Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Modelling and developing a renewable energy system for the cold stores of a food park in the UK

To cite this article: Xiaojun Li *et al* 2019 *J. Phys.: Conf. Ser.* **1343** 012102

Modelling and developing a renewable energy system for the cold stores of a food park in the UK

Xiaojun Li, Phillip Jones and Joanne Patterson

Welsh School of Architecture, Cardiff University, Bute Building, King Edward VII Avenue, Cardiff CF10 3NB, United Kingdom

Junglix@cardiff.ac.uk

Abstract. An on-site renewable energy system is developed and presented in this paper to supply electricity usage of potato cold stores in a UK food park. The system is designed to use the mass of the potatoes to store surplus power from PV when there are days of high solar radiation. It can also be charged from the grid during off-peak time when there are longer periods of overcast conditions. The paper presents results to show energy generated by the PV that can be used in the cooling system, and the storage potential of the potatoes in offsetting grid supply. The dynamic thermal model HTB2 with an energy system extension is employed to design the energy system. The base case representing the existing scenario is validated with previous weekly metering data. The system performance is examined in terms of annual energy performance and long-term cost-effectiveness. The simulation results indicate, 1) the cold store with potato storage is able to maintain the required temperature ranges for most periods when cooling is only powered by electricity from PV during peak-time, and it contributes to energy cost savings and electricity import reduction, but almost no cooling reduction; 2) the system combination of solar PV and off-peak cooling can be paid back within its lifespan, with the most optimal case taking only 11 years. The outcome of the research demonstrates the benefits of the optimized renewable energy system, which provides free or cheap energy supply, reduces industry-related CO2 emission, and contributes to overall energy cost savings. This technique might be applied to other type of food storage, where the thermal mass can contribute to thermal storage.

1. Introduction

UK's industry sector accounts for some 17% of UK's final consumption in 2016 [1]. The rise of renewables in the past decades provides the potential for reducing energy use and CO2 emissions in UK industry. A suitable application of renewable energy is in the operation of cold stores, that provide long-term and short-term food storage for most food parks. It is a common and essential energy intensive building type, and can potentially utilize the thermal mass effect of food as thermal storage, that can be charged when there is solar radiation available and, provided the building is suitably insulated, can maintain low temperatures during periods of no solar radiation. An on-site renewable energy system is developed and presented in this paper to supply electricity usage of potato cold stores in a UK food park. The system is designed to use the mass of the potatoes to store surplus power from PV when there are days of high solar radiation. It can also be charged from the grid during off-peak time when there are longer periods of overcast conditions. The paper will examine how energy generated by the PV can be used in the cooling system, the storage potential of the potatoes in offsetting grid supply, and the economic feasibility of the system for the long term.

2. Method

The research is planned in the following four steps: site survey and metering data analysis, base case modelling and calibration, system design, annual performance prediction and long-term economic analysis.

2.1. Site survey and metering data

Information and data are collected through site visits, and provided by the industry partner, who has been sub-metering energy of individual cold stores, and recording potato box movements for years. The reading and analyzing of these data can assist understanding of the existing operating and energy patterns in the cold stores, identifying potentials for performance optimization, and preparing for building energy model at the next step. The following information and data are collected for this study: dimensions and fabric constructions of the buildings, monthly operating profile of the cold stores, weekly box moving in and out, weekly electricity usage, and weekly cooling temperature setpoints if available.

2.2. Base case modelling and validation

The existing building performance was modelled and compared with metering weekly data for calibration purpose, and to produce an hourly base for integrating with the renewable energy system. As operating behaviour of the cold stores is unpredictable, a seasonal average scenario was developed based on the seasonal operating profile of the cold stores, seasonal box moving in and out and seasonal cooling temperature setpoints. Cooling was set for the cold store based on the recommended operating profile and seasonal cooling setpoints. Infiltration was assumed using the recommended infiltration rate for cold store in CIBSE Guide A [2]. Ventilation was estimated based on frequency of box movements, and the time required per opening is adjusted through modelling calibration to account for the associated ventilation heat losses. Two types of internal heat gains are considered, such as the constant heat gains and the intermittent heat gains. The constant heat gains include heat evolved in storage (450kcal/ton/day for 5C potato) and heat of respiration (assuming a respiration rate of 10W/ton) [3]. They can vary according to the temperature of potato [4]. The intermittent heat gains include heat from equipment such as lighting and other equipment if applicable, and heat gains from occupants in the cold store, which are very small, so can be ignored. The early model underwent a series of calibrations as more and more information being gathered and checked, and results of the calibrated model were compared with the metering data.

