmers routine could be modified to optimise energy use in off-peak periods (currently from 00:00 to 09:00 h). In the future farmers will need to develop strategies to adapt to these electricity pricing influences. However to react appropriately farmers need information about how their electricity costs will vary according to future tariff structures. The objective of this study was to provide information on the changes in dairy farm electricity costs through the simulation of various electricity tariffs that may exist in the future, which, to our knowledge, has not been reported in the literature. The impact of modifying the farms daily routine by shifting the milking operation to an earlier or later time to reduce electricity costs for each electricity tariff was investigated. It is anticipated that this analysis will help support the decision-making process at farm level around increasing energy efficiency and electricity cost forecasting in future electricity pricing tariff structures.

2 Materials and Methods

Electricity consumption model

A model for electricity consumption on dairy farms (MECD), developed by Upton et al. (2014), was used to apply five electricity tariffs to a number of simulated electricity consumption trends of three representative dairy farms in Ireland. The MECD was designed to simulate the electricity consumption and electricity costs on dairy farms. The MECD is a mechanistic mathematical representation of the electricity consumption that simulates 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 7 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 energy consumption matrix by the tariff matrix.

Model Inputs

The electricity consumption and related costs of a small farm (SF) with 45 milking cows, a medium farm (MF) with 88 milking cows and a large farm (LF) 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 each of these three farms. The SF, MF and LF were spring calving herds operating grass-based milk production systems with low supplementary feed input (mean of 1.19 kg concentrate/100 kg of milk produced in 2011) similar to most Irish dairy farmers. In 2011, actual milk production was 255,278 L for SF; 499,898 L for MF and 774,089 L for LF. Further data relating to the scale and production levels of the SF, MF and LF are presented in table 1. All farms engaged herringbone milking plants with two stalls per milking unit and were fitted with oil lubricated centrifugal vane vacuum pumps without variable speed control. Milking parlour size varied from 8 units on SF, 14 units of MF and 24 units on LF. All farms used direct expansion milk cooling systems with pre-cooling of milk via well water before entry to the bulk tank. The SF and MF used a milk pre-cooling system which chilled warm milk to 25°C before entry to the milk cooling system, whereas the pre-cooling system on the LF was not as effective and cooled the milk to 30°C via the same method. Standard pressurised cylinder water heating systems were used on all farms. The system efficiency of the heating systems was 90% for the SF and MF. The the heating system of the LF was operating with a lower system efficiency (80%) due to a lack of insulation of hot-water piping and fittings around the water heater.

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 2010. This year was chosen as the reference year because the smart metering consumer behaviour trial was rolled out in Ireland by the CER at this time. The Flat and Day&Night tariffs used in this analysis were taken from the dairy farm electricity prices from 2010 for the SF, MF and LF. The TOU tariffs were identical to those applied to the 650 SME participants in the consumer behaviour trial of the CER. The RTP tariff was also normalised using 2010 national grid load data.

Flat and Day&Night Tariffs. Two commonly used existing tariff structures were used in this analysis (Flat and Day&Night) to act as reference tariffs, and to highlight any potential cost savings or increases that may occur due to the implementation of TOU or RTP tariffs. A Flat tariff implied electricity price of €0.16/kWh throughout the year, whereas a Day&Night tariff implied a price of €0.16/kWh from 09:00 to 00:00 h and of €0.08/kW from 00:00 to 09:00 h. The mean electricity price on the Day&Night Tariff, therefore, was €0.13/kWh (figure 1).

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. The structure of these tariffs is presented in figure 1. Their structure was similar to that of the Day&Night tariff except that an extra price band was introduced between 17:00 and 19:00 h. The mean electricity price of TOU1 was €0.15/kWh (range 0.14-0.22 €/kWh), the mean electricity price of TOU2 was €0.13/kWh (range 0.08-0.23 €/kWh), see figure 1.

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 2010 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 in 2010 were sourced from Deane et al. (2013). The RTP tariff, therefore, was computed as:

$$RTP(i,j) = SMP(i,j) + Tc + Bc + Dc + Rm \quad [1]$$

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 €0.13/kWh (range 0.11 - 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.

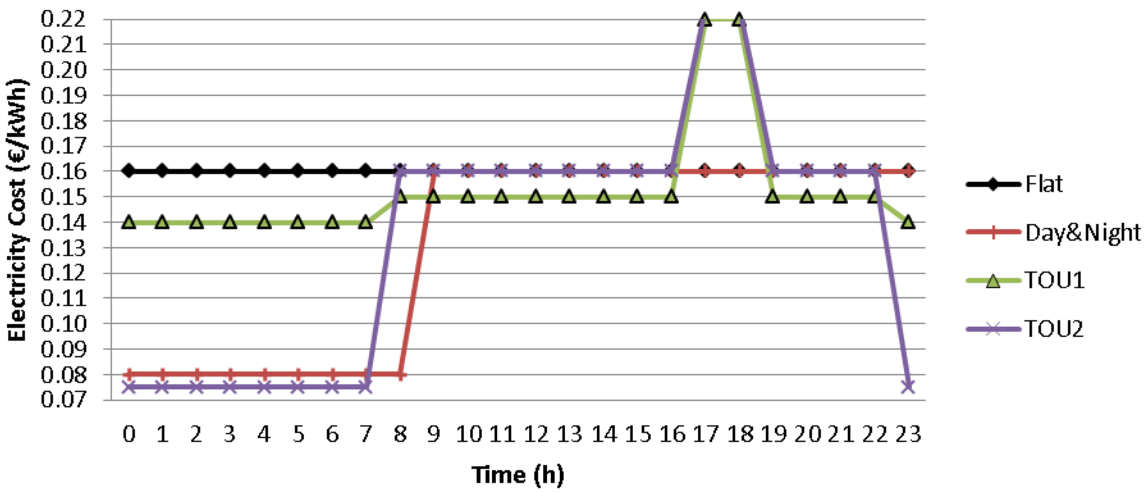

Figure 1; Graph of electricity costs (€/kWh) by hour of the day for 4 of the tariffs used in this analysis. Flat, Day&Night, Time Of Use1 (TOU1) and TOU2.

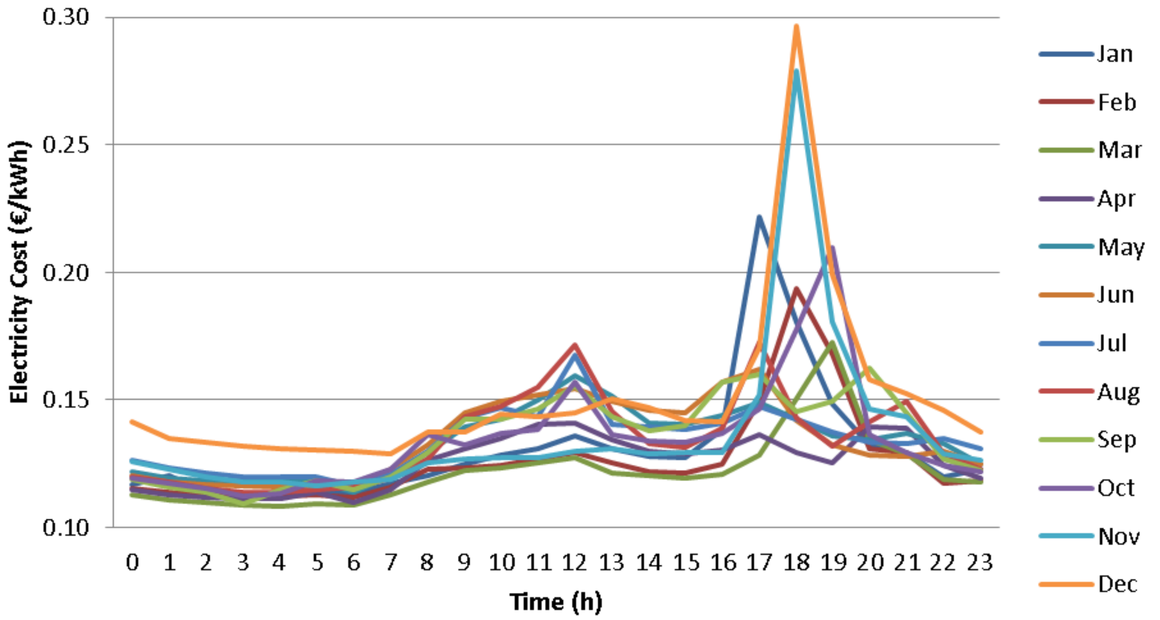

Figure 2; Graph of electricity costs (€/kWh) by hour for an average day in each month of the year (2010) for the Real Time Pricing (RTP) Tariff used in this analysis.

Milking start time analysis

The SF, MF and LF carried out milkings twice a day. Default milking start times were standardised to 07:00 and 17:00 h for all three farms. Milking start time(s) were included in the MECD. Variations in AM milking start time were tested from 05:00 to 10:00 h in steps of one hour. Variations in PM milking start time were tested from 15:00 to 20:00 h in steps of one hour. The impact of adjusting milking start times on the electricity consumption and related costs was simulated for each of the electricity tariffs.

The time of day that milking(s) occur could affect the electricity costs of the dairy farm through two mechanisms: i) moving the milking start time could move the consumption of electricity from one tariff rate into another, altering the electricity costs, ii) moving the milking start time could change the quantity of electricity consumed in the milk cooling system, because the quantity of electricity used is influenced by the cooling systems coefficient of performance (COP) (equation 2), which in turn is influenced by the ambient temperature according to equation 4 (Upton et al., 2014).

$$Q_{mc}(i,j) = \frac{C_m \times \Delta T(i,j) \times M_m(i,j)}{COP(i,j) \times 3600} \qquad [2]$$

Where $\Delta T(i,j) = T_{bulk}(i,j) - T_{final}$ [3]

And $COP(i,j) = \left(\frac{T_{evap}}{T_{amb}(i,j) - T_{evap}} \right) \times a$ [4]

Where $Q_{mc}(i,j)$ is electricity consumed for milk cooling in month i (1-12) and hour j (1-24) (kWh); C_m is specific heat capacity of milk (kJ/(kg.K)); $\Delta T(i,j)$ is difference in temperature between the milk entering the storage tank ($T_{bulk}(i,j)$) and the milk tank set point (T_{final}) (K). T_{bulk} was calculated based on 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). M_m is the mass of milk to be cooled (kg) where it was assumed that 60% of the milk was extracted in the morning milking (O'Callaghan and Harrington, 2000), COP is the milk cooling system coefficient of performance, dimensionless (-). T_{evap} is the evaporator temperature of the refrigeration system (assumed to be 268K for a direct expansion milk tank). T_{amb} (K) is hourly ambient temperature taken from a local weather station. *a* is an adjustment factor to account for inefficiencies in real world systems (assumed 0.10 for this analysis). This approach yielded a range in COPs for a direct expansion system of 1.2 to 4.1. Effects of milk production variations due to a change in milking start time were not included in this analysis.

3 Results

Electricity consumption and costs

Table 1 shows the simulated electricity consumption (kWh) for each of the 7 main infrastructural systems on each of the 3 farms. On average, milk cooling made up 38% of total electricity consumption across all 3 farms (range 25 – 46%), water heating 29% (range 26 – 35%), milking machine 19% (range 18 – 25%), wash pump 0.2% (range 0 – 1%), water pump 7% (range 0 – 9%), automatic scrapers 3% (range 0 – 7%) and lighting 3% (range 2 – 5%). The simulated electricity consumption and electricity costs per litre of milk were lowest for the SF, i.e. 33 Wh/L and €0.0037/L. The corresponding figures for the MF were 41 Wh/L, €0.0044, whereas for the LF they were 42 Wh/L, €0.0046 €/L.

Effect of milk starting time on electricity consumption

Simulated electricity consumption was determined by variations in AM and PM milking start times, see table 2. The earliest AM milking start time and the latest PM milking start time resulted in the lowest electricity consumption.

SF. In the case of the SF the simulated electricity consumption was 8,498 kWh. A range of milking start times between 05:00 vs. 10:00 h (AM) resulted in a variation of 410 kWh for the year, whereas a range of milking start times between starting the PM milking at 15:00 vs. 20:00 h resulted in a variation of 208 kWh. In total this gave a variation between lowest and highest consumption of 618 kWh per year, which represented about 7% of the total default electricity use of the SF.

MF. In the case of the MF the simulated electricity consumption was 20,631 kWh. A range of milking start times between 05:00 vs. 10:00 h (AM) resulted in a variation of 658 kWh for the year, whereas a range of milking start times between starting the PM milking at 15:00 vs. 20:00 h resulted in a variation of 348 kWh. In total this gave a variation between lowest and highest consumption of 1,006 kWh per year, which represented about 5% of total default electricity use of the MF.

LF. In the case of the LF the simulated electricity consumption of 32,407 kWh. A range of milking start times between 05:00 vs. 10:00 h (AM) resulted in a variation of 952 kWh for the year, whereas a range of milking start times between starting the PM milking at 15:00 vs 20:00 h resulted in a variation of 778 kWh. In total this gave a variation between lowest and highest consumption of 1,729 kWh per year, which represented about 5% of total default electricity use of the LF.

Table 1; Mean values of characteristics and simulated electricity consumption values of the three farms, SF (small farm), MF (medium farm) and LF (large farm).

Farm Characteristics	**SF**		**MF**		**LF**	
Farm Area (ha)	48		70		110	
Dairy herd Size	45		88		195	
Stocking Density (LU/ha)[1]	1.68		1.90		2.43	
Milk Production (Liters/annum)	255,278		499,898		774,089	
Milk cooling (kWh, % of total)	3,322	39%	5,206	25%	14,978	46%
Water heating (kWh, % of Total)	2,444	29%	7,294	35%	8,303	26%
Milking machine (kWh, % of Total)	2,131	25%	3,628	18%	6,124	19%
Wash pump (kWh, % of Total)	NA	NA[2]	145	1%	NA	0%
Water pump (kWh, % of Total)	NA	0%	1,832	9%	2,452	8%
Auto scrapers (kWh, % of Total)	422	5%	1,533	7%	NA	0%
Lighting (kWh, % of Total)	179	2%	994	5%	493	2%
Electricity Use (Wh/Liter)	33.3		41.3		41.9	
Total (kWh)	8,498		20,631		32,407	
Electricity costs (€/Liter)	0.0037		0.0044		0.0046	
Total electricity costs (€)	933		2,184		3,586	

[1] LU/ha = Livestock Units per hectare

[2] NA = Not applicable

Table 2; Deviation in total annual simulated electricity consumption (kWh) from the default milking start times (values in italics) for three Irish dairy farms, Small Farm (SF), Medium Farm (MF) and Large Farm (LF). Within each row negative values indicate a reduction and positive values indicate an increase in electricity consumption from the default milking start times (07:00 and 17:00 h). Maximum range (kWh and % in parentheses shows the total combined variation of AM and PM milking times.

Farm Type	**AM Milking Time**						**PM Milking Time**						**Maximum Range (%)**
	5	**6**	**7**	**8**	**9**	**10**	**15**	**16**	**17**	**18**	**19**	**20**	
SF	-166	-90	*8,498*	92	177	244	63	37	*8,498*	-46	-96	-145	618 (7)
MF	-258	-140	*20,631*	148	286	400	109	64	*20,631*	-76	-158	-239	1006 (5)
LF	-500	-245	*32,407*	211	366	452	313	164	*32,407*	-167	-324	-465	1729 (5)

Variation in electricity costs with electricity tariffs and milking start time

Data pertaining to electricity costs for the three farms on 5 tariffs for various AM and PM milking times are presented in table 3. Data pertaining to the maximum adjustment potential (MAP) within tariffs and the predicted increase from the lowest cost tariff within farms are presented in table 4. The MAP describes the greatest difference between lowest and highest total annual electricity costs within an electricity tariff.

SF. With default milking times the total annual electricity costs varied from €933 on the Day&Night tariff to €1,360 on the Flat tariff, implying an increase in costs of approximately 46% given the Day&Night tariff. If the SF were operating on TOU1 in 2010 a 39% (€362) increase in total electricity costs would have been realised. Similarly costs would have increased by 15% (€138) on TOU2 tariff and by 18% (€167) on RTP tariff. The highest MAP existed on TOU2 (€421, 39% of total annual electricity costs on TOU2), whereas the lowest MAP existed on the Flat tariff (€99, 7% of total annual electricity costs on Flat).

MF. With default milking times the total annual electricity costs varied from €2,184 on the Day&Night tariff to €3,301 on the Flat tariff, implying an increase in costs of approximately 51% given the Day&Night tariff. If the MF were operating on TOU1 in 2010 a 45% (€979) increase in total electricity costs would have been realised. Similarly costs would have increased by 18% (€395) on TOU2 tariff and by 21% (€467) on RTP tariffs. The highest MAP existed on TOU2 (€885, 34% of total annual electricity costs on TOU2), whereas the lowest MAP was on the Flat tariff (€161, 5% of total annual electricity costs on Flat).

LF. With default milking times the total annual electricity costs varied from €3,586 on the Day&Night tariff to €4,250 on the Flat tariff implying an increase in costs of approximately 19% given the Day&Night tariff. If the LF were operating on TOU1 in 2010 a 19% (€672) increase in total electricity costs would have been realised. Similarly costs would have increased by 17% (€616) on TOU2 and 3% (€125) on RTP tariffs. The highest MAP existed on TOU2 (€1,394, 33% of total annual electricity costs on TOU2) and the lowest MAP was on the Flat tariff (€277, 7% of total annual electricity costs on Flat).

Table 3; Deviation in total annual electricity costs (€) from the default milking start times (values in italics) for three Irish dairy farms, Small Farm (SF), Medium Farm (MF) and Large Farm (LF) for 5 different electricity tariffs. Within each row, negative values indicate a reduction and positive values indicate an increase in electricity costs from the default milking start times (07:00 and 17:00 h).

	Tariff Structure	**AM Milking Start Time**						**PM Milking Start Time**					
		5	**6**	**7**	**8**	**9**	**10**	**15**	**16**	**17**	**18**	**19**	**20**
	Flat	-27	-14	*1,360*	15	28	39	10	6	*1,360*	-7	-15	-23
SF	Day Night	-47	-30	*933*	62	163	250	11	7	*933*	-8	-17	-26
	TOU1[a]	-37	-22	*1,294*	28	42	55	-23	-9	*1,294*	56	21	-74
	TOU2	-132	-86	*1,070*	132	147	160	-18	-6	*1,070*	50	15	-79
	RTP[b]	-49	-31	*1,099*	35	63	82	-6	-5	*1,099*	9	5	-17
	Flat	-41	-22	*3,301*	24	46	64	17	10	*3,301*	-12	-25	-38
MF	Day Night	-80	-52	*2,184*	155	390	514	20	12	*2,184*	-14	-30	-47
	TOU1	-75	-48	*3,163*	45	69	88	-116	-98	*3,163*	94	-43	-195
	TOU2	-348	-249	*2,579*	210	235	255	-102	-88	*2,579*	82	-51	-200
	RTP	-97	-61	*2,652*	64	111	150	-30	-24	*2,652*	29	22	-41
	Flat	-80	-39	*4,250*	34	59	72	50	26	*4,250*	-27	-52	-74
LF	Day Night	-254	-149	*3,586*	254	545	682	83	44	*3,586*	-59	-122	-188
	TOU1	-153	-81	*4,257*	71	108	151	-98	-117	*4,257*	82	-142	-333
	TOU2	-576	-340	*4,202*	265	302	344	-36	-74	*4,202*	37	-215	-437
	RTP	-174	-97	*3,711*	82	134	175	3	-16	*3,711*	5	-17	-121

[a] TOU = time of use

[b] RTP = real time pricing

Table 4; Maximum adjustment potential (defined the difference between highest and lowest total farm electricity costs within a tariff) in total annual electricity costs (€) and % of total annual electricity costs within a tariff for three Irish dairy farms, Small Farm (SF), Medium Farm (MF) and Large Farm (LF) for 5 different electricity tariff structures. The percentage increase in annual electricity costs from the lowest cost tariff (Day&Night) is also presented for each tariff on each farm.

