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Electricity consumption of medical plug loads in hospital laboratories: Identification, evaluation, prediction and verification

Nils Christiansen[a,*], Martin Kaltschmitt[a], Frank Dzukowski[b], Friedrich Isensee[b]

[a] *Hamburg University of Technology (TUHH), Germany*
[b] *Klinik Facility-Management Eppendorf GmbH (KFE), Germany*

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ABSTRACT

Evaluating the energy demand of heating, ventilation and air conditioning (HVAC) as well as lighting equipment through standardized calculation methods has become a self-evident measure for planning and optimizing non-residential buildings in recent years. For the case of hospitals however, information about the magnitude of electricity consumption caused by the vast amounts of medical equipment is still lacking. Not least due to the strongly growing use of such electrically operated devices in an increasingly complex environment, electricity has become the major energy cost driver in modern hospitals. Against this background this paper presents a model approach based on over 33,500 h of measurements within a modern University Medical Center of Hamburg/Germany to assess the time-dependent course as well as the weekly sum of the demand for electrical energy due to medical laboratory plug loads. This assessment method allows for approximating the electricity demand of the installed equipment as a supplement to the established prediction methods for the electricity demand of HVAC, lighting, etc. It was found that only a few plug load groups contribute the greater part of the total electrical energy demand. Cumulative load predictions for a full building were possible with an error of less than 6%.

1. Introduction

The building sector within the European Union is responsible for about 40% of the region's total energy consumption [1,2]. With an estimated 38% this figure is very similar for Germany and can be split up between residential and non-residential buildings with fractions of two thirds and one third, respectively [3]. This share includes heating, cooling, domestic hot water provision and lighting. Additional types of energy consumption, for example through equipment like computers, kitchen appliances and other miscellaneous electrical devices, are not included in these statistics. While the latter groups have been estimated to contribute significant shares to the total energy consumption in non-residential (office) buildings of around 30% [4], the impact of medical equipment plug loads[1] in health care buildings remains widely undisclosed, exposing planning and layout as well as optimization efforts to high levels of uncertainty.

In 2012 the gross total expenses for German hospitals amounted to around 87 billion €, out of which 33.5 billion € were owed to material costs. Water and energy accounted for 6.6% of those expenditures, leading to a total of 2.2 billion € [5]. The increasing economic pressure within the German health sector has led to a widened focus on issues going significantly beyond purely medical subjects [6]. Along with the ubiquitous efforts to reduce Greenhouse Gas (GHG) emissions and consequently demonstrate "green" behavior, the rational use of energy and especially electricity has thus become a notable concern for hospitals in general.

To understand the patterns of hospital energy consumption for the subsequent identification of cost effectiveness measures, standards like DIN V 18599 are applied to quantify the shares of heating, domestic hot water, cooling, ventilation and lighting energy among the total building energy consumption [7]. Within these standards the internal heat loads caused by technical tools operated with electrical energy are approximated generically for each zone within a hospital. Additionally, a large spread of values (6, 18 and 63 W/m^2 for a low, medium and high scenario, respectively) is suggested as a reference for laboratories in general. The high degree of individuality between different hospital zones as well as the small number of scientific investigations on this matter raises questions about the usefulness of such rough approximations.

* Corresponding author.
E-mail address: nils.christiansen@tuhh.de (N. Christiansen).

[1] The term "medical equipment plug loads" in this paper describes electrical appliances in hospitals, mostly covered by the German "Medizinproduktegesetz". This electrical equipment can be connected to regular 220/230 V wall sockets.

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Against this background the overall goal of this paper is to present a methodological approach for a more accurate assessment of the electrical energy demand of medical equipment operated within modern hospitals/hospital laboratories. Therefore comprehensive measurements within the University Medical Center of Hamburg/Germany have been carried out. This hospital under investigation is equipped with over 10,000 medical devices for laboratory applications, encompassing close to 3700 different models. Almost half of those devices can be found in the two main research laboratories. Based on measurements the magnitude of their electrical energy consumption over time is evaluated and the most relevant plug loads are identified. This more detailed understanding of important drivers and factors allows for a transferable statement with regard to the plug load energy consumption in other hospital laboratories and thus complements existing energy demand calculation approaches.