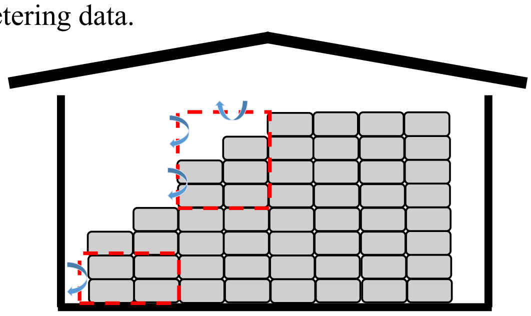

Figure 1. Virtual spaces in the cold store model

Figure 2. Layout of the potato food park

The dynamic model HTB2 [5] was employed in the thermal simulation, combined with VirVil SketchUp [6], an urban scale modelling tool to consider overshadowing impact from the neighborhood, and to identify surfaces with most solar potentials for PV installation. HTB2 is typical of the more advanced numerical models, using as input data, hourly climate for the location, building materials and constructions, spatial attributes, system and occupancy profiles, to calculate the energy required to maintain specified internal thermal conditions. The main challenge for this research is the modelling of the potato movements. The specific thermal properties of potato, such as high density and high specific heat capacity, make it a good thermal mass material, possessing an ability of store cold or heat. The moving-in of boxes brings in heat gains from potatoes being moved in with a temperature higher than that indoors, and increases the capacity of thermal mass from potato storage, while the moving-out of potato contributes to a reduction of thermal mass. In order to simulate the incidental gains and changing of thermal mass from the movements, the HTB2 model employs a series of virtual spaces as shown in Figure 1, each one of which accommodates a groups of potato mass to be moved in or out. They can be scheduled individually to be cooled through ventilation between the virtual spaces and the cold store. When there are boxes moving in, ventilation of the relevant virtual spaces would be enabled; while when boxes being moved out, ventilation of the associated virtual spaces having been enabled, would be disabled.

2.3. System design
The development of the renewable energy system aims to maximize on-site renewable energy generation, reduce dependency on grid import at peak time and save costs for electricity usage. A solar analysis was carried out in VirVil Sketchup to identify and locate PV on roof areas with the most solar potential. The PV area was then calculated considering dimensions of the selected roofs and PV module to achieve maximum electricity production. Bolt on PV is employed considering its cheap price and good performance. The system is designed with electricity generated by PV supplying simultaneous cooling electricity usage, and the surplus electricity will be exported to the grid. The calibrated model from the last step was employed to optimize the system working pattern with the grid supply, such as comparing the scenario of using grid-powered cooling when needed with that of using grid-powered cooling only at the off-peak time, such as evening and weekend. On the second scenario, the indoor set-point will be checked and adjusted if needed to ensure indoor temperature won't go beyond the criteria set for potato storage when cooling is off.

2.4. Annual performance prediction and a long-term economic analysis
The modelling of the renewable system has been carried out using the integrated model of Energy Demand, Supply and Storage (EDSS). The EDSS model is an extension of HTB2, serving as a post-processer of HTB2 outputs. The model mainly deals with domestic service systems, such as the integration of energy demand of electricity, space heating and hot water, with renewable energy supply from solar PV, solar thermal and Heat pump, assisted by battery storage and thermal storage. The Model has been used in previous domestic projects [7], proving to be flexible and reliable. Based on the EDSS model, building performance is examined further in terms of annual energy bill, annual income from renewables and annual CO2 emission.

The Return On Investment (ROI) method is employed in the long-term economic analysis of the renewable energy system. The ROI measures the amount of return on a particular investment, relative to the investment's cost, as shown in the Equation (1). The ROI varies with the increasing of gain or loss from the investment and if applicable the adding of extra investments over time. The cost of investment in this case study is the investment on the renewable energy system, while the gain from investment includes saving from energy bills and income from renewables, such as the selling of electricity to the grid. Additional expenses for maintaining, also including replacement costs for components with lifespans shorter than the designed system lifespan, are also considered. The designed system lifespan is assumed to be 30 years for this case study. The degradation of component performance over time has also been considered, such as an annual degradation rate of 0.7% for PV capacity [8], and a degradation rate of 10-24% for chillers COP for every 10 year [9]. Besides, a standard UK discount rate of 3.5% [10] is used to calculate the present value of future cash flows, therefore enable a comparison of investments and benefits in the long term. The year when the total gain from investment is equal to the total cost of investment is the payback time.