	Tariff Structure	Maximum adjustment potential (MAP)			Increase from Day&Night Tariff	
		€	%	€/1,000 L of milk	€	%
	Flat	99	7%	0.39	427	46%
SF Energy Costs	Day&Night	334	36%	1.31	0	0%
	TOU1[a]	222	17%	0.87	362	39%
	TOU2	421	39%	1.65	138	15%
	RTP[b]	157	14%	0.61	167	18%
	Flat	161	5%	0.32	1,117	51%
MF Energy Costs	Day&Night	660	30%	1.32	0	0%
	TOU1	452	14%	0.90	979	45%
	TOU2	885	34%	1.77	395	18%
	RTP	317	12%	0.63	467	21%
	Flat	277	7%	0.36	664	19%
LF Energy Costs	Day&Night	1,206	34%	1.56	0	0%
	TOU1	720	17%	0.93	672	19%
	TOU2	1,394	33%	1.80	616	17%
	RTP	475	13%	0.61	125	3%

[a] TOU = time of use

[b] RTP = real time pricing

4 Discussion

Variations in electricity use

Table 2 showed that the simulated total annual electricity consumption of the three farms studied varied according to milking start time. The difference between the lowest and highest electricity consumption within a farm was 7% for SF, 5% for MF and 5% for LF. This difference was accounted for by the variation of the COP of the milk cooling system (according to equation 4), which in turn varied the electricity consumed by the milk cooling system (equation 2). Milking earlier in the morning/later in the evening meant that the cooling system was operating at lower ambient air temperature (T_{amb}) which increased the COP of the milk cooling system and in turn reduced the electricity consumption of the milk cooling system (equation 2). As CO_2 emissions from electricity consumption are directly associated with electricity consumption, the potential of adjusting milking time to reduce CO_2 emissions can be computed via direct multiplication with the factor 0.53 kg CO_2 per kWh (Howley et al., 2011). Hence, the difference between the lowest and highest annual CO_2 emissions within a farm was 330 kg for SF, 553 kg for MF and 917 kg for LF. In reality CO_2 emissions are not equal across all hours of the day due to intermittent wind energy penetration on the national electricity grid and fluctuating fuel mixes for electricity generation. We were informed at the time of writing by the national electricity grid operator (Eirgrid) that the dynamic CO_2 emissions data for 2010 were unavailable, therefore we used a national average figure.

Influence of farm size on electricity costs

The simulated electricity consumption of the SF (33.3 Wh/Litre) was lower than those of the MF (41.3 Wh/L) and LF (41.9 Wh/L). The electricity costs were lower also for SF (€0.0037/L) than for MF (€0.0044/L) and LF (€0.0046/L). This indicates that electricity consumption and costs per litre of milk produced increased along with farm size. This is largely explainable by the fact that the SF and MF used a milk pre-cooling system which chilled warm milk (via ground water in a plate heat exchanger) to 25°C before entry to the milk cooling system, whereas the pre-cooling system on the LF was not as effective and cooled the milk to 30°C via the same method. This is a common problem on large milking parlours where a large milk pump is required to rapidly clear milk from the receiver jar, thereby forcing high volumes of milk through the pre-cooling system resulting in sub-optimal pre-cooling.

Adjusting the daily milking time could help to keep electricity related costs as low as possible. Table 4 showed that the highest MAP per litre of milk produced within a tariff was on the LF, with the exception of the RTP tariff. For example, on the Day&Night tariff the MAP of the SF was €1.31/1000L of milk, however on the LF the MAP was €1.56/1000L. This information is very relevant for farmers considering increasing milk production because as farm size increases higher cost savings can be realised by modifying milking start times and choosing the correct electricity tariff.

Tariff structure assumptions

The outcomes of this analysis were dependent on the structure of the tariffs used as inputs to the MECD. All tariffs were normalised to 2010 to correspond with the smart metering consumer behaviour trial which was initiated in Ireland by the CER at this time. The CER study did not include any agricultural premises, the SME sample was made up of retail, service, office, entertainment and manufacturing enterprises, which highlights the role of the present study in identifying suitable future tariff options for dairy farms. It was found that the SME consumers in the trial reduced their overall electricity usage by 0.3% (CER, 2011a). Real time pricing was not part of the study carried out by the CER, probably because this type of pricing has been reserved for large energy consumers in the past. However it would seem likely that this is the natural next step in the smart metering debate. Also, from an academic perspective it is interesting to examine what this type of structure would look like and how it would affect dairy farm electricity costs if it were implemented in reality. To our knowledge, analysis of RTP tariffs in relation to dairy farms has never been reported. Many authors, however, have derived RTP tariffs to demonstrate the load shifting capability of an appliance (Finn et al., 2013) or energy storage device (Zhanbo et al., 2012), while operating in a RTP environment. When comparison from one tariff to another is not the goal of a particular study it is common to use the wholesale price of electricity as a pseudo RTP, as in Tiptipakorn and Wei-Jen (2007). In our analysis, however, this would imply using the SMP as the RTP, which would result in a very low price per kWh. Where a population demographic, such as residential or SME consumers, are exposed to a RTP tariff, it is more appropriate to include the extra charges, such as transmission costs, balancing costs, distribution costs and retail margin. We followed a similar methodology to Allcott (2011) in the analysis of RTP tariffs on residential consumers in the USA. In that case the RTP was derived by using the day ahead wholesale electricity price, adding a distribution charge (5.0 cents/kWh) and subtracting a participation incentive (1.4 cents/kWh). A similar approach was used in this analysis (equation 1), except no participation incentive was included. Alcott's analysis concluded that households with the RTP tariff saved $13 per annum (1-2% of households total electricity expenditure) which did not substantially outweigh the gross cost of advanced metering infrastructure required to observe hourly consumption, which were estimated to be $150 per household (Allcott, 2011).

Applications of tariff analysis

In the next decade more choice will become available for electricity consumers, such as dairy farmers, in relation to the electricity tariff that they subscribe to. The analysis presented here aims to provide information to help the decision-making process, which could be used to forecast dairy farm energy costs in a variety of electricity pricing tariff environments, helping the farmer/advisor to choose the best option for a given farm. The milking time analysis is presented simply to illustrate that electricity consumption and to an even greater extent the electricity cost of dairy farms is influenced by milking start time and that the least cost tariff for a particular farm may change if the milking routine is altered. Individual farmers will also consider some other effects, such as the social effects associated with milking at 5 AM or the milk yield effect, if the milking interval is extended beyond a ratio of 16:8.

International relevance: The results of this study pertaining to electricity consumption trends and their relationship to the demand profile on the national grid may be of relevance to dairy industries internationally. In the United Kingdom over 4.5 million residential consumers avail of TOU tariffs. To participate in these programmes the consumer needs a radio or tele-switch meter connected to the load shifting appliances (Torriti et al., 2010). In July 2007, the Office of gas and electricity metering (OFGEM) in the United Kingdom launched the energy demand research project (EDRP). The EDRP consisted of 61,000 residential electricity consumers, of which 18,000 were supplied with smart meters. The use of smart metering and in-home displays resulted in a 3% (0 – 11% range) overall load reduction and the implementation of TOU tariffs promoted an increase in load shifting of up to 10% (OFGEM, 2011). The mass rollout of smart meters in the UK was due to begin in 2014, however due to technical difficulties Ofgem has delayed the project by 12 months.

Estonia, Finland, France, Ireland, Italy, Malta, The Netherlands, Norway, Portugal, Spain, Sweden and the United Kingdom are all classified as "Dynamic Movers" in relation to the implementation of smart grid infrastructure. These countries have a clear path towards a full rollout of smart metering. Either the mandatory rollout is already decided, or there are major pilot projects that are paving the way for a subsequent decision (Hierzinger et al., 2012). Other countries, such as Australia and New Zealand, have recognised smart metering as a method of improving resource use efficiency and have carried out some early stage feasibility studies and cost benefit analysis calculations (Energy Fed NZ, 2010; DRET, 2008). Many of these countries have well established milk production industries that may be able to use smart grid infrastructure to their advantage by observing that quite large electricity cost increases could occur if a farmer chooses the incorrect electricity tariff. In addition the fact that moving milking times can reduce electricity costs by a significant amount on some tariffs, i.e Day&Night or TOU2, should be applicable to dairy farmers in countries outside of Ireland, especially farmers with a twice a day milking routine.

Milking start time effect on milk yield

The effect of milking interval on milk yield of the herd, i.e. an increase or decrease, was not included in this analysis. The work presented in this paper aims to identify potential electricity cost differences associated with altering milking start time only. The longest interval that could occur from milking earliest in the morning (05:00 h) and latest in the evening (20:00 h) was 15 hours. Milking at the earliest evening time (15:00 h) and latest in the morning time (10:00 h) would result in a milking interval of 19 hours.

Many studies have been carried out to examine the effect of milking interval on milk yields. Short term studies of milking once a day (OAD) have reported milk yield reductions from 7% in late lactation to 40% in early lactation (Davis et al., 1999; O'Brien et al., 2002; Phyn et al. 2010; Rémond and Pomiès, 2005; Stelwagen, 2001). A study conducted by Rémond et al. (2009) described the normal milking interval ranges as being between 10:14 and 12:12 for twice daily milking, and used intervals of 10:14 as default milking interval values in two of the experiments described when comparing the milk yield effect of milking at intervals of 5:19 and AOD. Rémond et al. (2009) found that it was possible to milk cows using twice daily milking schedules with much wider time intervals than typically used without significant losses in milk production. Differences in milking intervals of 11:13 to 7:17 were not significantly different, however increasing the interval to 5:19 resulted in a decrease in milk yield of 4.1%. In summary it is unlikely that a milking interval of 15:9 (which would result from milking at the earliest morning milking time and the latest evening milking time presented in this analysis) would significantly decrease milk yields. On the other hand, milking with an interval of 5:19, which would correspond with milking latest in the morning and earliest in the evening may impact more significantly on milk yields, however this would also be the least favourable in relation to electricity use and electricity costs at farm level.

Future work

The analysis presented here showed that dairy farm energy costs are influenced by the tariff that the farm subscribes to and that costs may also change if milking is carried out at a different time. However, technology and management may also play a significant role in reducing electricity costs. Further work is required in order to assess alternative technologies and strategies when upgrading milk harvesting and other dairy farm infrastructure. Similarly if the MECD were integrated with a whole farm modelling system the impact of scenarios such as once a day milking vs. twice a day milking on energy efficiency and energy costs could be examined along with other management strategies such as spring vs. autumn calving.

5 Conclusion

This study presented novel data regarding the simulated variations in total annual electricity costs for 5 different electricity tariffs (Flat, Day&Night, TOU1, TOUs and RTP) on three representative Irish dairy farms (SF,MF and LF). On all three farms, costs were lowest on the Day&Night Tariff and highest on the Flat Tariff (between 19% and 51% higher than Day&Night). An analysis of simulated electricity costs while varying milking start time revealed that both electricity consumption and costs decreased if milking started earlier in the morning and later in the evening. The highest maximum adjustment potential existed on TOU2, whereas the lowest maximum adjustment potential existed on the Flat tariff. The maximum adjustment potential was highest on the LF indicating that larger farms could make more significant savings by adjusting milking start times. The methodology presented here will help forecast dairy farm energy costs in a variety of electricity pricing tariff environments, helping the farmer/advisor to choose the least cost option for a given farm.

References

Allcott, H. 2011. Rethinking real-time electricity pricing. Resource and Energy Economics 33(4):820-842.

Avci, M., M. Erkoc, A. Rahmani, and S. Asfour. 2013. Model predictive HVAC load control in buildings using real-time electricity pricing. Energy and Buildings 60(0):199-209.

CER. 2011a. Electricity Smart Metering Customer Behaviour Trials (CBT) Findings Report, CER11080a. Commission for Energy Regulation, Dublin, Ireland.

CER. 2011b. Second Consultation on Possible National Rollout Scenarios for the Smart Metering Cost Benefit Analysis CER10197. Commission for Energy Regulation, Dublin Ireland.

DAFM. 2010. Food harvest 2020 – A vision for Irish agri-food and fisheries. Department of Agriculture Food and the Marine, Dublin, Ireland.

Davis, S. R., V. C. Farr, and K. Stelwagen. 1999. Regulation of yield loss and milk composition during once-daily milking: A review. Livestock Production Science 59(1):77-94.

DCENR. 2009. Maximising Ireland's Energy Efficiency. The National Energy Efficiency Action Plan 2009-2020. Department of Communications, Energy and Natural Resources, Dublin, Ireland.

Deane, P., J. Fitzgerald, L. Malaguzzi-Valeri, A. Touhy, and D. Walsh. 2013. Working Paper No. 452. Irish and British historical electricity prices and implications for the future. Economic and Social Research Institute (ESRI), Dublin, Ireland.

Di Giorgio, A. and F. Liberati. 2014. Near real time load shifting control for residential electricity prosumers under designed and market indexed pricing models. Applied Energy 128(0):119-132.

DRET. 2008. Cost-benefit analysis of options for a national smart meter roll-out: Phase Two—Regional and detailed analyses regulatory impact statement. Department of Resources Energy and Tourism (DRET), Canberra, Australia.

Energy Federation of New Zealand. 2010. Developing our energy potential, New Zealand Energy Efficiency and Conservation Strategy. Energy Federation of New Zealand, Wellington, New Zealand

Ericson, T. 2011. Households' self-selection of dynamic electricity tariffs. Applied Energy 88(7):2541-2547.

EU. 2006. Directive 2006/32/EC of the European Parliment and of the council on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Official Journal of the European Union.

Eurostat. 2013. Eurostat energy price tables. Accessed 09-10-2013, http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database.

Ferreira, R. S., L. A. Barroso, and M. M. Carvalho. 2012. Demand response models with correlated price data: A robust optimization approach. Applied Energy 96(0):133-149.

Finn, P. and C. Fitzpatrick. 2014. Demand side management of industrial electricity consumption: Promoting the use of renewable energy through real-time pricing. Applied Energy 113(0):11-21.

Finn, P., M. O'Connell, and C. Fitzpatrick. 2013. Demand side management of a domestic dishwasher: Wind energy gains, financial savings and peak-time load reduction. Applied Energy 101(0):678-685.

Goodman, R., G. Jones, J. Kelly, E. Slowey, and N. O'Neill. 2004. Geothermal Energy Resource Map of Ireland. Sustainable Energy Ireland. Dublin, Ireland.

Herter, K. and S. Wayland. 2010. Residential response to critical-peak pricing of electricity: California evidence. Energy 35(4):1561-1567.

Hierzinger R., M. Albu, H. van Elburg, A. J. Scott, A. Lazicki, L. Penttinen, F. Puente, and H. Sale. 2012. European Smart Metering Landscape Report, SmartRegions Deliverable 2.1. Accessed May 24, 2013. http://www.energyagency.at/fileadmin/dam/pdf/projekte/klimapolitik/SmartRegionsLandscapeReport2012.pdf

Howley, M., E. Dennehy, M. Holland, and B. O'Gallachoir. 2011. Energy in Ireland 1990–2010. Energy policy statistical support unit. Sustainable Energy Ireland. Dublin, Ireland.

Joskow, P. L. 2012. Creating a Smarter U.S. Electricity Grid. Journal of Economic Perspectives 26(1):29-48.

King, C. and J. Strapp. 2012. Chapter 11 - Software Infrastructure and the Smart Grid. Pages 259-288 in Smart Grid. F. P. Sioshansi, ed. Academic Press, Boston.

Lam, J. C., H. L. Tang, and D. H. W. Li. 2008. Seasonal variations in residential and commercial sector electricity consumption in Hong Kong. Energy 33(3):513-523.

Mathieu, J. L., D. S. Callaway, and S. Kiliccote. 2011. Variability in automated responses of commercial buildings and industrial facilities to dynamic electricity prices. Energy and Buildings 43(12):3322-3330.

O'Brien, B., G. Ryan, W. J. Meaney, D. McDonagh, and A. Kelly. 2002. Effect of frequency of milking on yield, composition and processing quality of milk. Journal of Dairy Research 69(3):367-374.

O'Callaghan, E. and D. Harrington. 2000. Effect of Liner Design on Milking Characteristics. Irish Journal of Agricultural and Food Research 39(3):383-399.

OFGEM. 2011. Energy Demand Research Project: Final Analysis. Office of gas and electricity metering, Report no. 60163857. Hertfordshire, United Kingdom.

Phyn, C. V. C., J.K. Kay, A. G. Rius, S. R. Davis, E. H. Hillerton, J. R. Roche, and K. J. Stelwagen. 2010. Review: Impact of short-term alterations to milking frequency in early lactation. 4th Australasian Dairy Science SympCaxton Press, New Zealand 156–164.

Rastegar, M., M. Fotuhi-Firuzabad, and F. Aminifar. 2012. Load commitment in a smart home. Applied Energy 96(0):45-54.

Rémond, B. and D. Pomiès. 2005. Once-daily milking of dairy cows: A review of recent French experiments. Animal Research 54(6):427-442.

Rémond, B., D. Pomiés, C. Julien, and J. Guinard-Flament. 2009. Performance of dairy cows milked twice daily at contrasting intervals. Animal 3(10):1463-1471.

Samadi, P., A. H. Mohsenian-Rad, R. Schober, V. W. S. Wong, and J. Jatskevich. 2010. Optimal Real-Time Pricing Algorithm Based on Utility Maximization for Smart Grid. in Proc. First IEE International conference on Smart Grid Communications (SmartGridComm). PP 415-420.

SEMO. 2013. Single Electricity Market Operator website. Accessed 20 Dec 2013. http://www.sem-o.com/AboutSEMO/Pages/default.aspx

Stelwagen, K. 2001. Effect of milking frequency on mammary functioning and shape of the lactation curve. J. Dairy Sci. 84(SUPPL.):E204-E211.

Tiptipakorn, S. and L. Wei-Jen. 2007. A Residential Consumer-Centered Load Control Strategy in Real-Time Electricity Pricing Environment. Pages 505-510 in Proc. Power Symposium, 2007. NAPS '07. 39th North American.

Torriti, J., M. G. Hassan, and M. Leach. 2010. Demand response experience in Europe: Policies, programmes and implementation. Energy 35(4):1575-1583.

Torriti, J. 2012. Price-based demand side management: Assessing the impacts of time-of-use tariffs on residential electricity demand and peak shifting in Northern Italy. Energy 44(1):576-583.

Upton, J., J. Humphreys, P. W. G. Groot Koerkamp, P. French, P. Dillon, and I. J. M. De Boer. 2013. Energy demand on dairy farms in Ireland. Journal of Dairy Science 96(10):6489-6498.

Upton, J., M. Murphy, P. French, and P. Dillon. 2010. Energy Use on Dairy Farms Pages 87-97 in Teagasc National Dairy Conference. Teagasc, Mullingar.

