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Research Paper

Energy and economic savings through a plant supervised management in large-scale commercial activities

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HIGHLIGHTS

- The energy savings achieved with the management of HVAC and lighting were estimated;
- The consumptions of seven supermarkets monitored for four years were analysed;
- A procedure to filter-out the influence of external temperature was proposed;
- The economic savings, the initial costs and the PBP were shown;
- The effectiveness of the management technique was assessed.

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ABSTRACT

In a commercial activity, the energy consumption is due to several nearly independent subsystems, which are potential targets for specific energy saving actions. One of the most promising technique consists in a supervised management of some of these subsystems. This approach leads to improve the energy utilization efficiency without invasive or costly interventions. To assess the potential of such technique, a preliminary analysis of the consumption components is needed. Since the energy consumption is strongly affected by several specific and highly variable parameters, the impact of the management cannot be estimated in a traditional way. Rather than formulating detailed and specific models, whose development is not always possible, a more simplified, yet accurate, approach can be followed. In this study, the yearly consumption of seven Italian supermarkets was analysed and divided into its main components to evaluate the potentiality of a grey-box approach to model the consumption of these commercial activities. With little modifications due to significant different systems layouts, not only the approach, but also the model parameters can be used to characterize several supermarkets. The consumptions before and after the supervised management implementation has been compared by calculating the savings achieved in each consumption component, and thus assessing the economic and energy potential of such techniques.

1. Introduction

The increasing concern for the impact of human activities, coupled with the global growth of energy consumption and a negative economic conjuncture in some countries, has strongly encouraged a more efficient energy usage [1,2]. This change of paradigm has affected all the productive sectors, the commercial one included.

Since the three main consumption shares in a supermarket are food refrigeration, lighting and HVAC, many solutions have been proposed to reduce their consumption. For what concerns the refrigeration, many CO_2 transcritical applications have been recently investigated. Beside using an environmental friendly refrigerant, these systems may also feature coefficients of performance higher than the traditional ones. This happens, for example, when the heat rejected in the gas cooler is recuperated to feed the HVAC system or for the hot water production. These systems traditionally perform better in cold climates, but may outperform the traditional systems also in warmer locations [3–6]. The integration between the refrigeration and HVAC systems is not bound to the use of CO_2, and such solution has been proposed also for traditional systems [7,8].

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Nomenclature

Symbols and acronyms

A_s	total retail sale area [m^2]
C_0	purchasing and installation costs [k€]
En	energy [kWh]
HVAC	heating, ventilation and air conditioning
I	global horizontal irradiance [W/m^2]
K	fixed share of consumption [kWh]
LT	low temperature refrigeration
NT	normal temperature refrigeration
N_{rec}	number of receipts [–]
PBP	payback period [year]
R^2	coefficient of determination [–]
RH_{ext}	external relative humidity [kWh]
RMSE	root mean square error [–]
RRMSE	relative root mean square error
T	temperature [°C]

Superscripts and subscripts

cr	cold room
ext	external (related to environment)
e	electric
k	*k*-th year among 2012, 2013 and 2014
light	lighting
nor	normalized (Eq. (1))
rd	refrigerated display
tot	annual total

Greeks

μ_{en}	energy data average value [kWh]
ρ_s	Spearman's correlation coefficient [–]
γ_{CO2}	CO_2 produced for each kWh_e [g_{CO2}/kWh_e]

The above-mentioned solutions may be very effective in terms of energy savings but require the replacement of the food refrigeration system and the modification of the HVAC one. Given that, these applications are likely to be successful for new buildings and are less suitable for the retrofit of the already existing retails.

Another effective, yet impactful and capital intensive, solution is the introduction of cogeneration and trigeneration, systems [9–15]. These solutions tend to show substantial implementation costs, hence long payback periods.

Conversely, automatic plant management techniques are gaining relevance [16–19]. These techniques, which were developed in the industrial and manufacturing sectors, allow a plant operation, which is always very close to its optimal conditions. These can be readily applied to the commercial sector, in which they have been used to manage the lighting and the HVAC systems [20,21].

The present study aims to assess the energy saving potential of the automatic management techniques in the commercial sector, focussing on the food retail sector. To achieve this purpose, a case study of seven supermarkets, in which a commercial automatic plant management system has been installed, has been thoroughly analysed.

To calculate the energy savings, the simplest approach is to compare two corresponding periods before and after the supervised management introduction. However, since the supermarket energy consumption is influenced by several external variables (such as the weather) it could be difficult to distinguish between the effect of the supervised monitoring and that of the different operative conditions. To overcome this, the consumption of the supermarket must be modelled, defining a reference consumption as a function of the parameters that characterize the supermarket. Two examples of supermarket consumption modelling techniques can be found in [22,23]. Since the reference consumption is necessarily calculated with an uncertainty, the savings must be estimated with the related error band. This uncertainty region may provide useful information to identify the minimum savings that can be measured, since savings equal or lower to the model uncertainty could be hard to guarantee. In other words, under a certain savings value, the effect of the implemented solutions is potentially overshadowed by that of external parameters.

The variables which could be theoretically considered to model the supermarket consumption are: the thermal performances of the envelope, the climate conditions, the customer attendance, as well as the technical features and the usage pattern of the HVAC, lighting and refrigeration systems. Given the availability of this data, highly detailed models can be formulated [24–28]. Nonetheless, it is not always possible to develop such models due to the scarcity of data itself [29]. In practice, it is very difficult to have access to detailed and extensive data on building envelope, or internal temperature and humidity. Moreover, highly detailed models are essentially tailored on the investigated facility, and the analysis becomes very specific losing its generality and reusability. Therefore, it is interesting to develop simplified, yet sufficiently accurate, models that may be used to forecast the supermarket consumption (and the different contributions of its main subsystems) in any given situation. Such simplified models can be generalized more easily than their detailed counterparts and thus they can be useful in those cases in which a proper data time-series is absent or limited, like the case of recently started commercial activities.

In conclusion, the contribution of this study is two-fold; on one hand, a simplified, but accurate, model of the supermarket consumption is developed. Such model is based on the data which is easy to retrieve (consumption and climatic variables), so it can be applied to any supermarket. On the other hand, once the reference consumption has been defined, it is used to assess the energy saving potential of a commercial supervised management technique, which controls the HVAC and lighting subsystems. Furthermore, a real-life case study is analysed, and the profitability of the management system evaluated. This provides data about the achieved economic savings, the implementation costs and the related payback period.

2. Case study description

2.1. Supermarket consumption data

To define the reference consumption needed to calculate the energy savings achieved with the supervised management implementation, the supermarket energy consumption must be modelled. To build and validate a model, the consumption data of seven Italian supermarkets, located in the Tuscany costal area (central Italy) is used.

The supermarkets are different in size, envelope and equipment age and technical features. Despite this, some common consumption patterns and useful information can be deduced from their comparison. In Table 1, some key features of these supermarkets are presented. These are: the size of the sale area, the number of total annual working hours, the total annual electric consumption, as well as the volume of the cold storage and the length of the refrigerated displays. In the analysis, all these parameters, except for the energy consumption, are assumed to be constant, since no major modification affected the retail layouts in the reference period. Further details about the supermarket HVAC system configurations are reported in Table A.1 in Appendix A.

It is worth noting that the consumptions reported in Table 1 are consistent to those reported in [30,31]. The first of these two references provide also an analytical expression of the annual consumption as a

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