$$ROI = (\text{gain from investment} - \text{cost of investment}) / \text{cost of investment} \quad (1)$$

3. An analysis of the metering data
The food park where the cold stores sit is in west Wales, UK. The cold stores in the existing site are placed in the two big buildings on the north, as shown on the top right of Figure 2. Among them, the

bigger building holds 6 stores for potato storage, while the smaller one holds 2 for potato storage and 1 for seasonal vegetable and flower storage. They all operate on a seasonal basis on demand. Only the cold stores in the bigger building are considered in the study, as energy use of the smaller building has been metered as a whole. The bigger building was built in 2010s, and well insulated. Each cold store has an area of 460m^2, which can accommodate up to 1392 tons potatoes. The cold stores are cooled by chilled air supplied from the duct inlets close to the ceiling, and the chillers supplying the air have a COP of 2.12.

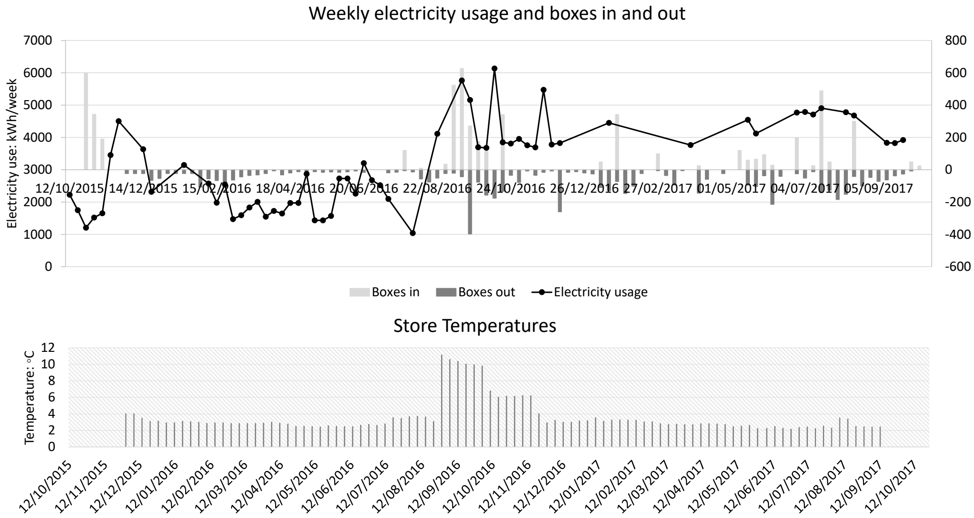

Figure 3. Weekly electricity usage, temperature set-points and potato boxes moving in and out.

The metering data of one of the cold stores are presented in Figure 3. The following patterns can be found: 1) the highest electricity usage of the cold store took place from late August to October, the main harvest season for potato; 2) electricity usage increases as potatoes being moved in or out; 3) on average, the activity of potato moving in produces more electricity increase compared with the activity of moving out; 4) for moving the same amount of potato boxes in or out in the same season, the more movements taken the more electricity usage; 5) electricity usage increases when cooling set-point reduces; 6) electricity usage maintains a constant value when there are quite fewer potato movements, along with no change of cooling set-point in winter time; 7) on average, the more potato in store the more electricity usage. The major factors impacting the electricity usage of the cold stores can be identified, including the movements of the potato boxes, indoor temperature set-point for cooling, building air tightness, outside temperature, and the amount of potatoes in store. The movements of the potato boxes not only contribute to heat gains and changing of thermal mass quantity, but also produce considerable ventilation heat losses through door opens, which explains the big variation of electricity usage for moving the same number of potato boxes in the same season. However, the amount of time per movement is not recorded, and it can vary greatly among the year, which adds difficulty in producing prediction close to the real scenario. The impact from ventilation heat losses has also been investigated and proved by other researchers [11]. The cooling temperature set-point is adjusted over time to provide an appropriate temperature environment for potato storage based on the general growth pattern of potato. Building air tightness can be checked on the base load model which is when there is no door open and close, and all ventilation losses are from infiltration. Since the more potatoes in store the more heat gains produced by potato, the more electricity usage will be required for cooling. Besides, it should be noted, the rise of electricity usage in summer is coupled with higher solar radiation, as a result higher electricity generation by PV compared with those of the other seasons.