Upton, J., M. Murphy, L. Shalloo, P. W. G. Groot Koerkamp, and I. J. M. De Boer. 2014. A Mechanistic Model for Electricity Consumption on Dairy Farms: Definition, Validation and Demonstration. Journal of Dairy Science, 97(8):4973-4984.

Valenzuela, J., P. R. Thimmapuram, and J. Kim. 2012. Modeling and simulation of consumer response to dynamic pricing with enabled technologies. Applied Energy 96(0):122-132.

Wang, Y. and L. Li. 2013. Time-of-use based electricity demand response for sustainable manufacturing systems. Energy 63(0):233-244.

Woo, C. K., P. Sreedharan, J. Hargreaves, F. Kahrl, J. Wang, and I. Horowitz. 2014. A review of electricity product differentiation. Applied Energy 114(0):262-272.

Zhanbo, X., G. Xiaohong, J. Qing-Shan, W. Jiang, W. Dai, and C. Siyun. 2012. Performance Analysis and Comparison on Energy Storage Devices for Smart Building Energy Management. Smart Grid, IEEE Transactions on 3(4):2136-2147.

Chapter 6

Investment Appraisal of Technology Innovations on Dairy Farm Electricity Consumption

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Abstract

The aim of this study was to conduct an investment appraisal for milk harvesting, milk cooling and water heating technologies on a range of farm sizes in two different electricity pricing environments. This was achieved by using a model for electricity consumption on dairy farms to simulate the effect of six technology investment scenarios on the electricity consumption and electricity costs of the three largest electricity consuming systems within the dairy farm (i.e. milk cooling systems, water heating systems and milking machine systems). The technology investment scenarios considered included direct expansion milk cooling systems, ice bank milk cooling systems, milk pre-cooling systems, solar water heating systems, and variable speed drive vacuum pump milking systems. A dairy farm profitability calculator was combined with the electricity consumption model to assess the impact of each investment scenario on the annual net income after tax over a ten year period subsequent to the investment taking place. Included in the calculations were the initial investments which were depreciated to zero over the 10 year period. The return on investment for each scenario was computed as the investment appraisal metric. The results of this study showed that the highest return on investment figures were realised by using a direct expansion milk cooling system with pre-cooling of milk to 15°C with well-water prior to entry to the milk tank, heating water with an electrical water heating system and using standard vacuum pump control on the milking system. Return on investment figures did not exceed the suggested hurdle rate of 10% for any of the ice bank scenarios making the ice bank system reliant on a grant aid framework to reduce the initial capital investment and improve the return on investment. Equally, farmers seeking to shift the milk cooling electricity consumption away from milking times for operational reasons may favour the ice bank system, even though return on investment figures were below the suggested hurdle rate of 10%. The solar water heating and variable speed drive vacuum pump scenarios failed to produce positive return on investment figures on any of the three farm sizes considered on either the Day&Night tariff or the Flat tariff, even when the technology costs were reduced by 40% in a sensitivity analysis of technology costs.

1 Introduction

Global energy prices increased steadily over the last 5 years, resulting in increases in electricity costs on European farms of over 30% from 2007 to 2013 (Eurostat, 2013). Electricity consumption represents 60% of direct energy use, or 0.31 MJ per liter of milk produced on Irish dairy farms (Upton et al., 2013). The quantity of electricity consumed per liter of milk produced on dairy farms may increase in the coming years, if farmers respond to government policies in countries such as Ireland, where increases in milk output are actively encouraged as a result of the abolition of European Union (EU) milk quotas in 2015 (DAFM, 2010). Increased milk production is generally associated with investments in labour-saving technology to manage larger dairy herds, along with more industrial milk harvesting and cooling equipment, which might increase electricity consumption per liter of milk. The major electricity consuming systems on Irish dairy farms were found to be milk cooling (31% of total), water heating systems (23% of total) and milking systems (20% of total). The remaining 26% of total electricity consumption was made up of lighting, water pumping and wintering facility electricity consumption (Upton et al., 2013). Decision making at farm level around the investment in milk harvesting equipment, milk cooling, water heating technologies and farm infrastructure is often influenced by intergenerational heuristic perspectives or coloured by various marketing materials rather than through quantification of interactions between capital investment and energy requirements. To make informed decisions farmers need insight into the electricity consumption and associated costs of potential technology investment strategies. The aim of this study, therefore, was to provide a scientific-based investment appraisal around the optimum combination of milk harvesting, cooling and water heating technologies on a range of farm sizes in two different electricity pricing environments. This objective was achieved by using a model for electricity consumption on dairy farms (MECD; (Upton et al., 2014)) to analyse the effect of various technologies on the electricity consumption and costs on the three largest electricity consuming systems within the dairy farm (i.e. milk cooling systems, water heating systems and milking machine systems). The model outputs were used in a farm profitability calculator along with annual farm related costs from the Teagasc Eprofit Monitor for 2011. The Eprofit monitor is a financial benchmarking tool supplied by Teagasc. The combined models were used to compute the annual after tax income and return on investment (ROI) for six investment choices over a 10 year period.

2 Materials and Methods

Outline of the MECD

A model for electricity consumption on dairy farms (MECD), developed by Upton et al. (2014) was used to simulate the annual electricity consumption and associated costs of six technology investment scenarios on three representative farms in Ireland. 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 numbers 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, frequency of milking and milking start time). The energy consumption of each of the 7 dairy farm 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). Both of the electricity tariffs were compiled in an identical 12 x 24 matrix. Dairy farm electricity costs were then calculated by multiplying the energy consumption matrix by the tariff matrix. For this analysis a technology permutation algorithm was developed and applied to the MECD, which allowed for autonomous cycling through technologies and tariffs. The outputs from the MECD were annual electricity consumption (kWh) and associated costs (€) for each of the six technology investment scenarios studied under two electricity pricing structures (Flat tariff and Day&Night tariff). The outputs of the MECD of total annual electricity consumption and related costs were computed for each technology scenario. The farms morning milking time was set to 07:00 h and the evening milking time was set to 17:00 h.

Model Inputs

The electricity consumption and related costs of a small farm (SF) with 45 milking cows, a medium farm (MF) with 88 milking cows and a large farm (LF) with 195 milking cows was simulated using the MECD. Background data from an on-farm 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 each of these three farms. The SF, MF and LF were spring calving herds operating grass-based milk production systems with low supplementary feed input (mean of 1.19 kg concentrate/100 kg of milk produced) similar to most Irish dairy farmers. Milk production was 255,278 L for SF, 499,898 L for MF and 774,089 L for LF. Further data relating to the scale and production levels of the SF, MF and LF are presented in table 1.

Scenario Description

Technologies chosen for analysis in this study were: milk cooling systems, water heating systems and milking systems. There are a range of technologies commercially available to reduce the electricity consumption of these systems. For the analysis the range of possibilities was represented by six investment scenarios. In the analysis presented it was assumed that there was a requirement for investment in a milk cooling system, milking system vacuum pumps and a water heating system. The scenarios were:

1) Base. The Base scenario included investment in a direct expansion (DX) milk cooling system, standard milking system vacuum pumps (i.e. without variable speed drive (VSD)) and an electrical water heating system. All other options were compared to this baseline scenario. 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.

2) Direct expansion cooling system with pre-cooling of milk (DXPHE). This scenario included investment in a DX milk cooling system with a water cooled plate heat exchanger (PHE) pre-cooling system which cooled milk to 15°C before entry to the milk storage tank, the milking system remained standard and water heating remained electric. The pre-cooler 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.

3) Ice Bank cooling system without pre-cooling (IB). This scenario included investment in an ice bank milk cooling system instead of a DX system, the milking system remained standard and water heating remained electric. Ice bank (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 et al., 2013). IB cooling systems are less efficient in terms of electricity consumed per liter 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).

4) Ice Bank with pre-cooling of milk (IBPHE). This scenario includes investment in an IB milk cooling system with a pre-cooler which chilled milk to 15°C before entry to the milk storage tank, the milking system remained standard and water heating remained electric. The cost of pumping extra water through the pre-cooler was included in the calculations.

5) Solar. This scenario included investment in solar thermal panels in addition to the electric water heating system. A DX milk cooling system was included with standard milking system vacuum pumps. Solar water systems have been shown to reduce the electricity consumption of dairy water heating systems by 40-50% (Morison et al., 2007), however this can vary strongly according to latitude. It was assumed that the solar thermal collector reduced the annual electricity costs of the farms water heaters by an average of 45%.

6) Variable Speed Drive milking system (VSD). In this scenario VSD was added to the milking system vacuum pumps, a DX milk cooling system was included with electric water heating. VSD vacuum systems have been shown to reduce the electricity consumption of milking systems by between 56% and 65% (Ludington et al., 2004; Morison et al., 2007; Upton et al., 2010). The addition of a VSD to a standard milking system was considered. It was assumed that the VSD milking system reduced the annual electricity costs of the farms vacuum pumps by an average of 60%.

Farm Income Calculations

The profitability calculator was used to assess the after tax net income of the SF, MF and LF arising from the six technology investment scenarios over a ten year period subsequent to investment (2014-2023). The profitability calculator used average financial performance data, and variable and fixed cost data from 1,133 dairy farms from the farm financial benchmarking tool of Teagasc, known as Teagasc Eprofit monitor. It was assumed that the capital expenditure required for each investment scenario was borrowed from a financial institution at 5% annual percentage rate over a 10 year period, this rate was based on consultation with the banking industry in Ireland. Income before tax was calculated using the formula:

$$\text{Income before tax} = \text{gross revenue} - \text{total variable costs} - \text{total fixed costs} \quad [1]$$

Where gross revenue included both milk sales and livestock sales. Base milk price was set to 30 cent/L. Variable costs included costs of feed, fertilizer, veterinary support, artificial insemination, electricity and contractors. In all cases the electricity consumption was calculated by the MECD and this was combined with electricity unit costs. Similar to all costs included in the analysis, electricity costs were inflated by 2% per annum to account for the effect of inflation in input costs (consumer price index inflation rate for Ireland).

The fixed costs included hired labour, equipment and building maintenance and depreciation, costs associated with rented land and car/phone expenses. Costs of the farmers own labour were excluded from the calculations. Income before tax was calculated under the assumption that all new investments in equipment were depreciated to zero over a ten year period. The financial implications of each scenario were measured annually over the 10 years that were evaluated. After tax net income was computed as:

$$\text{net income} = \text{total income} - \text{tax paid} \qquad [2]$$

Taxation is included in these calculations because large farms will pay tax at a higher rate than smaller farms and it is important to take this into account when considering the value of an investment to a particular farm. Within the Irish taxation system there are two rates of personal tax: 20% of income below €32,000 and 41% of income above €32,000. Both rates apply to the taxable income, which is the net income earned less any capital or other allowances. Therefore the net income earned affects the return on investment figure for a given investment.

Return on investment calculations

ROI is a performance measure of the efficiency of each technology investment scenario. ROI is calculated by dividing the average difference in yearly net income before interest and tax by the difference in investment versus the base investment for each investment scenario on an annual basis. Where ROI is described by equation 3;

$$ROI = \frac{(\text{Income inv x} - \text{Income base}) + (\text{Interest inv x} - \text{Interest inv base})}{\text{Investment x} - \text{Investment Base}} \qquad [3]$$

Investment figures for all scenarios are presented in table 2.

The ROI is used in this analysis to provide a metric of how effectively each technology investment scenario used capital invested to generate income.

Electricity Tariffs

Two commonly used existing tariff structures were used in this analysis, a Flat and a Day&Night tariff. 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. These electricity costs were sourced from an Irish comparison of energy prices from 2013 (SEAI, 2014).

Technology Costs and Sensitivity Analysis

Investments for DX and IB milk cooling systems as well as pre-cooling systems were sourced from Irish government reference cost guidelines (DAFM, 2013). Costs associated with appropriately sized water heating systems and vacuum pump systems for the SF, MF and LF were sourced from local equipment suppliers in November 2013. Details of these costs are included in table 2. From time to time the Department of Agriculture Food and the Marine (DAFM) in Ireland operate a capital grant scheme for the installation of milk harvesting and milk cooling systems. The grant rates that applied to the targeted agricultural modernisation scheme (TAMS) administered by DAFM in 2012 and 2013 were applied to create the grant aided reduced technology costs (RTC) sensitivity analysis. The TAMS grant rate was 40% for milk cooling systems up to a maximum of €25,000 and 40% for milking systems including water heating systems up to a maximum of €40,000.

The TAMS grant did not support solar water heating systems. For this analysis, however, the costs of the solar water heating systems were reduced by 40% in the RTC sensitivity analysis. Likewise, a sensitivity analysis was carried out on increased electricity costs (IE), where a 4% per year increase in electricity cost was included rather than the 2% included in the base analysis. Finally the RTC and IE parameters were combined to examine the cumulative effect of both reduced technology costs arising from the grant aiding of equipment and the 4% per annum rate of increase in electricity costs, this sensitivity analysis case was termed RTC&IE.

3 Results

Electricity consumption and costs

Table 1 shows the simulated electricity consumption (kWh) for each of the seven main infrastructural systems on each of the three farms under the Base scenario. On average, milk cooling made up 45% of total electricity consumption across all 3 farms (range 39 - 50%), water heating 26% (range 23 - 29%) and the milking machine 17% (range 14 - 20%). Other electricity consumption by wash pumps, water pumps, automatic scrapers and lighting consumed 12% (range 4 - 18%). The simulated electricity consumption and costs per liter of milk were lowest for the SF, i.e. 41 Wh/L and €0.0057/L. The corresponding figures for the MF were 51 Wh/L, €0.0067, whereas for the LF they were 42 Wh/L, €0.0059 €/L. Simulation results pertaining to total annual electricity consumption and electricity costs under the Day&Night and Flat tariff structures for each of the six technology investment scenarios are presented in table 3. The annual net income after tax for the ten year period after investment for each investment scenario for Day&Night tariff are presented in table 4, and for Flat tariff in table 5.

Effect of technology investments on electricity consumption and electricity costs

SF. On the Base scenario the total annual electricity consumption was 10,413 kWh (see table 3). The DXPHE resulted in the largest saving in annual electricity consumption, 28% (2,877 kWh) over the Base scenario, whereas IBPHE reduced electricity consumption by 26% (2,707 kWh), VSD by 10% (1,047 kWh) and Solar by 8% (806 kWh). IB, however, increased electricity consumption by 389 kWh (4%).

The total annual cost was €1,445 on Day&Night tariff and €2,083 on Flat tariff (44% higher than Day&Night tariff). IBPHE on Day&Night tariff resulted in the largest annual cost reduction, saving 46% (€668) on electricity costs versus the Base case on Day&Night. DXPHE saved 39% (€570), and IB saved 29% (€414) of annual electricity costs versus the Base scenario on Day&Night. Solar and VSD scenarios resulted in savings of 4% (€64) and 9% (€134) of total annual electricity costs on the Day&Night Tariff.

The Flat tariff, however, was not as favourable to the IBPHE scenario resulting in cost savings of 26% (€541), the IB scenario increased electricity costs by 4% (€78), and the DXPHE scenario resulted in the largest cost saving of 28% (€575) over the base case. Solar and VSD scenarios resulted in savings of 8% (€161) and 10% (€209) of electricity costs on the Flat Tariff.

MF. On the Base scenario the total annual electricity consumption was 25,252 kWh (see table 3). The DXPHE resulted in the largest electricity saving, 22% (5,643 kWh) in total electricity consumption over the Base scenario, whereas IBPHE reduced electricity consumption by 21% (5,258), VSD by 7% (1,840) and Solar by 9% (2,269 kWh). IB, however, increased electricity consumption by 4% (1,047 kWh).

The total annual cost was €3,334 on Day&Night tariff and €5,050 on Flat tariff (51% higher than Day&Night tariff). IBPHE on Day&Night tariff resulted in the largest annual cost reduction, saving 38% (€1,259) on electricity costs versus the Base case. DXPHE saved 32% (€1,083), and IB saved 21% (€703) of annual electricity costs versus the Base scenario. Solar and VSD scenarios resulted in savings of 5% (€182) and 7% (€238) of total annual electricity costs on the Day&Night Tariff.

The Flat tariff however was not as favourable to the IBPHE scenario resulting in cost savings of 21% (€1,052), the IB scenario increased electricity costs by 4% (€209), and the DXPHE scenario resulted in the largest cost saving of 22% (€1,129) over the base case. Solar and VSD scenarios resulted in savings of 9% (€454) and 7% (€368) of electricity costs on the Flat Tariff.

LF. On the Base scenario the total annual electricity consumption was 32,670 kWh (see table 3). The DXPHE resulted in the largest electricity saving, 28% (9,010 kWh) in total electricity consumption over the Base scenario, whereas IBPHE reduced electricity consumption by 26% (8,489 kWh), VSD by 10% (3,168 kWh) and Solar by 18% (5,764 kWh). IB, however, increased electricity consumption by 6% (2,107 kWh).

The total annual cost was €4,571 on Day&Night tariff and €6,534 on Flat tariff (43% higher than Day&Night tariff). IBPHE on Day&Night tariff resulted in the largest annual cost reduction, saving 45% (€2,044) on electricity costs versus the Base scenario. DXPHE saved 38% (€1,714), and IB saved 17% (€778) of annual electricity costs versus the Base scenario. Solar and VSD scenarios resulted in savings of 10% (€461) and 9% (€428) of total annual electricity costs on the Day&Night Tariff.

The Flat tariff however was not as favourable to the IBPHE scenario resulting in cost savings of 26% (€1,698), the IB scenario increased electricity costs by 6% (€421) and the DXPHE scenario resulted in the largest cost saving of 28% (€1,802) over the base case. Solar and VSD scenarios resulted in savings of 18% (€1,153) and 10% (€634) of electricity costs on the Flat Tariff.

ROI analysis and farm income

The net income after tax over a ten year period for all six investment scenarios are displayed in table 4 for the Day&Night tariff and in table 5 for the Flat tariff. The ROI, which is the investment appraisal metric, for all 6 scenarios on both the Day&Night and Flat tariffs are displayed in table 6.

SF. The level of investment required in the Base scenario was €20,159 (table 2). Under the Day&Night tariff the highest ROI was delivered by the DXPHE investment scenario which was 17%. All other investment scenarios lead to negative ROI values. The ROI of the IB scenario was -3%, IBPHE was -9%, Solar was -25% and VSD was -22%.

Under the flat tariff, the trend was the similar, with DXPHE delivering the highest ROI of 17%. The largest difference between tariffs was the ROI of the IB scenario, which dropped to -31% since it could not benefit from lower night rate electricity tariffs.

MF. The level of investment required in the Base scenario was €23,977 (table 2). Under the Day&Night tariff the highest ROI was delivered by the DXPHE investment scenario which was 19%. The IB scenario also returned a positive ROI of 7%. All other investment scenarios lead to negative ROI values. The ROI of the IBPHE was -3%, Solar was -18% and VSD was -19%.

Under the flat tariff, the trend was similar with DXPHE delivering the highest ROI of 21%. The largest difference between tariffs was the ROI of the IB scenario, which dropped to -29% since it could not benefit from lower night rate electricity tariffs.

LF. The level of investment required in the Base scenario was €29,715 (table 2). Under the Day&Night tariff the highest ROI was delivered by the DXPHE investment scenario which was 21%. The IB scenario also returned a positive ROI of 6%. All other investment scenarios lead to negative ROI values. The ROI of the IBPHE was -1%, Solar was -16% and VSD was -13%.

