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Comparison of control systems for the optimisation of ice storage in a dynamic real time electricity pricing environment

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HIGHLIGHTS

- A cold thermal energy storage system model was created and validated.
- Pseudo real time electricity pricing was derived to represent the smart grid.
- A demand side management optimisation algorithm was developed.
- Demand side management algorithm performance was compared to a standard controller.
- Overall the demand side management algorithm produced modest cost savings.

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ABSTRACT

The objective of this study was to assess the benefits of introducing a demand side management optimisation controller to a cold thermal storage ice bank. This controller consisted of an ice bank model, an air temperature forecast model and an optimisation algorithm. The financial and grid utilisation benefits produced by implementation of this controller over the current state of the art in ice bank load shifting control was tested in a day ahead real time electricity pricing forecast environment. This hypothetical real time electricity price was based on the cost of electricity in the Irish wholesale market. Multiple ice bank charge levels were simulated in order to quantify the performance of two control methods for varying operating conditions. First, the "standard controller" was based on the current modus operandi for ice bank systems where ice was generated for food cooling at night when the off-peak electricity tariff is available (00:00–08:00 h). Second, the "upgraded controller" was developed as a bespoke Demand Side Management control system for food refrigeration in a future electricity pricing environment. It consisted of a dual function load shifting optimisation algorithm, an ice bank model, and a predictive air temperature model. A preliminary study was also carried out to test the robustness of the controller's performance in an uncertain real time electricity pricing forecast scenario. Both economic and grid management benefits were found by simulating the operation of the cold thermal storage load shifting controller in a forecasted day ahead real time electricity pricing environment. The energy savings achieved for 100% ice bank charge were low, but as the desired charge level was reduced to 75%, 50% and 25% the savings potential increased. The introduction of uncertain real time electricity pricing forecasts nullified any cost savings made by the load-shifting controller in comparison to the current state of the art.

1. Introduction

Increased penetration of intermittent power sources such as wind, solar and bioenergy are posing an immediate problem for national grid management. Time Of Use (TOU) and real time pricing (RTP) tariffs have long been proposed as a method of reducing the peak to average grid load ratio (PAR) and optimising consumer power consumption [1–3]. While the proliferation of plug-in electric vehicles and smart energy storage systems will create opportunities to capitalise on potentially cheap electricity prices during certain periods, it may also become problematic for residential load control management [4]. To facilitate the ever increasing use of renewable energy in the national grid and the adoption of intelligent Demand Side Management (DSM) techniques, new control practices for a smart grid have been explored

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Nomenclature

Abbreviations

ANN	artificial neural network
ATM	air temperature model
COP	coefficient of performance
CTES	cold thermal energy storage
DSM	Demand Side Management
ECMWF	European Centre for Medium Range Weather Forecasts
IB	Ice Bank
IBM	Ice Bank Model
MAPE	mean absolute percentage error
NARX	non-linear auto-regressive with exogenous input
PAR	peak to average ratio
RMSE	Root mean square error
RNN	Recurrent Neural Network
RTP	real time pricing
SC	step combinations
TDL	tapped delay line
TOU	Time Of Use
UGLCF	upgraded grid utilisation cost function
UMCF	upgraded monetary cost function

Symbols

a	Fourier coefficient
B	Fourier coefficient
C_p	chiller power (kW)
$ﬁf_w$	enthalpy of fusion for water
K	degrees kelvin
kW h	kilowatt hour
MW	megawatt
T	period (s)
T_c	evaporator temperature (K)
T_h	condenser temperature (K)
U	uniform distribution
α	Perturbed Fourier coefficient
β	Perturbed Fourier coefficient
ç	ice charge (%)
Ƥ	perturbed period (s)
η	True COP factor
ρ_i	density of ice (kg/m^3)
V	ice volume (m^3)
°C	degrees celsius
€	Euro

[5–7]. The introduction of RTP may yield lower operational costs for domestic and commercial electricity consumers depending on the variability of the electricity price, onsite specific characteristics [8] and dwelling type [9]. There may also be environmental and grid management benefits associated with reducing demand on conventional power generation via thermal load shifting [10].

While previous studies have focused on developing control and optimisation techniques for consumers in a hypothetical smart grid network with advanced electricity metering infrastructures and integrated communication methods [5,11,12], this study focuses on assessing the benefits of applying a bespoke optimal load shifting control method to a specific appliance in comparison to the current state of the art. The RTP structure used in this study was a best guess leveraging on existing data and future operating projections [13]. It was not assumed that advanced two-way communication between the utility provider and the consumer was available. This arrangement was deemed to be the most realistic possible manifestation of a "smart grid" in an Irish scenario within the next decade.

In this study we employed two methods of controlling an Ice Bank (IB) cold thermal energy storage (CTES) system as a load shifting mechanism in a light commercial cooling plant. In Ireland CTES is commonly used in food processing, alcohol brewing and air conditioning systems. The CTES system used in this study was an Ice Bank (IB) for the refrigeration of raw food which was being produced on-site on a daily basis.

To investigate the potential of applying DSM techniques to the operation of the food refrigeration IB system, two different controller methods were tested in this study: The "standard controller" and the "upgraded controller".

First, the standard controller was based on the current modus operandi for food cooling IB systems: Ice for food cooling is generated at night when the off-peak electricity tariff (night rate) is available. The window of the off-peak electricity tariff (summer period: 12:00–8: 00 h) occurs during the valley of the daily electricity demand profile and when the ambient air temperature is low. The current control method used in commercial IB systems is an on/off timer set to the off-peak electricity tariff schedule. Once the off-peak period begins the IB is turned on and will not shut off until the desired charge is met. This load shifting strategy is well suited to the current two-tier TOU tariff structure in Ireland (night rate).

Second, the upgraded controller was developed as a bespoke DSM control system for food refrigeration in a RTP environment. It consisted of a dual function load shifting optimisation algorithm, an IB model, and a predictive air temperature model (ATM). The purpose of the upgraded controller was to actively shift the ice generation load to the periods of lowest electricity cost.

Both the standard and upgraded controllers were tested in a day ahead RTP forecast environment where the RTP is declared by the Utility provider a day in advance. The RTP structure used was a pseudo RTP based on the current wholesale cost of electricity in Ireland. The economic and grid utilisation performance of both controllers were tested in this scenario for four difference ice charge levels (25%, 50%, 75%, and 100%). A preliminary investigation was also carried out in which the upgraded controller was tested in an uncertain RTP forecast environment. In this scenario the RTP was declared by the Utility provider a day in advance, however this forecast was uncertain. The perturbation in forecasted RTP was designed to simulate stochastic or difficult to accurately predict events which determine the short-term cost of electricity (e.g. wind energy production or weather events).

The aims of this study were firstly; to investigate both the economic and grid utilisation benefits produced by replacing the standard controller with the upgraded controller for a food refrigeration system with CTES in a day ahead RTP environment and secondly; to test the robustness of the upgraded controller's performance in an uncertain RTP forecast environment.

2. Materials and methods

2.1. Ice bank model

The CTES system used in this study was external melt ice on coil thermal storage unit (Fig. 1). It consisted of a stainless steel water storage tank (1), an inline copper coil array evaporator (2), a scroll compressor (3), A thermostatic expansion valve (4), a finned tube air cooled condenser (5) and an external air fan (6). The water