Only one of the cold stores which is in frequent use was modelled. To reduce the foreseeable performance gap between modelling and monitoring, the model was built and calibrated based on lessons learned from the metering data analysis. A comparison of metered and modelled electricity usage is presented in Figure 4. A close match has been achieved for most months, except February, June and

August, where performance gaps present. This could be due to an irregular long time per door open, and differences between the real weather data and the test reference year data used in the modelling.

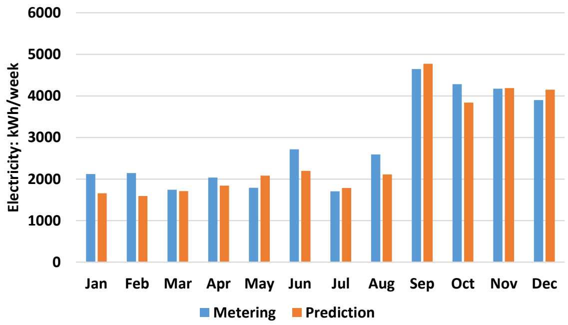

Figure 4. Average weekly electricity usage per month: metering vs prediction

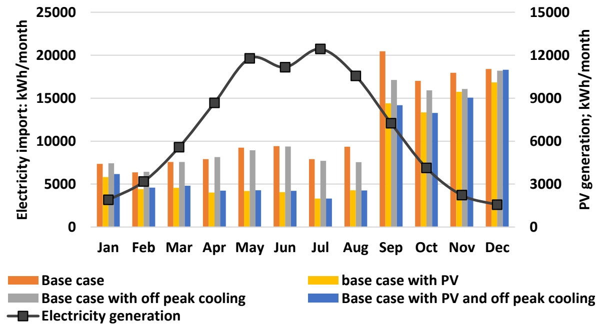

Figure 5. Predicted monthly electricity import from grid and electricity generation by PV.

4. Simulation results and discussion

In total four scenarios have been simulated, including a base case, base case with PV roof, base case with cooling only at off-peak time, such as evening and weekend, base case with PV roof and cooling at off-peak time. The base case represents the existing system scenario without any intervention. The employing of off-peak cooling only is mainly to reduce energy bill. A comparison of different scenarios in Figure 5 indicates: the solar PV system will greatly reduce electricity import, in particular from April to September, when the majority of annual yield from solar PV is produced; cooling the store only during off-peak time won't necessarily reduce the electricity import, implying a time delay of cooling through using the potato thermal mass, which means a bigger cooling capacity would be needed; electricity generation in summer is much more than demand. Besides, to achieve and maintain the required temperature range in both off-peak cooling scenarios with or without PV, the cooling set-points should be reduced properly, so the warming-up during the cooling-off period won't bring the temperature up beyond the limits. Also a more efficient ventilation system will be needed to boost the movements of chilled air around the potato boxes, to accelerate the cooling process. Above all, the combination of solar PV and off-peak cooling can greatly reduce electricity import and energy bill, without compromising the environmental temperature for potato storage.

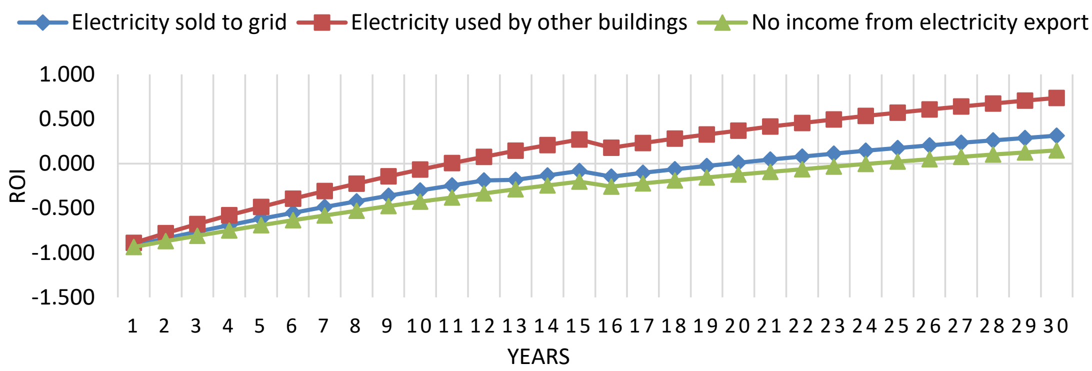

Figure 6. A comparison of the ROIs for different cases.