Under the flat tariff, the trend was similar with DXPHE delivering the highest ROI of 23%. The largest difference between tariffs was the ROI of the IB scenario, which dropped to -35% since it could not benefit from lower night rate electricity tariffs.

Table 1; Mean values of characteristics and simulated electricity consumption values (kWh) and related costs (€) of the three farms, SF (small farm), MF (medium farm) and LF (large farm) for the Base scenario.

Farm Characteristics	SF		MF		LF	
Farm Area (ha)	48		70		110	
Dairy herd Size	45		88		195	
Stocking Density (LU/ha)[1]	1.68		1.90		2.43	
Milk Production (Liters/annum)	255,278		499,898		774,089	
Milk cooling (kWh) (% of total)	5,237	(50%)	9,826	(39%)	15,703	(48%)
Water heating (kWh) (% of Total)	2,444	(23%)	7,294	(29%)	7,842	(24%)
Milking machine (kWh) (% of Total)	2,131	(20%)	3,628	(14%)	6,124	(19%)
Wash pump (kWh) (% of Total)	NA[2]	(NA)	145	(1%)	NA	(0%)
Water pump (kWh (% of Total)	NA	(0%)	1,832	(7%)	2,452	(8%)
Auto scrapers (kWh) (% of Total)	422	(4%)	1,533	(6%)	NA	(NA)
Lighting (kWh) (% of Total)	179	(2%)	994	(4%)	493	(2%)
Electricity Use (Wh/Liter)	40.8		50.5		42.2	
Annual electricity consumption (kWh)	10,413		25,252		32,670	
Electricity costs (€/Liter milk)	0.0057		0.0067		0.0059	
Total electricity costs (€)	1,445		3,334		4,571	

[1] LU/ha = Livestock Units per hectare

[2] NA = Not available

Table 2; Total technology investments for all six investment scenarios on three farms, SF (small farm), MF (medium farm) and LF (large farm), with and without grant aid.

Scenario[1]	SF		MF		LF	
	Standard Cost (€)	Grant Aid Cost (€)	Standard Cost (€)	Grant Aid Cost (€)	Standard Cost (€)	Grant Aid Cost (€)
1. Base	20,159	12,095	23,977	14,386	29,715	18,141
2. DXPHE	21,243	12,746	25,551	15,331	32,107	19,576
3. IB	21,644	12,986	25,462	15,277	31,405	19,831
4. IBPHE	23,330	13,998	28,083	16,850	35,586	22,339
5. Solar	23,733	14,240	28,201	16,920	35,136	21,393
6. VSD	22,909	13,745	30,277	18,166	33,065	20,151

[1] Base = investment in direct expansion (DX) milk cooling system, standard milking system vacuum pumps and electric water heating system; DXPHE = as per Base with the addition of a milk pre-cooling system; IB = as per Base but includes an ice bank (IB) milk cooling system instead of a DX milk cooling system; IBPHE = as per IB with the addition of a pre-cooling system; Solar = as per Base with the addition of solar thermal panels; VSD = as per Base with the addition of variable speed drive on the milking systems vacuum pumps

Table 3; Deviation from the Base scenario for total annual electricity consumption (kWh) and electricity costs (€) for Day&Night and Flat tariffs for all investment scenarios on three farms, SF (small farm), MF (medium farm) and LF (large farm).

	SF			MF			LF		
Scenario[1]	**Electricity Consumed (kWh)**	**Cost Day&Night (€)**	**Cost Flat (€)**	**Electricity Consumed (kWh)**	**Cost Day&Night (€)**	**Cost Flat (€)**	**Electricity Consumed (kWh)**	**Cost Day&Night (€)**	**Cost Flat (€)**
Base	*10,413*	*1,445*	*2,083*	*25,252*	*3,334*	*5,050*	*32,670*	*4,571*	*6,534*
DXPHE	-2,877	-570	-575	-5,643	-1,083	-1,129	-9,010	-1,714	-1,802
IB	389	-414	78	1,047	-703	209	2,107	-778	421
IBPHE	-2,707	-668	-541	-5,258	-1,259	-1,052	-8,489	-2,044	-1,698
Solar	-806	-64	-161	-2,269	-182	-454	-5,764	-461	-1,153
VSD	-1,047	-134	-209	-1,840	-238	-368	-3,168	-428	-634

[1] Base = investment in direct expansion (DX) milk cooling system, standard milking system vacuum pumps and electric water heating system; DXPHE = as per Base with the addition of a milk pre-cooling system; IB = as per Base but includes an ice bank (IB) milk cooling system instead of a DX milk cooling system; IBPHE = as per IB with the addition of a pre-cooling system; Solar = as per Base with the addition of solar thermal panels; VSD = as per Base with the addition of variable speed drive on the milking systems vacuum pumps.

Table 4; Annual after tax net income (€; for ten years after investment) for the six investment scenarios on three farms, SF (small farm), MF (medium farm) and LF (large farm) on the *Day&Night* tariff.

Scenario (Farm)					**Year**					
(SF)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Base	30,249	29,619	29,030	28,322	27,432	26,630	25,920	25,390	24,990	24,675
DXPHE	30,380	29,732	29,128	28,535	27,628	26,815	26,099	25,531	25,136	24,830
IB	30,233	29,575	28,962	28,243	27,323	26,498	25,773	25,269	24,869	24,560
IBPHE	30,100	29,408	28,765	27,937	26,978	26,122	25,443	24,946	24,543	24,239
Solar	29,716	29,009	28,277	27,196	26,214	25,413	24,811	24,301	23,885	23,571
VSD	29,884	29,195	28,554	27,540	26,582	25,724	25,127	24,624	24,214	23,901
(MF)										
Base	45,584	44,681	43,825	43,019	42,265	41,566	40,925	40,346	38,602	38,156
DXPHE	45,908	44,983	44,108	43,287	42,522	41,817	41,174	40,598	38,782	38,349
IB	45,721	44,793	43,916	43,092	42,324	41,616	40,970	40,389	38,574	38,136
IBPHE	45,600	44,621	43,699	42,836	42,036	41,303	40,639	40,049	38,098	37,667
Solar	45,010	44,017	43,081	42,204	41,391	40,643	39,966	39,363	37,391	36,947
VSD	44,710	43,673	42,697	41,786	40,942	40,171	39,476	38,860	36,776	36,332
(LF)										
Base	66,460	65,230	64,055	62,940	61,887	60,900	59,983	59,139	56,850	56,166
DXPHE	66,990	65,725	64,523	63,386	62,317	61,321	60,403	59,564	57,166	56,503
IB	66,605	65,346	64,147	63,011	61,942	60,944	60,021	59,176	56,804	56,130
IBPHE	66,613	65,276	64,009	62,816	61,701	60,667	59,720	58,864	56,281	55,622
Solar	65,844	64,501	63,226	62,023	60,896	59,850	58,888	58,016	55,438	54,760
VSD	66,156	64,857	63,622	62,454	61,357	60,335	59,392	58,533	56,067	55,388

Table 5; Annual after tax net income (€; for ten years after investment) for the six investment scenarios on three farms, SF (small farm), MF (medium farm) and LF (large farm) on the *Flat* tariff.

Scenario[1] (Farm)	Year									
(SF)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Base	29,911	29,274	28,666	27,680	26,778	25,963	25,337	24,846	24,434	24,108
DXPHE	30,044	29,390	28,779	27,898	26,979	26,152	25,481	24,990	24,584	24,267
IB	29,634	28,964	28,140	27,107	26,164	25,397	24,809	24,303	23,884	23,556
IBPHE	29,695	28,995	28,241	27,169	26,194	25,402	24,802	24,292	23,876	23,559
Solar	29,430	28,716	27,744	26,652	25,666	24,969	24,358	23,838	23,414	23,090
VSD	29,586	28,891	28,041	26,975	26,005	25,255	24,656	24,144	23,724	23,401
(MF)										
Base	44,673	43,752	42,878	42,053	41,279	40,561	39,900	39,300	37,536	37,068
DXPHE	45,022	44,079	43,186	42,346	41,563	40,838	40,176	39,580	37,744	37,290
IB	44,327	43,371	42,465	41,612	40,815	40,076	39,400	38,788	36,940	36,470
IBPHE	44,579	43,580	42,637	41,753	40,932	40,176	39,490	38,877	36,902	36,447
Solar	44,244	43,236	42,284	41,391	40,562	39,798	39,104	38,483	36,494	36,032
VSD	43,869	42,814	41,821	40,892	40,031	39,242	38,528	37,893	35,790	35,327
(LF)										
Base	65,419	64,168	62,972	61,835	60,760	59,751	58,811	57,944	55,631	54,922
DXPHE	65,995	64,711	63,488	62,330	61,241	60,223	59,283	58,422	56,001	55,315
IB	64,927	63,635	62,402	61,231	60,127	59,092	58,132	57,249	54,839	54,125
IBPHE	65,388	64,027	62,735	61,516	60,375	59,315	58,341	57,458	54,846	54,158
Solar	65,170	63,813	62,524	61,307	60,166	59,106	58,129	57,242	54,648	53,954
VSD	65,223	63,906	62,652	61,465	60,348	59,306	58,342	57,462	54,974	54,274

Table 6; Return on Investment additional to the base investment (%) for Day&Night and Flat tariffs for all six investment scenarios on three farms, SF (small farm), MF (medium farm) and LF (large farm).

		Return on Investment Over Base Case					
Farm	**Tariff**	**Base[1]**	**DXPHE**	**IB**	**IBPHE**	**Solar**	**VSD**
SF	Day&Night	0%	17%	-3%	-9%	-25%	-22%
	Flat	0%	17%	-31%	-12%	-23%	-20%
MF	Day&Night	0%	19%	7%	-3%	-18%	-19%
	Flat	0%	21%	-29%	-6%	-15%	-17%
LF	Day&Night	0%	21%	6%	-1%	-16%	-13%
	Flat	0%	23%	-35%	-4%	-8%	-10%

[1] Base = investment in direct expansion (DX) milk cooling system, standard milking system vacuum pumps and electric water heating system; DXPHE = as per Base with the addition of a milk pre-cooling system; IB = as per Base but includes an ice bank (IB) milk cooling system instead of a DX milk cooling system; IBPHE = as per IB with the addition of a pre-cooling system; Solar = as per Base with the addition of solar thermal panels; VSD = as per Base with the addition of variable speed drive on the milking systems vacuum pumps.

Sensitivity Analysis

Table 7 presents the ROI based on the LF platform for the RTC (reduced technology costs), IE (increased electricity costs) and RTC&IE (both reduced technology costs and increased electricity costs) sensitivity analyses.

RTC sensitivity analysis. Even with a significant grant rate of 40%, the Solar and VSD options did not result in positive ROI figures, in fact the Solar scenario ROI was -13% and VSD scenario ROI was -8%. The ROI figures were positive for DXPHE (49%), IB (6%) and IBPHE (8%).

IE sensitivity analysis. The Solar and VSD options did not result in positive ROI figures in this sensitivity analysis, in fact the Solar scenario ROI was -15% and the VSD scenario ROI was -12%. The ROI figures were positive for DXPHE (26%), IB (9%) and IBPHE (2%).

RTC&IE sensitivity analysis. The Solar and VSD options did not result in positive ROI figures in this sensitivity analysis, in fact the Solar scenario ROI was -12% and the VSD scenario ROI was -7%. The ROI figures were positive for DXPHE (57%), IB (9%) and IBPHE (11%).

Table 7; ROI figures for reduced technology costs and higher electricity costs after applying the six investment scenarios on the LF (large farm) on the Day&Night tariff.

Case[1]	Metric[2]	Base	DXPHE	IB	IBPHE	Solar	VSD
RTC	ROI	0%	49%	6%	8%	-13%	-8%
IE	ROI	0%	26%	9%	2%	-15%	-12%
RTC&IE	ROI	0%	57%	9%	11%	-12%	-7%

[1] RTC = reduced technology costs, IE = increased electricity costs (i.e. 4% per annum instead of 2% per annum), RTC&IE = reduced technology costs and increased electricity costs.

[2]ROI = return on investment

4 Discussion

Application of this study

Applying a simple payback approach in order to generate a return on investment figure (in years) for an energy efficiency investment, as applied by Houston et al. (2014), can be somewhat misleading as the value of money over time decreases, there is an expected increase in electricity costs and the interest rate/opportunity cost of money are not taken into account. The analysis presented in this study, therefore, included these components in relation to the on-farm technology investments while evaluating them over their expected useful lives (ten years) from a farm profitability perspective taking cognisance of electricity consumption, electricity costs and capital costs of equipment.

ROI and the hurdle rate

The ROI calculation methodology can be used to provide farmers with a scientific approach to investment appraisal in relation to technologies that will return the greatest income for a specific investment over the useful life of the investment. The ROI in conjunction with a minimal acceptable rate of return, or hurdle rate, can be used as an investment appraisal metric to aide in the decision making process regarding a selection of investment options. A general guideline used in economic modelling is that an investment must return at least 3-7.5% above the cost of funds (Barker, 1999; Hayes and Garvin, 1982; Lang and Merino, 1993; Meier and Tarhan, 2006; Schall et al., 1978), which in this case would be 8-12.5% since the loan interest rate was 5%. For this analysis we suggest that a hurdle rate of 10% could be applied. For each individual farm business, however, the manager must decide if this 10% threshold is applicable or not based on the specific economic environment and financial circumstances in which the farm operates.

Application of the results to precision livestock farming

The benefits of the application of precision livestock farming were described as increased efficiency, reduced costs, improved product quality, minimized environmental impacts and improved animal health and well-being (Bewley, 2010). Efforts have been directed towards developing animal specific wireless sensors for monitoring body temperature (Ipema et al., 2008), clinical acidosis (Mottram et al., 2008), distribution of urine patches (Betteridge et al., 2010), automatic blood sampling (Fønss and Munksgaard, 2008), and prediction of milk yields (Grzesiak et al., 2006; Olori et al., 1999; Sharma et al., 2007). The sphere of precision livestock farming has not yet encompassed the area of electricity consumption or facility running costs. Improving the efficiency of electricity consumption through application of new technologies, and their management, would meet the objectives of precision livestock farming while improving understanding among the farming community about the impact of changing farm infrastructure on electricity consumption, electricity costs and long term profitability.

Scenario analysis

Cooling systems. The scenario DXPHE consistently yielded the highest net income and ROI values across farm sizes and across all tariffs, indicating that where possible a pre-cooling system should be used to cool milk to 15°C before the milk enters the milk storage tank. It is important to note that correct management of a milk pre-cooler is critical to achieving pre-cooling to 15°C. A system of controlling water flow rates during pumping of milk similar to that developed by Murphy et al. (2013) would be required to ensure the maximum pre-cooling performance. Where farms experience poor pre-cooling performance, the efficiency of the milk cooling system is reduced resulting in increased electricity consumption (MDC, 1995), which in turn would impact on ROI figures reported in this study.

The ROI figures of 7% and 6% for the IB scenario of the MF and LF, however, are not convincing and fall below the suggested hurdle rate of 10%. The ROI for the IB on LF was 9% for IE and RTC&IE sensitivity analyses, hence, the suggested hurdle rate of 10% was not met. However, it is important to note that many farms struggle to operate large milking systems and cooling systems simultaneously on a single phase electricity supply (230 volt), which may lead a farmer to choose an IB system with an ROI of less than 10% for operational reasons. When pre-cooling with water to 15°C was introduced, as in DXPHE and IBPHE, the relative electricity cost savings were not large enough to offset the extra investment in the IB technology. As a result the IBPHE scenario resulted in lower ROI values versus the DXPHE in all cases.

When the Flat rate tariff was considered the DXPHE returned the highest ROI figures on all farms. The combination of higher electricity consumption and the flat tariff made the IB and IBPHE scenarios unattractive on an ROI basis. The net income figures for all farms were lower on the Flat tariff indicating that dairy farms should operate on a Day&Night tariff whenever possible.

A final point that may influence a farmer's decision to choose an IB cooling system is their ability to be configured to cool milk below 4°C very quickly. This may produce milk quality benefits (i.e.

reduced total bacteria count) for the farmer. This would be especially relevant where direct collection of milk is practiced, where long storage times on farms are a reality (i.e. > 3 days) or where milk is stored in a non-refrigerated storage vessel. Total bacterial count (TBC) is one of the primary indicators of quality in raw milk. Microbial contamination of milk can occur from several sources such as; infection within the cow's udder, bacteria on the exterior of the udder, bacteria within components of the milking machine and improper sanitisation of the bulk storage tank (Murphy, 2001). It is important to prevent further growth of bacteria once it has reached the bulk tank, as some microbes are thermoduric and can survive pasteurisation. Most bacteria stop multiplying below 7.2°C, however during the cooling period microflora multiply, especially fast growing psychrotrophic bacteria that are produced in refrigerated bulk tanks (Gennari and Dragotto, 1992; Ternstroem et al., 1993). Psychrotrophic bacteria continue growing in population until the milk temperature drops below 4°C. Bacteria levels in raw milk not only affect value added products like cheese but also pasteurised milk for direct consumption (Barbano et al., 2006). Raw milk needs to be cooled as fast as possible to ensure maximum product quality, mixing of cooled milk with quantities of warmer milk must be avoided if possible to ensure the blend temperature does not exceed 4°C. The impact of this rapid cooling effect on TBC, however, is difficult to quantify and is not included in this analysis.

Heating Systems. The Solar scenario failed to pass the hurdle rate on any of the farms on either the Day&Night tariff or the Flat tariff, despite the reduction in total annual electricity consumption of the LF by 18%. The ROI for this scenario was negative, even when the RTC&IE sensitivity analysis was considered the ROI was -12%. The LF used over 7,800 kWh per annum for water heating purposes (table 1), the Solar scenario resulted in an ROI of -16%. This suggests that solar water heaters should not be considered as an investment option in the context of the farms described in this study.

Milking systems. The VSD scenario failed to pass the hurdle rate on any of the farms on either the Day&Night tariff or the Flat tariff, even when the RTC&IE sensitivity analysis on the LF was considered the ROI was -7%. The LF used over 5,700 kWh per annum for providing vacuum for the milking system (table 1), the VSD scenario resulted in an ROI of -13%. This suggests that VSD systems should only be considered for the farms studied in this analysis when technology costs reduce dramatically.

5 Conclusion

An investment appraisal methodology analysing the interaction of capital investment and energy consumption on a range of technologies across three farm sizes, under two different electricity pricing structures was described in this study. Of the investment scenarios considered the DXPHE returned the highest ROI figures across all three farm sizes and both electricity pricing scenarios. When the Day&Night tariff was considered, the IB scenario offered positive ROI figures, even though the electricity consumption of the IB scenario was higher and the hurdle rate was not met. This result is important for dairy farmers operating in water stressed areas where pre-cooling with water is not possible. To reduce the initial capital investment and improve the ROI of the IB however, a grant aid framework is required. Equally farmers seeking to shift the milk cooling electricity consumption away from milking times for operational reasons may favour the IB system. The Solar and VSD scenarios failed to pass the hurdle rate on any of the farms on either the Day&Night tariff or the Flat tariff, even when the technology costs were reduced by 40% through a grant aid.

References

Barbano, D. M., Y. Ma and M. V. Santos. 2006. Influence of Raw Milk Quality on Fluid Milk Shelf Life. Journal of Dairy Science 89, Supplement:E15-E19.

Barker, K. 1999. Investment policy and the Employer's perspective. In Driver, C., Temple, P., Investment Growth and Employment: Perspectives for Policy. Routledge, London, pp. 301–308 (ch. 14).

Betteridge, K., C. Hoogendoorn, D. Costall, M. Carter, and W. Griffiths. 2010. Sensors for detecting and logging spatial distribution of urine patches of grazing female sheep and cattle. Computers and Electronics in Agriculture 73(1):66-73.

Bewley, J. 2010. Precision Dairy Farming: Advanced Analysis Solutions for Future Profitability," Proceedings of the First North American Conference on Precision Dairy Management, pp. 1-16. Totonto, Canada.

DAFM. 2013. Department of Agriculture Food and the Marine, National Reference Costs, Dublin, Ireland.

DAFM. 2010. Food harvest 2020 – A vision for Irish agri-food and fisheries. Department of Agriculture Food and the Marine, Dublin, Ireland.

Eurostat. 2013. Eurostat energy price tables. Accessed 09-10-2013. http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database.

Fønss, A. and L. Munksgaard. 2008. Automatic blood sampling in dairy cows. Computers and Electronics in Agriculture 64(1):27-33.

Gennari, M. and F. Dragotto. 1992. A study of the incidence of different fluorescent Pseudomonas spp. and biovars in the microflora of fresh and spoiled meat and fish, raw milk, cheese, soil and water. J. Appl. Bacteriol 72:281–288.

Grzesiak, W., P. Blaszczyk, and R. Lacroix. 2006. Methods of predicting milk yield in dairy cows - Predictive capabilities of Wood's lactation curve and artificial neural networks (ANNs). Computers and Electronics in Agriculture 54(2):69-83.

Hayes, R. H. and D. A. Garvin. 1982. Managing as If Tomorrow Mattered. Harvard Business Review 60(3):70-79.

Houston, C., S. Gyamfi, and J. Whale. Evaluation of energy efficiency and renewable energy generation opportunities for small scale dairy farms: A case study in Prince Edward Island, Canada. Renewable Energy 67(0): 20-29.

Ipema, A. H., D. Goense, P. H. Hogewerf, H. W. J. Houwers, and H. van Roest. 2008. Pilot study to monitor body temperature of dairy cows with a rumen bolus. Computers and Electronics in Agriculture 64(1):49-52.

Lang, H. J. and D. N. Merino. 1993. The selection process for capital projects. J. Wiley & Sons. New York. ISBN 978-0-471-63425-6.

Ludington, D., E. Johnson, J. Kowalski, A. Magem, and R. Peterson. 2004. Dairy Farm Energy Efficiency Guide. Southern California Edison, USA. report I.D. 429.

MDC. 1995. Bulk milk tanking cooling efficiency, Milk Development Council UK. Accessed on April 02, 2014. http://www.teagasc.ie/advisory/farm_management/buildings/milkingEquipment/milk_cooling/mdc_report/mdc_report.pdf.

Meier, I. and V. Tarhan. 2006. Corporate investment decision practices and the hurdle rate premium puzzle. Working Paper, February 2006. Accessed on March 15 2014.

Available at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=960161.

Morison, K., W. Gregory, and R. Hooper. 2007. Improving Dairy Shed Energy Efficiency, Technical Report. New Zealand Centre for Advanced Engineering (CAENZ). Christchurch, New Zealand.

Mottram, T., J. Lowe, M. McGowan, and N. Phillips. 2008. Technical note: A wireless telemetric method of monitoring clinical acidosis in dairy cows. Computers and Electronics in Agriculture 64(1):45-48.

Murphy, M. D., J. Upton, and M. J. O'Mahony. 2013. Rapid milk cooling control with varying water and energy consumption. Biosystems Engineering 116(1):15-22.

Murphy, S. C. and K. Boor. 2001. Sources and causes of high bacteria counts in raw milk: an abbreviated review. Cornell University Ithaca, New York

Olori, V. E., S. Brotherstone, W. G. Hill, and B. J. McGuirk. 1999. Fit of standard models of the lactation curve to weekly records of milk production of cows in a single herd. Livestock Production Science 58(1):55-63.

SEAI. 2014. Domestic Fuels, Comparison of Energy Costs. Sustainable Energy Authouithy of Ireland (SEAI), Dublin, Ireland. Accessed on March 15 2014. http://www.seai.ie/Publications/Statistics_Publications/Fuel_Cost_Comparison/Domestic_Fuel_Cost_Comparison.pdf.

Schall, L. D., G. L. Sundem, and W. R. Geijsbeek. 1978. Survey and analysis of capital budgeting methods. The Journal of Finance, 33: 281–287.

Sharma, A. K., R. K. Sharma, and H. S. Kasana. 2007. Prediction of first lactation 305-day milk yield in Karan Fries dairy cattle using ANN modeling. Applied Soft Computing 7(3):1112-1120.

Ternstroem, A., A. M. Lindberg, G. Molin. 1993. Classification of the spoilage flora of raw and pasteurized bovine milk, with special reference to Pseudomonas and Bacillus. J. Appl. Bacteriol (75):25–34.

Upton, J., J. Humphreys, P. W. G. Groot Koerkamp, P. French, P. Dillon, and I. J. M. De Boer. 2013. Energy demand on dairy farms in Ireland. Journal of Dairy Science 96(10):6489-6498.

Upton, J., M. Murphy, L. Shalloo, P. W. G. Groot Koerkamp, and I. J. M. De Boer. 2014. A Mechanistic Model for Electricity Consumption on Dairy Farms: Definition, Validation and Demonstration. Journal of Dairy Science, 97(8):4973-4984.

Upton, J., M. Murphy, P. French, and P. Dillon. 2010. Energy Use on Dairy Farms Pages 87-97 in Teagasc National Dairy Conference. Teagasc, Mullingar.

Chapter 7

General Discussion

1 Introduction

The aim of this thesis was to assess how, and to what extent, do managerial and technology changes affect electricity consumption, associated costs and greenhouse gas (GHG) emissions of dairy farms. First, state-of-the-art energy, and especially electricity consumption, on Irish dairy farms were inventoried. Moreover, areas where reductions in electricity use and associated costs could be made were highlighted for further research. Second, a model for electricity consumption on dairy farms was developed and used to quantify the effect of managerial and technology changes on electricity consumption, associated costs and GHG emissions of dairy farms. Third, optimal control was applied to a milk cooling system, to investigate if electricity consumption of current standard practices in the realm of milk cooling could be reduced through control of water flow through the pre-cooling system. Fourth, the impact of future electricity price tariffs on dairy farm energy costs was quantified and the efficacy of adjusting milking time to mitigate peak electricity prices was explored. Finally, a dairy farm economic model was developed and applied, to assess the potency of technology investment strategies to increase farm profitability and deliver a return on capital invested.

2 State-of-the-art of electricity consumption and deducing strategies to reduce its use on dairy farms

In order to develop strategies to reduce electricity consumption it was necessary to understand the consumption trends and the hot-spots of electricity consumption within the farm. In **Chapter 2** we performed a single-issue life cycle assessment (LCA) by quantifying the energy use of one kg of milk solids on 22 commercial Irish dairy farms, from cradle-to-farm-gate (ISO, 2006). This analysis demonstrated that a total of 31.73 MJ of energy was required to produce one kg of milk solids, of which 20% was direct and 80% was indirect energy use. These results fell within the range of results reported in the literature from studies on grass-based milk production systems (Basset-Mens et al., 2009; O'Brien et al., 2012; Wells, 2001). Electricity consumption was found to represent 12% of total cradle-to-farm-gate energy use. Other major contributors to total energy use were identified as artificial fertilizers (57% of total energy use), supplementary concentrate feed (21% of total energy use) and fuel (8% of total energy use). Electricity accounted for 60% of the direct energy use and was centred around milk harvesting. Major consumers of electricity were: milk cooling (31%), water heating (23%), milking (20%), pumping water (5%), lighting (3%), whereas other miscellaneous consumptions, such as winter housing systems, consumed 18% of the electrical energy. Hence, the electricity consumption related directly to milk harvesting (milk cooling, water heating and milking) accounted for 74% of on-farm electricity use, or about 9% of total energy use. This is significant, especially because electricity consumption is under the control of the farmer and can be influenced through management decisions and application of technologies. Furthermore, we examined daily and seasonal electricity consumption patterns on dairy farms and found that over 60% of electricity was consumed at peak periods (00:00 to 09:00 h). Clearly, if peak electricity prices increase, as implied by the Energy Services Directive (EU, 2006), mitigation strategies will be required.

This thesis tested two main groups of strategies, from both economic and environmental viewpoints. The first group, referred to as 'cost strategies', consisted of measures that could save on-farm costs but not energy or related emissions; for example, moving to a new electricity tariff. Another 'cost strategy' is decoupling large electricity users, such as water heating, from milking times and shifting them to off-peak periods when electricity price is lower. This could also be achieved by adjusting milking start times to avoid consuming electricity at peak electricity prices. The second group, referred to as the 'energy strategies', consisted of measures directed at reducing electricity consumption through changes in farm management and application of electricity-saving technologies. Possible 'energy strategies' are the use of variable speed vacuum pumps on the milking machine motors, pre-cooling of milk and solar thermal technologies to provide hot water for washing of milking equipment. These strategies could contribute to the 20-20 by 2020 initiative (EC, 2008) by helping the dairy sector reduce energy use, reduce GHG emissions and increase the portion of renewable energy use in dairy production. However, to evaluate their potency to contribute to these goals, a specialised model was needed.

3 The methodological approach for model development

A model may be defined as an ordered way of describing knowledge of some real system (McNamara, 2004). As far as modelling of complex processes is concerned, there are two different points of view: the empirical modelling point of view and the mechanistic modelling point of view. Mechanistic models are built on first principles in a bottom-up fashion, starting from a basic understanding of the mechanics of the underlying system (Karkhanis et al., 2004; Nestorov et al., 1999; Taha et al., 2008). Mechanistic modelling can be viewed as white-box modelling, as its key feature is to provide fundamental insight and potentially generate new knowledge about the modelled system (Eyerman et al., 2011). Empirical modelling, on the other hand, is typically a black-box approach which leverages statistical and machine learning techniques, such as regression modelling or neural networks, to automatically learn from training data (Joseph et al., 2006a,b; Vaswani et al., 2007). Whether to use an empirical or mechanistic approach is goal dependent (Alamir et al., 2013). Regression modelling is a widely accepted empirical approach to tackle complex and ill-defined problems (Kalogirou, 1999). Regression models, however, are used to predict the future trends of a system based on historic performance. Hence, a regression based electricity consumption model would only be valid if the infrastructure installed on the farm remained static. If one aims at optimizing a given process (e.g. reduce electricity consumption on a dairy farm) by introducing modifications of its equipment and management (e.g. invest in electricity saving equipment), then a mechanistic approach is advantageous (Alamir et al., 2013). Since our goal was to evaluate the impact of the 'cost strategies' and 'energy strategies' on dairy farm electricity consumption, associated costs and GHG emissions, a mechanistic modelling approach was chosen in this study.

4 Models to assess the economic and environmental consequences of 'cost strategies' and 'energy strategies'

4.1 Electricity consumption model

To examine the potential of the above described strategies to reduce electricity consumption and/or costs, we developed a model for simulating electricity consumption, associated costs and GHG emissions on dairy farms (MECD) (**Chapter 3**). The MECD is a mechanistic mathematical representation of electricity consumption that simulates farm equipment on an hourly and monthly basis under the following headings; milk cooling system, water heating system, milking machine system, lighting system, water pump system and the winter housing facilities. This model was validated by comparing simulated results against actual farm data, using empirical data of farms of varying scale from **Chapter 2**. The model's relative prediction error (RPE) of <10% for total annual electricity consumption was deemed satisfactory for the intended use of this model for evaluating 'cost strategies' and 'energy strategies', and in future as a decision support tool for dairy farmers. The models prediction of milk cooling consumptions, water heating consumptions and milking machine consumptions all yielded RPEs of less than 20%. The cooling, heating and milking machine predictions are also most important for the analysis of 'energy strategies' discussed in this thesis. Automatic scraper consumptions, lighting consumptions and water pump consumptions proved more difficult to predict. RPE values varied between 20% and 30% for water pump predictions, between 42% and 58% for automatic scraper consumptions and between 18% and 113% for lighting consumptions. However, these consumptions when totalled made up 14% of the total electricity consumption.

The farm simulation model DairyWise, reported by Schils et al. (2007a), which includes an extensive GHG module (Schils et al., 2007b), comes closest in structure to the MECD by providing a semi-empirical calculation to report electricity consumption of heating, cooling and milking systems. However, this model would not be capable of testing the 'cost strategies' described in this thesis because the model does not function on an hourly basis, preventing the placing of electricity consumed in the correct hour of consumption. Similarly, DairyWise could not simulate the 'energy strategies' because there is no adjustment for the change in performance in dairy farm equipment in response to ambient temperature fluctuations. Finally, there is no mechanism to accurately simulate the electricity consumption of the lighting systems, water pump systems and the winter housing facilities. The lack of a suitable model had prevented deeper analysis on the efficacy of alternative dairy farm technology options to affect electricity consumption, associated costs and GHG emissions. In order to develop a clearer panorama of how investments in technologies impact the return on capital invested on dairy farms, further modelling work was required.

4.2 Farm profitability module

A profitability module was added to the MECD to assess the return on investment (ROI) arising from a specific investment in an item of energy efficient technology **(Chapter 6)**. The profitability module used average financial performance data, and variable and fixed-cost data from Irish dairy farms. The motivation for the development of this economic model was to ensure that a complete picture of the impact of specific investments on farm profitability, and the return on capital invested was captured. Diederen et al. (2003) showed that profitability of the technology was one of the determinants of energy saving technology adoption. Up until now, energy efficiency measures on dairy farms have been evaluated using the net present value (NPV) method (Gebrezgabher et al., 2012; van Asseldonk et al., 1999), which provides information related to farm profitability but does not provide information on the efficiency of return on capital invested. The simple payback method (Houston et al., 2014) has also been used as a technology appraisal tool; however, it omits the value of money over time, increases in electricity costs and the interest rate of borrowed capital from financial institutions, all of which can impact on the effective return on investment of a technology.

4.3 Further developments of the MECD

Prediction of electricity consumption with the MECD relies heavily on milk production volume as an input. Murphy et al. (2014) developed a mathematical model to predict daily herd milk production with minimal data requirements that could be implemented at farm level. In previous studies, season of calving (Wood, 1967), climatic conditions (Smith, 1968), number of days in milk (Grzesiak et al., 2006) and stocking rate (McCarthy et al., 2011) were found to have an impact on milk yield from dairy cows. In the study of Murphy et al. (2014) the farm grazing area remained static, while the number of cows grazing varied throughout the year. Similarly, the season of calving (spring) remained constant in the herd over several years. Murphy et al. (2014) concluded that a non-linear auto-regressive model with exogenous input (NARX) was most accurate over a 305 day prediction horizon, delivering a root mean squared error (RMSE) of 8.6%. The NARX milk prediction model can be combined in the future with the MECD to create a complete electricity forecasting and simulation platform. This combined model could be utilised for farm financial budgeting, choosing electricity tariffs or analysing technology investment strategies.

5 Technology development: milk cooling

To explore the efficacy of technology investments regarding reductions in energy consumption, associated costs and GHG emissions, detailed information was required on the performance of existing and future technology. In **Chapter 4**, the functionality of existing and future milk cooling technology was explored. A control system for rapid milk cooling was tested using eight different pre-cooling set points (13°C to 20°C in steps of 1°C), where milk was cooled with ground water in a plate heat exchanger (PHE) before entry to a refrigerated milk storage vessel. Optimum water utilisation rates were calculated for varying water costs (€0.05 m^{-3}, €0.1 m^{-3}, €0.15 m^{-3} and €0.2 m^{-3}), with electricity costs of €0.18 per kWh for day rate and €0.10 per kWh for night rate electricity tariffs. These calculations represented the ideal combination of ground water and power consumption per unit of milk flow to produce the most financially efficient means of cooling, and demonstrated that milk cooling costs could be reduced by 35% through correct water utilisation in the pre-cooler. The impact of this milk cooling system (where milk is cooled to 15°C before entry to the bulk tank) was modelled as one of the 'energy strategies' in **Chapter 6**.

6 An economic and environmental assessment of cost and energy reduction strategies

6.1 Cost reduction strategies

Adjusting milking start time was initially thought to be a 'cost strategy'. We, however, discovered that milking earlier in the morning and later in the evening (strategy 1-5 in table 7.1) also reduced the simulated annual electricity consumption and related GHG emissions by between 5% and 7%, depending on farm size, relative to the base case (strategy 0-5 in table 7.1). This reduction was accounted for by the improvement in performance of the milk cooling system, because the efficiency of cooling increased as the ambient temperature decreased. Indeed, the strategy of milking earlier in the morning and later in the evening was effective in reducing electricity costs by €344 for a small farm (SF) with 45 milking cows, €660 for a medium farm (MF) with 88 milking cows and €1,206 for a large farm (LF) with 195 cows. The milking time analysis is presented to illustrate that electricity consumption and costs of dairy farms are influenced by milking start time. Individual farmers will also consider some other effects, such as the social effects associated with milking at 5 AM, or the milk yield effect if the milking interval is extended beyond a ratio of 16:8.

There are four types of electricity tariff discussed in this thesis: *Flat tariff* consisted of one electricity price for all time periods; *Day&Night* tariff consisted of two electricity prices, a high rate from 09:00 to 00:00 h and a low rate thereafter; *Time of use (TOU) tariff* structures were similar to that of the Day&Night tariff, except that a peak price band was introduced between 17:00 and 19:00 h; *RTP (Real Time Pricing) tariff* varied dynamically according to the electricity demand on the national grid. Work has been carried out to describe the effect of both TOU and RTP electricity tariffs in the residential sector (Allcott, 2011; Ericson, 2011; Finn et al., 2012; Torriti, 2012) and the industrial sector (Avci et al., 2013; Finn et al., 2014; Wang et al., 2013). So far, however, similar analysis has not been reported in relation to the agricultural sector. Furthermore, the smart metering trial conducted in Ireland by the commission for energy regulation (CER) did not include agricultural premises in the SME sector, instead it focused on retail, service, office, entertainment and manufacturing enterprises. We provided information on this issue in **Chapter 5** by showing that the Day&Night electricity tariff minimised annual electricity costs, while a Flat tariff would increase the electricity costs of the SF by 31%, MF by 34% and LF by 16%, (strategy 2-5 in table 7.1). Likewise an investigation of a RTP tariff showed that annual electricity costs would increase by 15% for SF, 18% for MF and 3% for LF, (strategy 3-

5 in table 7.1). This information will help dairy farmers choose the most appropriate electricity tariff in future. Of course, the type of technology used will also dictate the extent to which a farm can avail of a low off-peak rate (i.e. a Day&Night tariff).

6.2 Energy reduction strategies

An analysis of the three most interesting 'energy strategies' are presented in table 7.1. The base level of investment in strategies 4-6, 5-6 and 6-6 included investment in a direct expansion (DX) milk cooling system, standard milking system vacuum pumps and electric water heating system. Table 7.1 presents data pertaining to three other alternative investment strategies: strategy 4-6) termed DXPHE, where the investment included a DX milk cooling system with the addition of a milk pre-cooling system; strategy 5-6) termed IBPHE, used an Ice bank (IB) milk cooling system with the addition of a pre-cooling system, and strategy 6-6) termed Solar, which was similar to the Base level of investment with the addition of solar thermal panels for water heating. Strategy 5-6 is based upon the novel milk cooling system described in **Chapter 4** of this thesis.