A ROI analysis was used to examine the affordability of the system. As discussed above, there would be surplus electricity generation in summer. In regards to this, a group of three options was investigated, such as case 1 surplus electricity sold to the supply company, case 2 surplus electricity supplied to the other buildings in the Food Park and case 3 electricity export without income. A comparison of their ROIs in Figure 6 indicates great impact on system payback time from the ways of dealing with surplus electricity, with case 2 being the best with a payback time of only 11 years, while case 3 being the worst with a payback time of 24 years, all within the designed system lifespan of 30 years.

5. Conclusion

This paper describes the development of an on-site renewable energy system for supplying electricity usage of potato cold stores in a UK food park. Analysis has been carried out based on a validated thermal and energy model, also taking into account potential financial scenarios. The results have shown, the system of solar PV combined with off-peak cooling for potato storage can greatly reduce electricity import and energy bill without compromising the environmental temperature for potato storage, and the system can be paid back within its lifespan, with the best case taking only 11 years. Above all, the outcome of the research has demonstrated the technical and economic feasibility of this optimized renewable energy system for potato storage, which provides free or cheap energy supply, reduces industry-related CO2 emission, and contributes to overall energy cost savings.

Areas of future research include: the combination of cold stores of different working profiles to increase whole site electricity self-sufficiency; vertical temperature measurements to ensure all boxes of potatoes are stored in the required temperature environment; reducing cooling demand by employing a smart door operating system through reducing ventilation heat losses from door opens.

Acknowledgments

This research is part of the SPECIFIC 2 Low Carbon Built Environment project at Cardiff University and was supported by Puffin Produce Ltd. SPECIFIC is part-funded by the European Regional Development Fund (ERDF) through the Welsh Government, and also by InnovateUK and the Engineering and Physical Sciences Research Council (EPSRC).

References

[1] DBEIS 2018 *Energy Consumption In The UK* (London: BEIS)
[2] CIBSE 2015 *GVA/15 CIBSE Guide A: Environmental Design 2015* (London: CIBSE)
[3] Sakare P 2014 Design of Cold Storage Structure For Thousand Tonne Potatoes *Int. J. Agriculture and Food Sci. Technol.* **5** 171-8
[4] Fennir M A, Landry J A and Raghavan G S V 2003 Respiration rate of potatoes (Solanum tuberosum L.) measured in a two-bin research scale storage facility, using heat and moisture balance and gas analysis techniques *Canadian Biosystems Engineering* **45** 4.1-9
[5] Lewis P T and Alexander D K 1990 HTB2: a flexible model for dynamic building simulation *Build Environ* **25** 7-16
[6] Jones P, Lannon S, Li X, Bassett T and Waldron D 2013 Intensive building energy simulation at early design stage *Proc. 13th Int. Conf. of Int. Building Performance Simulation Association* (Chambéry: IBPSA) pp 25-8
[7] Jones P, Li X, Perisoglou E and Patterson J 2017 Five energy retrofit houses in South Wales *Energy and Buildings* **154** 335-342
[8] Jordan D C, Smith R M, Osterwald C R, Gelak E and Kurtz S R 2010 *Proc. the 35th IEEE Photovoltaic Specialists Conf.* (Hawaii: IEEE)
[9] Waddicor D A, Fuentes E, Sisó L, Salom J, Favre B, Jiménez C and Azar M 2016 Climate change and building ageing impact on building energy performance and mitigation measures application: a case study in Turin, northern Italy *Building and Environment* **102** 13-25
[10] HM Treasury 2018 *The Green Book: Central government guidance on appraisal and evaluation* (London: HM Treasury)
[11] Tian S, Gao Y, Shao S, Xu H and Tian C 2018 Measuring the transient airflow rates of the infiltration through the doorway of the cold store by using a local air velocity linear fitting method *Applied Energy* **227** 480-7
Tian S, Gao Y, Shao S, Xu H and Tian C 2017 An experimental investigation of the single-sided infiltration through doorways of the cold store *Int. J. Refrigeration* **73** 175-182