The strategies DXPHE, IBPHE and Solar all reduced electricity consumption, CO_2 emissions and electricity costs. The strategy IBPHE reduced electricity consumption most; 46% for SF, 38% for MF and 45% for the LF. ROI figures of IBPHE, however, were all negative; -9% for SF, -3% for MF and -1% for LF. Likewise, even though the Solar strategy reduced electricity consumption, CO_2 emissions and electricity costs, the ROI figures were all negative; -25% for the SF, -18% for the MF and -16% for the LF. The most attractive ROI figures resulted from the DXPHE strategy; 17% for SF, 19% for MF and 21% for LF, ceteris paribus. These results highlight the usefulness of ROI as a tool to assess the efficiency of an energy saving technology to deliver on the capital invested.

7 Effect of farm size on electricity consumption

The simulated electricity consumption of the SF (33.3 Wh/litre) was lower than those of the MF (41.3 Wh/L) and LF (41.9 Wh/L) in the base scenario of **Chapter 5**. The electricity costs were lower also for SF (€0.0037/L) than for MF (€0.0044/L) and LF (€0.0046/L). This indicated that electricity consumption and costs per litre of milk produced increased along with farm size. This could be explained by three mechanisms. First, the SF and MF used a milk pre-cooling system which cooled warm milk via ground water in a plate heat exchanger to 25°C before entry to the milk cooling system, whereas the pre-cooling system on the LF was not as effective and cooled the milk to 30°C via the same method. Second, the water heating costs per litre of milk increased along with farm size. Hot water consumption is dictated by the hot washing frequency and the number of units to be washed (8 units on SF, 14 units on MF and 24 units on LF). Larger farms are more likely to use automatic wash systems, which are factory set to carry out one hot wash cycle per day, for labour saving purposes. Whereas smaller farms are more likely to hot wash the milking units manually, on alternate days with the washing of the milk storage tank (milk is typically collected every other day in Ireland). Third, expanding dairy farms in Ireland often experience increased business risk and cash-flow deficits as a result of capital expenditure on livestock and winter facilities (McDonald et al., 2013). As a result, milk harvesting technology is often not upgraded in line with the capacity needs of the expanded enterprise until the risk has stabilised (typically 5 years after expansion), thereby making sub-optimal cooling and heating equipment a commonplace on expanding farms. This was observed during the state-of-the-art assessment of energy use described in **Chapter 2**.

8 Relevance of energy reduction strategies to dairy farm sustainability

We expect an increase in the demand for animal products in the future because of growth of the global human population (especially in developing countries), growing incomes and increasing urbanization. The demand for animal products is expected to double by 2050 (FAO, 2009, Rae, 1998), which will create challenges to ensure that milk is produced in an environmentally efficient and sustainable manner. The livestock sector already competes increasingly for scarce resources, such as land, water, and fossil energy. The livestock sector currently contributes to about 15% of global anthropogenic emissions of greenhouse gasses, uses about 70% of all agricultural land and represents about 8% of the global water withdrawals (Steinfeld et al., 2006). The need for mitigation of GHG emissions from dairy farms has been widely acknowledged. However, there is barely any knowledge on GHG emissions and mitigation options on commercial dairy farms (Vellinga et al., 2011). Any contribution to reduced CO_2 emissions from agriculture should be investigated further to help combat climate change. Considering that the atmospheric concentrations of CO_2 have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions (IPCC, 2013), reducing CO_2 emissions from agriculture is particularly important. Reduced energy use is one way to reduce GHG emissions from dairy farming (Smith et al., 2008).

Sustainability is based upon the three central pillars of people, planet and profit (Elkington, 1998). This thesis focuses mainly on the pillar of profit, whereas the pillar of planet is addressed via energy depletion, exploration of solar energy, and reduction of GHG emissions. The electricity related GHG emissions from the average dairy farm studied in **Chapter 2** was found to be about 23.7 tonnes CO_2 equivalent (CO_2-eq) per annum. To put this in context, the total emissions from a seasonal grass based dairy farm was found to be 11.7 tonnes of CO_2-eq per tonne of milk solids (O'Brien et al., 2012). This would result in total annual emissions of about 515 tonnes CO_2-eq for the average farm of the 22 farms studied in **Chapter 1**, of which only about 5% results from electricity consumption

The impact of reducing electricity consumption on reducing energy depletion, therefore, is relatively more important than on reduction of GHG emissions because, in dairy production CH_4 and N_2O are the dominant GHG (Basset-Mens et al., 2009; Cederberg and Flysjö, 2004; O'Brien et al., 2012; Thomassen et al., 2009; Wells, 2001). In this thesis, the indicators of GHG emissions and energy consumption per litre of milk were used as proxies for the environmental performance of dairy farms. We acknowledge that electricity consumption is also associated with other environmental impacts (i.e. acidification potential due to emissions of SO_2 and NO_x); however, these impacts are related to electricity consumption via a fixed multiplication factor of 2.76 g/kWh for SO_2 and 1.2 g/kWh for NO_x (Huijbregts, 1999).

9 Trade-offs between strategies

If a farmer has a goal of minimising fossil energy consumption then he or she could invest in a solar thermal water heater. This strategy can reduce their electricity consumption by over 18%, saving over 3 tonnes of CO_2 per annum on a large farm (see strategy 6-6, table 7.1). The trade-off for this fossil energy saving, however, is a negative ROI of -16% (**Chapter 6**). Likewise, adopting the goal of minimising energy costs on a large farm would lead a farmer to the IBPHE investment strategy. The trade-off for adopting the IBPHE scenario is a negative ROI of -1%, along with increased electricity consumption and associated emissions. Investment in technologies such as pre-cooling coupled with direct expansion milk cooling systems (as in DXPHE from table 7.1), however, services the goal of increasing profitability. The DXPHE strategy reduced electricity consumption by 28% reduced annual CO_2 emissions by 4.8 tonnes and returned a positive ROI of 21% on LF. These results broadly agree those of Vellinga et al. (2011) who noted that the combined use of a heat pump and pre-cooling equipment was a cost effective method to reduce GHG emissions. However, when only a heat pump was used farm income decreased, implying that low cost GHG mitigation strategies are also the most effective from a farm profitability perspective.

10 Future technology requirements for dairy farms

The results of the Solar strategy discussed above suggest that we are yet some distance away from the mass proliferation of capital intensive energy saving technologies on dairy farms. In **Chapter 5** we showed that even when the capital investment in solar thermal water heaters were reduced by 40% and electricity price was increased by 4% per annum, the ROI still remained negative (-12%) on LF.

Clearly a balance is required between the ability of a technology to reduce electricity costs and its initial capital investment. One example of this balance is the application of optimal control to pre-cooling systems, in order to reduce electricity consumption and associated costs of the milk cooling system. This technology is inexpensive to implement and can reduce electricity consumption by 34%. This example ideally represents the path that technology development for dairy farms should follow. Dairy farmers are currently unaware of the energy efficiency of their milk harvesting equipment. Therefore, technology development should focus on two key areas: 1) energy efficiency by design, where products are designed with energy efficiency in mind. For example water heaters should be designed with minimal heat loss, and the capacity of equipment should match the demand especially in the case of pre-cooling systems on larger farms, 2) improved management of dairy farm technologies for energy efficiency. This must encompass built-in active energy monitoring to help with demand side management of electricity use at farm level. For example, if farmers are aware that their pre-cooling systems or water heating systems are operating with reduced efficiency, they will be empowered to take remedial action.

11 Applicability of results to other regions

Our results, pertaining to electricity consumption trends on dairy farms, and the impact of various future electricity pricing tariffs on dairy farm electricity costs, may be of relevance to dairy industries internationally, especially where dairy farms are expanding and investment in new technology is required. In the United Kingdom, over 4.5 million residential consumers avail of time of use (TOU) tariffs (OFGEM, 2011). The mandatory rollout of smart metering is already well underway in Estonia, Finland, France, Ireland, Italy, Malta, The Netherlands, Norway, Portugal, Spain and Sweden (Hierzinger et al., 2012). Other countries, such as Australia and New

Zealand, have recognised smart metering as a method of improving resource use efficiency through incentivised demand side management (Energy Fed NZ, 2010; DRET, 2008). Many of these countries have well established milk production industries that may be able to use smart metering to their advantage, by observing that quite large electricity cost increases could occur if a farmer chooses the incorrect electricity tariff (see table 7.1). In addition, the fact that moving milking times can reduce electricity costs by a significant amount on some tariffs (i.e. Day&Night), should be applicable to dairy farmers in countries outside of Ireland, especially farmers with a twice a day milking routines.

The data presented in **Chapters 5** and **6** represent the energy prices and equipment costs related to the Irish economic environment, thus the impacts of various pricing structures and technology investment strategies would likely differ from region to region. The MECD described in **Chapter 3** is comprehensive and covers all the necessary systems (i.e. milk cooling, water heating, milking machine, lighting, water pump and housing) to model electricity consumption on confinement dairy systems and automatic milking systems. Confinement systems were not examined in this thesis since the Irish production system is centred around seasonal grass based milk production, but it is likely that a higher electricity consumption would result in a different set of return on investment figures for various technology investment strategies. Moreover, the profitability calculator used in **Chapter 6** to model ROI figures could easily be updated to incorporate dairy farm financial performance data from other regions. Furthermore, the methodologies used to compute these metrics of investment appraisal are easily updatable to account for variations in key external factors acting on dairy farming business such as financial institution interest rate, margin over cost of funds, depreciation, electricity costs, investment costs or milk price.

12 Implications for policy makers

We have provided information about the impact of both TOU tariffs and RTP tariffs on dairy farms of different scales. This information could be used by policy makes to derive suitable tariffs for dairy farmers that would encourage electricity consumption in off peak periods while promoting conservation during peak periods (typically 17:00 to 19:00 h) through the use of energy storage and demand side management technologies. Likewise, we have shown that dairy farms can contribute to Ireland's energy reduction targets by adjusting farm management practices and application of technology. For example, by combining strategies 4-6 and 6-6 (table

7.1) a saving of over 45% in annual electricity consumption and related GHG emissions could be achieved, thereby contributing to the energy efficiency, GHG emissions and renewable energy goals set out by the Irish government's national energy efficiency action plan (DCENR, 2009). We, however, did not assess the attitude or willingness of dairy farmers to adjust their management behaviour or equipment in response to changes in electricity price structure. This information is missing from the literature. While RTP tariffs may entail more uncertainty for end-users with respect to the frequency and timing of high peak prices (Ericson, 2011), it has been shown to be the most efficient tool that can urge consumers to consume more wisely and efficiently (Samadi et al., 2010).

13 Implications for farmers

The results of this study showed that the most efficacious technology investment strategy to increase farm profitability consisted of a direct expansion milk cooling system with pre-cooling of milk to 15°C, heating water with an electrical water heating system and using standard vacuum pump control on the milking system. We suggested a minimum acceptable rate of return of 5% above the cost of capital. Therefore, for a loan interest rate of 5%, the rate of return would be 10%; however, an individual farmer can decide if this 10% threshold is applicable or not based on the specific economic environment and financial circumstances in which the farm operates.
Up until now the impact of TOU and RTP electricity tariffs on dairy farm electricity costs had remained undocumented. This will become more topical because it seems likely that dairy farms in Ireland will increase milk production in the future due to the abolition of the EU milk quota regime in 2015 coupled with the potential for expansion identified by the policy document 'Food Harvest 2020' (DAFM 2010).

Analysis of various electricity tariffs showed that the Day&Night electricity tariff minimised annual electricity costs. This information will be critical for farm budgeting and planning in the future, when new electricity pricing tariffs, such as those trialled in Ireland by the commission for energy regulation (CER, 2011), become available to farmers. Likewise, we have provided information showing that electricity cost savings of over 30% can be realised by milking earlier in the morning and later in the evening (strategy 1-5 in table 7.1).

Moreover, **Chapter 5** of this thesis showed that larger farms have higher electricity costs per litre of milk, especially if the farm is going through an expansion phase and capital is not available to upgrade equipment with poor performance. We found that the ideal blend of technologies to maximise farm profitability, while also reducing electricity consumption and

GHG emissions, consisted of a direct expansion milk tank with pre-cooling of milk with well water to 15°C, electrical water heating and standard vacuum pumps (strategy 4-6 in table 7.1).

14 Main conclusions

The following conclusions can be drawn from the research presented in this thesis:

- A total of 31.73 MJ was required to produce one kg of milk solids from cradle-to-farm gate on Irish dairy farms, of which 20% was direct and 80% was indirect energy use. Electricity was found to represent 12% of total energy use.
- A mechanistic model for dairy farm electricity consumption was developed that enabled simulation of the electricity consumption of farm equipment under the headings of: milk cooling, water heating, milking machine, lighting, water pump and the winter housing facilities. The model delivered an acceptable RPE of <10% for total electricity consumption.
- Energy consumption during milk cooling can be reduced by over 34% through the use of a control system to adjust water flows through the milk pre-cooling system.
- Changes in milking start time could reduce annual electricity consumption of dairy farms by between 5% and 7% depending on farm size.
- The Day&Night electricity tariff minimised annual electricity costs, while a Flat tariff increases the electricity costs of dairy farms by 16 to 34%, depending on farm size.
- A real time electricity tariff would increase annual electricity costs by 3 to 18%, depending on farm size.
- Ice bank milk cooling systems could reduce electricity consumption by 45% on a large farm with about 195 cows, without delivering a positive ROI in the ten year period subsequent to the investment.
- Dairy farm profitability can be increased through investment in a direct expansion milk cooling system with pre-cooling, heating water with an electrical water heating system and using standard vacuum pumps, relative to other technology investment strategies studied.

Table 7.1. Summary of the impact of selected electricity reduction strategies on total annual electricity consumption (kWh) associated CO_2 emissions (kg) and associated costs (€) on three farm sizes SF (small farm), MF (medium farm) and LF (large farm) as reported in this thesis. Costs are based on the Day&Night tariff for all strategies except 2-5 and 3-5.

Strategy Number	Farm Name	Strategy Name[1]	Energy (kWh)	(%)	CO_2	(%)	Costs* (€)	(%)
0-5	SF	Base	8,498	0	4,504	0	933	0
	MF		20,631	0	10,934	0	2,184	0
	LF		32,407	0	17,176	0	3,586	0
1-5	SF	Milk at 5am & 8pm	-618	-7	-328	-7	-334	-36
	MF		-1,006	-5	-533	-5	-660	-30
	LF		-1,729	-5	-916	-5	-1,206	-34
2-5	SF	Move to Flat tariff	0	0	0	0	427	31
	MF		0	0	0	0	1,117	34
	LF		0	0	0	0	664	16
3-5	SF	Move to RTP tariff	0	0	0	0	166	15
	MF		0	0	0	0	468	18
	LF		0	0	0	0	125	3
0-6	SF	Base	10,413	0	5,519	0	1,445	0
	MF		25,252	0	13,384	0	3,334	0
	LF		32,670	0	17,315	0	4,571	0
4-6	SF	DXPHE[2]	-2,876	-28	-1,524	-28	-570	-39
	MF		-5,644	-22	-2,991	-22	-1,083	-32
	LF		-9,010	-28	-4,775	-28	-1,714	-37
5-6	SF	IBPHE[2]	-2,706	-26	-1,434	-26	-667	-46
	MF		-5,258	-21	-2,787	-21	-1,259	-38
	LF		-8,489	-26	-4,499	-26	-2,044	-45
6-6	SF	Solar	-806	-8	-427	-8	-64	-4
	MF		-2,270	-9	-1,203	-9	-182	-5
	LF		-5,764	-18	-3,055	-18	-461	-10

[1]Strategy 1-5 is additive with 2-5 and 3-5. Strategy 6-6 is additive with 4-6 and 6-6

[2] Base = investment in direct expansion (DX) milk cooling system, standard milking system vacuum pumps and electric water heating system; DXPHE = as per Base with the addition of a

milk pre-cooling system; IBPHE = Ice bank (IB) milk cooling system with the addition of a pre-cooling system; Solar = as per Base with the addition of solar thermal panels.

References

Alamir, M., E. Witrant, G. Della Valle, O. Rouaud, C. Josset, and L. Boillereaux. 2013. Estimation of energy saving thanks to a reduced-model-based approach: Example of bread baking by jet impingement. Energy 53(0):74-82.

Allcott, H. 2011. Rethinking real-time electricity pricing. Resource and Energy Economics 33(4):820-842.

Avci, M., M. Erkoc, A. Rahmani, and S. Asfour. 2013. Model predictive HVAC load control in buildings using real-time electricity pricing. Energy and Buildings 60(0):199-209.

Basset-Mens, C., S. Ledgard, and M. Boyes. 2009. Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecol. Econ. 68(6):1615-1625.

Cederberg, C. and A. Flysjö. 2004. Life cycle inventory of 23 dairy farms in southwestern Sweden. SIK Report Nr 728. The Swedisch Institute for Food and Biotechnology, Göteborg, Sweden.

CER. 2011. Second Consultation on Possible National Rollout Scenarios for the Smart Metering Cost Benefit Analysis. Commission for Energy Regulation, Dublin Ireland.

DAFM. 2010. Food harvest 2020 – A vision for Irish agri-food and fisheries. Department of Agriculture Food and the Marine, Dublin Ireland.

DCENR. 2009. Maximising Ireland's Energy Efficiency. The National Energy Efficiency Action Plan 2009-2020. Department of Communications, Energy and Natural Resources, Dublin, Ireland.

Diederen, P., F. van Tongeren, and H. van der Veen. 2003. Returns on Investments in Energy-saving Technologies Under Energy Price Uncertainty in Dutch Greenhouse Horticulture. Environ Resource Econ 24(4):379-394.

DRET. 2008. Cost-benefit analysis of options for a national smart meter roll-out: Phase Two—Regional and detailed analyses regulatory impact statement. Department of Resources Energy and Tourism (DRET), Canberra, Australia.

EC. 2008. 20 20 by 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - 20 20 by 2020 - Europe's climate change opportunity, European Commission, Brussels, Belgium.

Elkington, J. 1998. Cannibals with forks: The triple bottom line of 21st century business. New Society Publishers, Gabriola Island, Canada.

Energy Federation of New Zealand. 2010. Developing our energy potential, New Zealand Energy Efficiency and Conservation Strategy. Energy Federation of New Zealand, Wellington, New Zealand

Ericson, T. 2011. Households' self-selection of dynamic electricity tariffs. Applied Energy 88(7):2541-2547.

EU. 2006. Directive 2006/32/EC of the European Parliment and of the council on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Official Journal of the European Union.

Eyerman, S., K. Hoste, and L. Eeckhout. 2011. Mechanistic-empirical processor performance modeling for constructing CPI stacks on real hardware. Pages 216-226 in Proc. of the IEEE International Symposium on Performance Analysis of Systems and Software (ISPASS). 10-12 April, Austin, TX.

FAO. 2009. The state of food and agriculture. Livestock in balance. Sales and marketing group, communication division, FAO, Rome, Italy.

Finn, P. and C. Fitzpatrick. 2014. Demand side management of industrial electricity consumption: Promoting the use of renewable energy through real-time pricing. Applied Energy 113(0):11-21.

Finn, P., C. Fitzpatrick, and D. Connolly. 2012. Demand side management of electric car charging: Benefits for consumer and grid. Energy 42(1):358-363.

Gebrezgabher, S. A., M. P. M. Meuwissen, and A. G. J. M. Oude Lansink. 2012. Energy-neutral dairy chain in the Netherlands: An economic feasibility analysis. Biomass and Bioenergy 36(0):60-68.

Grzesiak, W., P. Blaszczyk, and R. Lacroix. 2006. Methods of predicting milk yield in dairy cows - Predictive capabilities of Wood's lactation curve and artificial neural networks (ANNs). Computers and Electronics in Agriculture 54:69-83.

Hierzinger R., M. Albu, H. van Elburg, A. J. Scott, A. Lazicki, L. Penttinen, F. Puente, and H. Sale. 2012. European Smart Metering Landscape Report, SmartRegions Deliverable 2.1. Accessed May 24, 2013. http://www.energyagency.at/fileadmin/dam/pdf/projekte/klimapolitik/SmartRegionsLandscapeReport2012.pdf

Houston, C., S. Gyamfi, and J. Whale. 2014. Evaluation of energy efficiency and renewable energy generation opportunities for small scale dairy farms: A case study in Prince Edward Island, Canada. Renewable Energy 67(0):20-29.

Huijbregts, M. A. J. 1999. Life-cycle impact assessment of acidifying and eutrophying air pollutants. Calculation of characterisation factors with RAINSLCA. Interfaculty Department of Environmental Science, Faculty of Environmental Science, University of Amsterdam.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

ISO. 2006. Environmental Management, The ISO 14000 Family of International Standards ISO Standard Collection. Geneve, Switzerland.

Joseph, P. J., K. Vaswani, and M. J. Thazhuthaveetil. 2006a. Construction and use of linear regression models for processor performance analysis. Pages 99-108 in Proc. of the Twelfth International Symposium on High-Performance Computer Architecture. 11-15 Feb, Austin, TX.

Joseph, P. J., K. Vaswani, and M. J. Thazhuthaveetil. 2006b. A Predictive Performance Model for Superscalar Processors. Pages 161-170 in Proc. of the International Symposium on Microarchitecture, 2006. MICRO-39. 39th Annual IEEE/ACM. Dec, Orlando, FL.

Kalogirou, S. A. 1999. Applications of artificial neural networks in energy systems - A review. Energy Conversion and Management 40(10):1073-1087.

Karkhanis, T. S. and J. E. Smith. 2004. A first-order superscalar processor model. Pages 338-349 in Proc. of the 31st Annual International Symposium on Computer Architecture. 19-23 June, München, Germany.

McCarthy, B., L. Delaby, K. M. Pierce, F. Journot, and B. Horan. 2011. Meta-analysis of the impact of stocking rate on the productivity of pasture-based milk production systems. Animal, 5:784-794.

McDonald, R., L. Shalloo, K. M. Pierce, and B. Horan. 2013. Evaluating expansion strategies for startup European Union dairy farm businesses. Journal of Dairy Science 96(6):4059-4069.

McNamara, J. P. 2004. Research, improvement and application of mechanistic, biochemical, dynamic models of metabolism in lactating dairy cattle. Animal Feed Science and Technology 112(1–4):155-176.

Murphy, M. D., M. J. O'Mahony, L. Shalloo, P. French, and J. Upton. 2014. Comparison of modelling techniques for milk-production forecasting. Journal of Dairy Science 97(6):3352-3363).

Nestorov, I., M. Rowland, S. T. Hadjitodorov, and I. Petrov. 1999. Empirical versus mechanistic modelling: Comparison of an artificial neural network to a mechanistically based model for quantitative structure pharmacokinetic relationships of a homologous series of barbiturates. AAPS PharmSci 1(4):5-13.

O'Brien, D., L. Shalloo, J. Patton, F. Buckley, C. Grainger, and M. Wallace. 2012. A life cycle assessment of seasonal grass-based and confinement dairy farms. Agric. Syst. 107:33-46.

OFGEM. 2011. Energy Demand Research Project: Final Analysis. Office of gas and electricity metering, Report n. 60163857. Hertfordshire, United Kingdom.

Rae, A. N. 1998. The effects of expenditure growth and urbanisation on food consumption in East Asia: a note on animal products. Agricultural Economics 18(3):291-299.

Samadi, P., A. H. Mohsenian-Rad, R. Schober, V. W. S. Wong, and J. Jatskevich. 2010. Optimal Real-Time Pricing Algorithm Based on Utility Maximization for Smart Grid. in Proc. First IEE International conference on Smart Grid Communications (SmartGridComm). PP 415-420.

Schils, R. L. M., M. H. A. de Haan, J. G. A. Hemmer, A. van den Pol-van Dasselaar, J. A. de Boer, A. G. Evers, G. Holshof, J. C. van Middelkoop, and R. L. G. Zom. 2007a. DairyWise, A Whole-Farm Dairy Model. Journal of Dairy Science 90(11):5334-5346.

Schils, R. L. M., J. E. Olesen, A. del Prado, and J. F. Soussana. 2007b. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livestock Science 112(3):240-251.

Smith, L. P. 1968. Forecasting annual milk yields. Agricultural Meteorology 5: 209-214.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach, and J. Smith. 2008. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences 363(1492):789-813.

Steinfeld, H., P. J. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan. 2006. Livestock's Long Shadow: environmental issues and options, Food and Agriculture Organization of the United Nations. Rome, Italy.

Taha, T. M. and D. S. Wills. 2008. IEEE Transactions on An Instruction Throughput Model of Superscalar Processors. Computers, 57(3):389-403.

Torriti, J. 2012. Price-based demand side management: Assessing the impacts of time-of-use tariffs on residential electricity demand and peak shifting in Northern Italy. Energy 44(1):576-583.

Thomassen, M. A., M. A. Dolman, K. J. van Calker, and I. J. M. de Boer. 2009. Relating life cycle assessment indicators to gross value added for Dutch dairy farms. Ecol. Econ. 68(8-9):2278-2284.

van Asseldonk, M. A. P. M., R. B. M. Huirne, A. A. Dijkhuizen, and A. J. M. Beulens. 1999. Dynamic programming to determine optimum investments in information technology on dairy farms. Agricultural Systems 62(1):17-28.

Vaswani, K., M. J. Thazhuthaveetil, Y. N. Srikant, and P. J. Joseph. 2007. Microarchitecture Sensitive Empirical Models for Compiler Optimizations. Pages 131-143 in Proc. of the International Symposium on Code Generation and Optimization.11-14 March, San Jose, CA.

Vellinga, T. V., M. H. A. de Haan, R. L. M. Schils, A. Evers, and A. van den Pol–van Dasselaar. 2011. Implementation of GHG mitigation on intensive dairy farms: Farmers' preferences and variation in cost effectiveness. Livestock Science 137(1–3):185-195.

Wang, Y. and L. Li. 2013. Time-of-use based electricity demand response for sustainable manufacturing systems. Energy 63(0):233-244

Wells, C. 2001. Total energy indicators of agricultural sustainability: Dairy farming case study. Technical Paper 2001/3 prepared for the New Zealand Ministry of Agriculture and Fisheries, Wellington, New Zealand.

Wood, P. D. P. (1967). Algebraic Model of the Lactation Curve in Cattle. Nature 216:164-165.

Summary

Dairy farms in Ireland are expected to expand in the future, due to policy incentives and the abolishment of European Union milk quotas in 2015, which will result in an increased use of resources such as land, water, and energy, and increased emissions to the environment. Expansion of a dairy enterprise requires significant capital investment in more industrial milk harvesting equipment, such as milking systems, cooling systems and heating systems, and more automation, such as automatic wash systems, which may increase the electricity consumption per litre of milk produced. Furthermore, the structure of electricity pricing systems are going through a period of change, due to the implementation of smart metering in many countries, which may expose dairy farmers to increases in electricity costs. The objective of this thesis was to assess how, and to what extent, do managerial and technology changes affect electricity consumption, associated costs and GHG emissions of dairy farms.

In order to develop strategies to reduce electricity consumption, associated costs and GHG emissions on dairy farms, a state-of-the-art assessment of direct and indirect energy use, and daily and seasonal consumption patterns of electricity are needed. In **Chapter 2** we performed a single-issue life cycle assessment (LCA) by quantifying the energy use of one kg of milk solids on 22 commercial Irish dairy farms, from cradle-to-farm-gate. This analysis demonstrated that a total of 31.73 MJ of energy was required to produce one kg of milk solids, of which 20% was direct and 80% was indirect energy use. Electricity consumption was found to represent 12% of total cradle-to-farm-gate energy use or 60% of direct energy, and was centred around milk harvesting. Hence, the electricity consumption related directly to milk harvesting (milk cooling, water heating and milking) accounted for 74% of on-farm electricity use which equalled 9% of total cradle-to-farm gate energy use. This is significant, especially because electricity consumption is under the control of the farmer and can be influenced through management decisions and the application of technologies.

We explored two types of strategies in this thesis, i.e. ‘cost strategies’ and ‘energy strategies’. ‘Cost strategies’ consisted of measures that are expected to save on-farm costs but no energy or related emissions, such as, moving to a new electricity tariff or decoupling large electricity users, such as water heating, from milking times and shifting them to off-peak periods when electricity price is lower. ‘Energy strategies’ were expected to reduce electricity consumption, and, therefore, inherently reduce costs and GHG emissions. Examples of ‘energy strategies’ are; the use of

variable speed vacuum pumps on the milking machine motors, pre-cooling of milk and solar thermal technologies to provide hot water for washing of milking equipment.

So far, the lack of a suitable model prevented deeper analysis on the efficacy of these strategies to affect electricity consumption, associated costs and GHG emissions of dairy farms. In **Chapter 3** we developed a mechanistic model of electricity consumption on dairy farms (MECD) that simulates farm equipment on an hourly and monthly basis under the following headings; milk cooling system, water heating system, milking machine system, lighting system, water pump system and the winter housing facilities. This model was validated by comparing the simulated results against empirical data of farms of varying scale from Chapter 2. In order to develop a clearer panorama of how investments in technologies impact the return on capital invested on dairy farms, a profitability module was added to the MECD. This module ensured that a complete picture of the impact of specific investments on farm profitability, and the return on capital invested, was captured.

To further evaluate the 'cost' and 'energy' strategies, detailed information was required on the performance of existing and future technology. In **Chapter 4**, a control system for rapid milk cooling was tested using eight different pre-cooling set points (13°C to 20°C in steps of 1°C), where milk was cooled with groundwater in a plate heat exchanger before entry to a refrigerated milk storage vessel. We found that milk cooling electricity consumption could be reduced by over 34% through the use of the new control system for water flows through the milk pre-cooling system. The impact of this milk cooling system (where milk is cooled to 15°C before entry to the bulk tank) was modelled as an 'energy strategy' in Chapter 6.

In **Chapter** 5, we used the MECD to explore the economic consequences of four tariff systems, and their interaction with shifting the milking operation to an earlier or later time of the day. The following four tariff systems were included: 1) Flat tariff, which consisted of one electricity price for all time periods, 2) Day&Night tariff, which consisted of two electricity prices; a high rate from 09:00 to 00:00 h and a low rate thereafter, 3) Time of use (TOU) tariff, the structure of which was similar to that of the Day&Night tariff except that a peak-price band was introduced between 17:00 and 19:00 h, and 4) Real time pricing (RTP) tariff, which varied dynamically according to the electricity demand on the national grid. The Day&Night electricity tariff minimised annual electricity costs, while a Flat tariff would increase the electricity costs by between 16% and 34%, depending on farm size. TOU tariffs increased electricity costs by between 14% and 39%. Likewise, an investigation of a RTP tariff showed that annual electricity costs would increase by between 3% and 18%, depending on farm size. This information will help dairy farmers choose the most appropriate electricity tariff in future.

Adjusting milking start time was initially thought to be a 'cost strategy'; however, we discovered that milking earlier in the morning and later in the evening also reduced the simulated annual electricity consumption and related GHG emissions by between 5% and 7%, depending on farm size. This energy reduction resulted from an improvement in performance of the milk cooling system, because the efficiency of cooling increased as the ambient temperature decreased. Indeed, the strategy of milking earlier in the morning and later in the evening was effective at reducing annual electricity costs by €344 for a small farm (SF) with 45 milking cows, €660 for a medium farm (MF) with 88 milking cows and €1,206 for a large farm (LF) with 195 cows.

An analysis of 'energy strategies' was carried out in **Chapter 6**. The Base level of investment in this analysis included investment in a direct expansion (DX) milk cooling system, standard milking system vacuum pumps and electric water heating system. The other investment strategies were: 'DXPHE', which included investment in a DX milk cooling system with the addition of a milk pre-cooling system; IB, which included investment in an ice bank (IB) milk cooling system; 'IBPHE', which included investment in an ice bank milk cooling system with the addition of a pre-cooling system; 'VSD', which included investment in a variable speed drive vacuum pump, and 'Solar', which was similar to the Base level of investment, with the addition of solar thermal panels for water heating. The strategies DXPHE, IBPHE, VSD and Solar all reduced electricity consumption, GHG emissions and electricity costs. The IB strategy increased electricity consumption by between 4% and 5% depending on farm size and resulted in ROI figures of -3% on SF, 7% on MF and 6% on LF. The strategy IBPHE resulted in the largest annual electricity cost-saving (46% for SF, 38% for MF and 45% for the LF); however, the ROI figures were all negative; (-9% for SF, -3% for MF and -1% for LF). The VSD strategy reduced electricity consumption by between -7% and -10% depending on farm size, however, the ROI figures were all negative, i.e. -22% for SF, -19% for MF and -13% for LF. Likewise, even though the Solar strategy reduced electricity consumption, GHG emissions and electricity costs, the ROI figures were all negative (-25% for the SF, -18% for the MF and -16% for the LF). The most attractive ROI figures resulted from the DXPHE strategy: 17% for SF, 19% for MF and 21% for LF, ceteris paribus. These results highlight the usefulness of ROI as a tool to assess the efficiency of an energy saving technology to deliver a return on the capital invested.

In **Chapter 7**, the contribution of the 'cost strategies' and 'energy strategies' to economic and environmental sustainability of dairy farms was discussed. This thesis focuses mainly on the pillar of profit, whereas the pillar of planet is addressed via energy depletion, exploration of solar energy, and reduction of GHG emissions. We concluded that the impact of reducing electricity consumption on energy depletion is relatively more important than on reduction of GHG emissions as, in dairy production, methane and nitrous oxide are the dominant GHGs.

Chapter 7 revealed that the ideal blend of technologies to maximize farm profitability, while also reducing electricity consumption and GHG emissions, consisted of a direct expansion milk tank with pre-cooling of milk with well water to 15°C, electrical water heating and standard vacuum pumps. An individual farmer can also choose to increase his or her use of renewable energy by adding solar thermal water heating with the trade-off of reduced profitability. Thie discussion chapter also revealed that larger farms have higher electricity costs per litre of milk, especially if the farm uses automatic hot washing systems, or if the farm is going through an expansion phase, and capital is not available to upgrade milk harvesting equipment in line with capacity requirements. Finally, we provide some practical advice for policy makers, where we identified the need for further assessment of the attitudes and willingness of dairy farmers to adjust their management behaviour or equipment in response to changes in electricity price structure.

The final conclusions from the research presented in this thesis are:

- A total of 31.73 MJ was required to produce one kg of milk solids from cradle-to-farm gate on Irish dairy farms, of which 20% was direct and 80% was indirect energy use. Electricity was found to represent 12% of total energy use.
- A mechanistic model for dairy farm electricity consumption was developed that enabled simulation of the electricity consumption of farm equipment under the headings of: milk cooling, water heating, milking machine, lighting, water pump and the winter housing facilities. The model delivered an acceptable RPE of <10% for total electricity consumption.
- Energy consumption during milk cooling can be reduced by over 34% through the use of a control system to adjust water flows through the milk pre-cooling system.
- Changes in milking start time could reduce annual electricity consumption of dairy farms by between 5% and 7% depending on farm size.
- The Day&Night electricity tariff minimised annual electricity costs, while a Flat tariff increases the electricity costs of dairy farms, by 16 to 34%, depending on farm size.

- A real time electricity tariff would increase annual electricity costs by 3 to 18%, depending on farm size.
- Ice bank milk cooling systems with pre-cooling could reduce electricity consumption by 45% on a large farm with about 195 cows, without delivering a positive ROI in the ten year period subsequent to the investment.
- Dairy farm profitability can be increased, while reducing energy use and greenhouse gas emissions, through investment in a direct expansion milk cooling system with pre-cooling, heating water with electrical water heating and using standard vacuum pumps relative to other technology investment strategies studied.

Samenvatting

Ierse melkveebedrijven zullen hun melkproductie de komende jaren waarschijnlijk verhogen, onder andere door de afschaffing van het Europese melkquoteringssysteem in 2015. Het produceren van meer melk betekent ook een groter beslag op grondstoffen, zoals als land, water en energie, en meer emissies naar het milieu. Uitbreiding van een melkveebedrijf vereist investeringen in melkapparatuur, zoals systemen voor het melken, koelen en automatisch reinigen, hetgeen kan leiden tot een toename van het elektriciteitsverbruik per liter melk. Daarnaast krijgen Ierse melkveehouders in de toekomst ook te maken met veranderingen in de energie-infrastructuur, zoals de introductie van 'slimme energiemeters', hetgeen kan leiden tot hogere kosten voor het verbruik van elektriciteit. Het doel van dit onderzoek was te beoordelen of, en zo ja, in welke mate, managementmaatregelen en technologische investeringen van invloed zijn op het verbruik en de economische en milieutechnische kosten (i.e. uitputting fossiele energie, emissies van broeikasgassen) van elektriciteit op melkveebedrijven.

Het kiezen van managementmaatregelen of technologische investeringen die mogelijk elektriciteit besparen vereist inzicht in het verbruik van energie in de melkketen, en specifiek de hoeveelheid en het patroon van elektriciteitsverbruik op het bedrijf. **Hoofdstuk 2** beschrijft een schatting van het energieverbruik in de melkketen (exclusief verwerking en consumptie van melk), op basis van data van 22 Ierse praktijkbedrijven. De productie van 1 kg vet en eiwit vereist 31.73 MJ energie, waarvan 20% direct verbruikt wordt op het bedrijf en 80% verbruikt wordt voor het produceren en transporteren van aangekochte grondstoffen. Ongeveer 60% van het energieverbruik op het bedrijf betreft elektriciteit, hetgeen overeen komt met 12% van het energieverbruik in de onderzochte keten. Ongeveer driekwart van de elektriciteit op het bedrijf werd gebruikt tijdens het proces van melken (koelen melk, opwarmen reinigingswater, melken), hetgeen overeenkomt met 9% van het verbruik in de onderzochte keten. De melkveehouderij kan door managementmaatregelen en investeringsbeslissingen het elektriciteitsverbruik rondom het melken daarom aanzienlijk beïnvloeden.

Om te anticiperen op de toekomst kunnen melkveehouders kiezen voor energiebesparende maatregelen, ofwel 'energiemaatregelen' genoemd, of maatregelen die geen energie maar enkel kosten besparen, ofwel 'kostenmaatregelen' genoemd. Energiemaatregelen, zoals bijvoorbeeld het voorkoelen van melk, het gebruik van vacuümpompen met een variabele snelheidsaandrijving of het gebruik van zonne-energie voor het verwarmen van reinigingswater, leiden ook altijd tot een vermindering van economische en milieutechnische kosten.

Kostenmaatregelen, zoals overstappen op een alternatief stroomtarief of het verplaatsen van het energieverbruik naar daluren, zijn enkel gericht op het verminderen van de kosten.

Hoofdstuk 3 beschrijft een mechanistisch model dat inzicht geeft in het effect van management- en investeringsmaatregelen op het elektriciteitsverbruik en bijbehorende kosten op een melkveebedrijf, genaamd MECD (Mechanistic model of Electricity Consumption on Dairy farms). Dit model simuleert het elektriciteitsverbruik van apparatuur op een melkveebedrijf dat nodig is voor het koelen van melk, het opwarmen van reinigingswater, de melkmachines, de verlichting, het oppompen van water, en huisvestingsfaciliteiten voor melkkoeien. Het model is gevalideerd op basis van de data van de 22 praktijkbedrijven, welke ook gebruikt zijn in Hoofdstuk 2. Het model bevat daarnaast ook een economische module die inzicht geeft in de economische consequenties van de diverse maatregelen.

Om de energie- en kostenmaatregelen goed te kunnen evalueren is gedetailleerde kennis nodig aangaande de technische prestatie van bestaande en toekomstige technologieën. **Hoofdstuk 4** beschrijft de ontwikkeling en het testen van een regelsysteem voor het voorkoelen van melk. Met behulp van dit systeem wordt melk voorgekoeld met grondwater in een platenwarmtewisselaar. Optimale regeling van het debiet van het grondwater tijdens het voorkoelen leidt tot een energiebesparing van ruim 34%. De economische en milieutechnische consequenties van dit regelsysteem, waarbij de melk wordt voorgekoeld tot 15°C, zijn geëvalueerd in Hoofdstuk 6.

Hoofdstuk 5 beschrijft de economische consequenties van vier energietarieven en de interactie van deze tarieven met het aanpassen van de melktijd op een bedrijf. De volgende vier energietarieven zijn bestudeerd: 1) een vast tarief; 2) een dag- en nacht tarief, met een dagtarief tussen 9:00 en 00:00 uur, en een lager nachttarief gedurende de rest van de 24 uur; 3) een gebruikstarief, hetgeen overeenkomt met een dag- en nachttarief, aangevuld met een piektarief (hoger dan het dagtarief) tussen 17:00 en 19:00 uur; en 4) een variabel tarief, hetgeen betekent dat het tarief meebeweegt met de markt. De elektriciteitskosten bleken het laagst bij het dag- en nacht tarief, en het hoogst bij het vaste tarief (i.e. 16%-35% hoger, afhankelijk van de bedrijfsgrootte). Het gebruikstarief en het variabele tarief lagen hier tussenin. Deze informatie helpt melkveehouders bij het kiezen van het juiste stroomtarief in de toekomst.

In eerste instantie werd het aanpassen van de melktijd beschouwd als een kostenmaatregel. De resultaten laten echter zien dat eerder of juist later melken dan gemiddeld het elektriciteitsverbruik juist verlaagt, en de emissie van broeikasgassen met 5% tot 7% vermindert, afhankelijk van de bedrijfsgrootte. Deze energiebesparing was het gevolg van een efficiënter werkend koelsysteem. De efficiëntie van het koelsysteem stijgt bij een lagere omgevingstemperatuur. Eerder of later melken resulteerde inderdaad ook in lagere jaarlijkse elektriciteitskosten, i.e. €334 voor een klein bedrijf (KB) met 45 melkkoeien, €660 voor een middelgroot bedrijf (MB) met 88 melkkoeien en €1,206 voor een groot bedrijf met 195 koeien (GB).

Hoofdstuk 6 beschrijft de vergelijking van het verbruik en de kosten van elektriciteit van een vijftal 'Energiescenario's' met een basisscenario. Het basisscenario veronderstelt investeringen in een melkkoelsysteem met directe verdamping, standaard vacuümpompen voor het melken en elektrische opwarming van reinigingswater. Het DXPHE scenario veronderstelt investeringen in een melkkoelsysteem met directe verdamping (in het Engels direct expansion, afgekort als DX) in combinatie met het voorkoelen van melk met een platenwarmtewisselaar (plate heat exchange oftewel PHE); het IB scenario veronderstelt investeringen in een melkkoelsysteem met ijswater (ice bank oftewel IB); het IBPHE scenario veronderstelt investeringen in een melkkoelsysteem met ijswater in combinatie met het voorkoelen van melk met een platenwarmtewisselaar; het VSD scenario veronderstelt investeringen in vacuümpompen met een variabele snelheidsaandrijving (variable speed drive vacuum pump oftewel VSD), en het Solar scenario is vergelijkbaar met de basissituatie, aangevuld met het gebruik van zonnepanelen voor het opwarmen van reinigingswater. Alle investeringsscenario's, behalve IB, resulteerden in een verlaging van het elektriciteitsverbruik en bijbehorende kosten (kosten elektriciteit en emissies van broeikasgassen). Het IB scenario verhoogde het elektriciteitsverbruik met 4% tot 5% (afhankelijk van de bedrijfsgrootte), terwijl het rendement op de investering (ROI) gelijk was aan -3% voor het KB, 7% voor MB en 6% voor GB. Het IBPHE scenario resulteerde in de grootste besparing van elektriciteit (46% voor KB, 38% voor MB en 45% voor GB), terwijl het ROI negatief was voor alle bedrijfsgroottes (-9% voor KB, -3% voor MB, -1% voor GB). Het VSD scenario verlaagde het elektriciteitsverbruik (-7% tot -10%), maar het ROI was negatief voor iedere bedrijfsgrootte (i.e. -22% voor KB, -19% voor MB, -13% voor GB). Het Solar scenario verlaagde niet alleen het elektriciteitsverbruik, en de economische kosten, maar ook specifiek de emissies van broeikasgassen, terwijl het ROI opnieuw negatief was voor iedere bedrijfsgrootte (i.e. -25% voor KB, -18% voor MB, -16% voor GB). DXPHE was het meest aantrekkelijke scenario, met een ROI van 17% voor KB, 19% voor MB en 21% voor LF. Deze resultaten benadrukken het belang van een ROI berekening om de effectiviteit van een technologische investering te beoordelen.

In **hoofdstuk** 7 wordt de bijdrage van energie- en kostenmaatregelen aan een verdere economische en milieukundige verduurzaming van melkveebedrijven bediscussieerd. Deze discussie richt zich met name op de economische aspecten van duurzaamheid. De milieukundige aspecten van duurzaamheid die zijn meegenomen in dit onderzoek zijn de uitputting van fossiele energiebronnen en het verminderen van broeikasgas emissies, en in een enkel geval het gebruik van zonne-energie. De bijdrage van energie- en kostenmaatregelen aan het verminderen van de uitputting van fossiele energie is groter dan de bijdrage aan het verminderen van de emissies van broeikasgassen, gezien het relatieve belang van de broeikasgassen methaan en lachgas in de melkveehouderij.

In hoofdstuk 7 blijkt dat de combinatie van een melkkoelsysteem met directe verdamping, het voorkoelen van melk met grondwater tot 15°C, en het gebruik van standaard vacuümpompen, het bedrijfsinkomen maximaliseert, en ook bijdraagt aan een vermindering van elektriciteitsverbruik en emissies van broeikasgassen. Een individuele boer met interesse voor het gebruik van hernieuwbare energie kan kiezen voor het verwarmen van reinigingswater met zonne-energie, met als neveneffect een lager bedrijfsinkomen. De discussie in Hoofdstuk 7 laat ook zien dat grotere bedrijven hogere elektriciteitskosten hebben per liter melk, vooral wanneer ze gebruik maken van een automatische reinigingssysteem met warm water of wanneer ze snel uitbreiden en onvoldoende kunnen investeren in benodigde apparatuur. Het hoofdstuk sluit af met enkele adviezen voor beleidsmakers, zoals de noodzaak tot een inventarisatie van de houding en bereidheid van boeren om hun management of apparatuur aan te passen aan veranderingen in de tariefstructuur van elektriciteit.

De belangrijkste conclusies van het in dit proefschrift gepresenteerde onderzoek zijn:

- De productie van 1 kg vet en eiwit op een Iers melkveebedrijf vereist 31.73 MJ energie, waarvan 20% direct gebruikt wordt op het bedrijf en 80% gebruikt wordt voor het produceren en transporteren van aangekochte grondstoffen. Het energieverbruik voor de verwerking en de consumptie van melk, nadat deze het bedrijf heeft verlaten, is hierin niet meegenomen. Het elektriciteitsverbruik op het melkveebedrijf bedraagt ongeveer 12% van het energieverbruik van de totale, onderzochte melkketen.
- Het in dit onderzoek ontwikkelde, mechanistisch model blijkt een acceptabele schatting (relatieve schattingsfout<10%) te geven van het effect van management- en investeringsmaatregelen op het elektriciteitsverbruik op een melkveebedrijf. Dit model simuleert het elektriciteitsverbruik van apparatuur op een melkveebedrijf dat nodig is

voor het koelen van melk, het opwarmen van reinigingswater, de melkmachines, de verlichting, het oppompen van water, en de huisvestingsfaciliteiten voor melkkoeien.

- Het energieverbruik tijdens het koelen van melk kan met 34% worden teruggebracht door gebruik van een regelsysteem dat het grondwaterdebiet in een platenwarmtewisselaar tijdens het voorkoelen van melk optimaliseert.
- Eerder of later melken dan gemiddeld kan het elektriciteitsverbruik op een melkveebedrijf met 5% tot 7% terugdringen, afhankelijk van de bedrijfsgrootte.
- De elektriciteitskosten bleken het laagst bij het dag- en nacht tarief en het hoogst bij het vaste tarief (i.e. 16%-35% hoger, afhankelijk van de gebruiksgrootte).
- Een variabele tarief resulteerde in een stijging van de elektriciteitskosten (t.o.v. vast tarief) van 3% tot 18%, afhankelijk van de bedrijfsgrootte.
- Een melkkoelsysteem met ijswater in combinatie met het voorkoelen van melk kan het elektriciteitsverbruik op een bedrijf met 195 melkkoeien tot 45% terugdringen. Het rendement op de investering is echter negatief (-1%).
- De combinatie van een melkkoelsysteem met directe verdamping, het voorkoelen van melk met grondwater tot 15°C, en het gebruik van standaard vacuümpompen verhoogt het bedrijfsinkomen, terwijl het elektriciteitsverbruik en de emissies van broeikasgassen worden verlaagd.

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About the author

John Upton was born in Cork, Ireland, and grew up on his parent's dairy farm. After completing secondary school in CBS Midleton (2003) he studied Mechanical Engineering in Cork Institute of Technology where he completed his final year thesis 'Heating System Performance' in 2007. After obtaining his bachelor of engineering from Cork Institute of Technology he went to work for Glen Dimplex Group Purchasing where he provided technical support and modelling expertise for various cost reduction projects. He started work in the Animal and Grassland research and Innovation centre in Teagasc Moorepark in 2008 where he began working as a researcher on the Interreg NWE funded project Dairyman, which focused on resource use efficiency of dairy farms. John contributed to this project by carrying out benchmarking energy audits, renewable energy experiments and energy efficiency trial work. He also published a number of conference papers and popular articles. John sought the supervision of experts in the field of resource use efficiency and technology assessment in order to progress his own PhD research project which led him to contact Wageningen University. He enrolled as a part time PhD student with the Animal Production Systems Group in 2011 and wrote his PhD research proposal focussing on electricity reduction on dairy farms. He completed his PhD thesis in May 2014 and is looking forward to continue working in the research area of dairy farm efficiency. Johns other research interests include smart networks, demand side management in agriculture, water consumption on dairy farms, developing guidelines for best practice in dairy production, automatic milking systems and milking machine performance. John also operates and maintains the Teagasc energy research laboratory and national milking machine test equipment calibration laboratory.

Publications

Refereed scientific publications

- Upton, J., J. Humphreys, P. W. G. Groot Koerkamp, P. French, P. Dillon, and I. J. M. D. Boer. 2013. Energy demand on dairy farms in Ireland. Journal of Dairy Science 96(10):6489-6498. (Chapter 2)
- Upton, J., M. Murphy, L. Shalloo, P. W. G. Groot Koerkamp and I. J. M. D. Boer. 2014. A mechanistic model for electricity consumption on dairy farms: Definition, validation and demonstration. Journal of Dairy Science 97(8):4973-4984. (Chapter 3)
- Murphy, M.D., J. Upton and M. J. O'Mahony, Rapid milk cooling control with varying water and energy consumption. (2013). Biosystems Eng. 116(1): 15-22. (Chapter 4)
- Upton, J., M. Murphy, L. Shalloo, P. W. G. Groot Koerkamp, and I. J. M. De Boer. 2014. Assessing the Impact of Electricity Price Structure Changes on Dairy Farm Energy Costs. Submitted to Applied Energy. (Chapter 5)
- Upton, J., M. Murphy, P. W. G. Groot Koerkamp, I. J. M. D. Boer, L. Shalloo. 2014. Investment Appraisal of Technology Innovations on Dairy Farm Electricity Consumption. Submitted to Journal of Dairy Science. (Chapter 6)
- Murphy, M. D., M. J. O'Mahony, L. Shalloo, P. French, and J. Upton. 2014. Comparison of modelling techniques for milk-production forecasting. Journal of dairy science 97(6):3352-3363.

Articles in conference proceedings

- Upton, J., M. Murphy, P. French, and P. Dillon. 2010. Energy Use on Dairy Farms. Teagasc National Dairy Conference. Teagasc, Mullingar, Ireland.
- Upton, J., M. Murphy, M.J. O'Mahony and P. French. 2010. Suitability of air-source heat pumps for water heating on Irish dairy farms. Agricultural Research Forum. Teagasc, Tullamore, Ireland.
- Upton, J., M. Murphy and P. French. 2011. Lessons Learned from Teagasc Energy Audits. Proceedings of the Teagasc National Dairy Conference. Teagasc, Cork, Ireland.
- Murphy, M., M.J. O'Mahony and J. Upton. 2012. A load shifting controller for cold thermal energy storage systems. IEEE International Conference on Green Technologies (ICGT12). Trivandrum, India.

- Boland, A., P. Murphy, J. Upton, E. Mihailescu, M. Yang and J. Humphreys. 2010. DAIRYMAN: a collaborative project to improve resource utilisation on dairy farms in northwest Europe. Agri-Environment conference. Teagasc, Tipperary, Ireland.
- Upton J., G. O'Riordan, B. O'Brien and S. Fitzgerald. 2012. Energy consumption of an automatic milking system. Agricultural Research Forum. Teagasc, Tullamore, Ireland.
- Murphy, M., M.J. O'Mahony, J. Willemse and J. Upton. 2012. Increasing the efficiency of cold thermal storage systems using predictive modelling and control. Proceedings of the International Conference on Clean Energy (ICCE 12). Quebec, Canada.
- Murphy, M., M.J. O'Mahony, P. French and J. Upton. 2012. Heat recovery in a milk refrigeration system with variable fan speed control. Agricultural Research Forum. Teagasc, Tullamore, Ireland.
- Murphy, M., M.J. O'Mahony, P. French and J. Upton. 2012. A dynamic artificial neural network for the prediction of milk yields from dairy cattle. International Proceedings of Chemical, Biological and Environmental Engineering IPCBEE vol.47. Bangkok, Thailand.
- Murphy, M., M.J. O'Mahony and J. Upton. 2013. A control system with disturbance rejection for variable flow milk cooling. Proceedings of the 30th International Manufacturing Conference. University College Dublin, Dublin, Ireland.
- Upton J. and B. O'Brien. 2013. Alanysis of energy consumption in robotic milking. European precision livestock farming conference. Leuven, Belgium.
- Murphy, E., T. Curran, J. Humphreys and J. Upton. 2014. Direct water use of Irish dairy farms. Agricultural Research Forum. Teagasc, Tullamore, Ireland.
- Upton, J., J. Humphreys, P. W. G. Groot Koerkamp, P. French, P. Dillon, and I. J. M. D. Boer. 2013. Life cycle assessment of energy use on Irish dairy farms. 2014. Agricultural Research Forum. Teagasc, Tullamore, Ireland.
- Upton, J., M. Murphy, L. Shalloo, P. W. G. Groot Koerkamp, and I. J. M. De Boer. 2014. Effect of electricity tariffs and cooling technologies on dairy farm electricity consumption, related costs and greenhouse gas emissions. Proceedings of AgEng 2014. Zurich, Switzerland.
- Upton, J., M. Murphy, L. Shalloo, P. W. G. Groot Koerkamp, and I. J. M. De Boer. 2014. Strategies to reduce electricity consumption on dairy farms. Proceedings of the ASABE annual meeting. Montreal, Canada.

Popular publications:

- Upton J. and M. Murphy. 2010. Meeting your Hot Water Demand. Teagasc TResearch 5(3): 26-27

- Boland, A., P. Murphy, J. Upton, E. Mihailescu, M. Yang and J. Humphreys. 2010. DAIRYMAN-bringing together the best in knowledge and innovation. Today's Farm 21 (4) 16-17
- Upton J. 2013. Energy demand in dairy. Teagasc TResearch 8(3): 12-14

Education certificate

Completed Training and Supervision Plan

Description	Year	ECTS*
The Basic Package		
WIAS Introduction Course	2012	1.5
Course on philosophy and ethics of science	2013	1.5
International conferences		
ASABE Annual International Meeting, Montreal, Canada	2014	1.1
European Conference on Precision Livestock Farming , Leuven, Belgium	2013	0.9
EurAgEng, Zurich, Switzerland	2014	1.4
Presentations		
Dairy energy efficiency, Teagasc Dairy Conference, Mullingar, Ireland	2010	1.0
Lessons learned from Teagasc energy audits, Teagasc Dairy Conference, Cork, Ireland	2011	1.0
Suitability of air source heat pumps for dairy water heating, ARF Tullamore, Ireland	2011	1.0
The performance of plate heat exchangers in milk cooling, ARF, Tullamore, Ireland	2011	1.0
Energy consumption of an automatic milking system, ARF, Tullamore, Ireland	2012	1.0
Heat recovery in a milk refrigeration system, ARF, Tullamore, Ireland	2012	1.0
Life cycle assessment of energy use on Irish dairy farms, ARF, Tullamore, Ireland	2014	1.0
In-Depth Studies		
Advanced LCA course Aalborg University	2012	3.0
Design of Experiments and data analysis. UCC statistical consultancy unit	2008	3.0
Professional Skills Support Courses		
Project and time management	2012	0.3
MatLAB fundamentals	2012	0.9
Labview basics 1	2009	0.6
Labview basics 2	2009	0.9
Scientific report writing,	2011	0.3
Research Skills Training		
Preparing own PhD research proposal	2011	6.0
Didactic Skills Training		
12 hours lecturing BAgSc Dairy Business students in UCD on dairy facilities	2012	0.4
12 hours lecturing BAgSc Dairy Business students in UCD on dairy facilities	2013	0.4
Supervising theses		
B. Eng. Thesis plate heat exchanger analysis for dairy applications	2010	1.0
B. Eng. Thesis variable speed vacuum pump control	2010	1.0
B. Eng. Thesis investigating the viability of solar water heating on dairy farms	2011	1.0
B. Eng. Thesis energy consumption of a robotic milking system	2012	1.0
Membership of boards and committees		
Board member of IMQCS (Irish milk quality co-operative society)	2014	0.9
Total		**34.0**

* one ECTS credit equals a study load of approximately 28 hours

With the activities listed the PhD candidate has completed the educational requirements set by the Graduate School of Wageningen Institute of Animal Science (WIAS).

Colophon

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