2. State of knowledge

Assessing and predicting usage-dependent energy consumption of electrical equipment in buildings has been performed in a variety of ways especially in the field of lighting. Yun and Kim [8] used a theoretical approach that first models a mock-up room to compare measured and simulated natural illuminance levels. The artificial lighting energy demand is then calculated by providing a fixed occupancy schedule and setting a target minimum illuminance level to be satisfied by the installed LED lighting system. Stokes et al. [9] modeled the energy consumption of domestic lighting for UK residential buildings. Averaged half-hourly end-use demands of a one year sample were employed to extract daily trends under the influence of seasonality and to generate forecasts of daily consumption patterns with high correlations to measured values. Similar results were obtained by Richardson et al. [10] using a high-resolution building occupancy model in connection with global irradiance data to predict lighting demands of individual as well as groups of dwellings.

Despite the similarity with plug load energy assessment regarding the need for usage time forecasts, evaluations of lighting energy show three major distinctions. Firstly, there is a significant dependence on an independent exterior factor (natural illuminance); secondly, the power ratings are usually easily accessible for a vast number of lighting technologies and in the third place, automated controls, which allow for limiting the influence of user behavior and optimizing reactions, e.g. to natural illuminance, are usually not applicable to technical tools. In the case of plug loads, the variety of appliance types is far greater and use patterns more often than not differ from each other. Consequently, investigations of small scale power equipment generally require a definition of appliance groups that can be assumed to display similarities in load profiles over time as well as in absolute power ratings.

Menezes et al. [11] compared two different models to describe the power consumption of four distinct appliance categories typical for office buildings: computers, screens, printers/copiers and catering equipment. The first model relies on monitored data obtained from sample measurements over a three months period. The second one employs benchmark values for power demand and four generic, representative user profiles. Either approach produced similarly useful predictions of the actual demand, underlining the applicability of measurement-based cumulative prediction methodologies similar to the one being performed in this work. Considerable error margins however need to be taken into account. The prediction of hourly demand for 12 different electrical consumers in a household measured by Jung and Savvides [12] yielded errors between 1% and 27%. Naturally, more accurate values with errors of only 4–6% were achieved for cooling equipment (refrigerators).

Research with a direct focus on electrical equipment in the hospital sector is still scarce and although its increasing importance is widely acknowledged [13,14], very few extensive studies can be found in the literature. Jensen and Petersen [15] presented some power consumption figures for selected electrical hospital equipment, partly based on information from manufacturers, but concluded that the energy related information available generally lacked detail. The same held true for interviews with medical staff, in which several questions regarding equipment operation (e.g. if and how often it can be switched on or off) details remained unanswered.

Electrical load estimations specifically aimed at medical equipment in hospitals have been conducted by Black et al. [16], using an approach that incorporates inventories for device selection, spot measurements (during maintenance, not in actual use) for load assessment and expert interviews to estimate the share of devices in use and their annual run time. Their methodology aims to account for the fact that “there are no meaningful bottom-up estimates that aggregated measured, or estimated, energy consumption of individual devices”. But even top-down approaches are rare, not least due to the typically high aggregation level of hospital electricity consumption data available, which in most cases does not allow for a distinction between e.g. HVAC, office equipment and medical appliances [17].

One investigation directly addressing the energy consumption of laboratory equipment performed by Hosni et al. [18] assessed cooling loads in hospitals. Here 28 devices out of 15 categories were measured for at least 30 min at 30-s intervals. The results were used to obtain information about the connection between actual power consumption and nameplate ratings.[2] This ratio has been found to be around 25–50% for equipment with a rated power below 1 kW. Section 4.4 shows that a generalization of this type cannot be confirmed entirely through this work, as several diverging observations have been made.

A major benefit of figures resulting from plug load estimates is their usability for building layout, especially in terms of cooling capacity planning. Mathew et al. noted that such equipment loads are difficult to estimate and are often overestimated by building designers, leading to oversized cooling [19]. Frenze et al. quantified this oversizing tendency as two to five times (design vs. maximum apparent load) in a sample study of seven laboratory spaces in a building at UC Davis, CA [20].

Altogether, the data necessary to predict the energy consumption of medical laboratory buildings is still largely unavailable at present. Additionally, long-term measurement results under real working conditions, especially including validations, have not been published for the major part of devices yet.

3. Methodology

The assessment of electrical plug loads for laboratories requires an integrated approach accounting for a broad variety of different challenges (e.g. large quantities of different products from numerous manufacturers, difficulties in determining adequate levels of aggregation, unknown relationship between rated (nameplate) and actual peak power, highly specific and strongly varying usage times, etc.). In view of this complexity the assessment approach selected here includes seven individual steps from clustering and identifying the potentially most relevant devices via determining their power ratings to analyzing their consumption patterns through

[2] “Nameplate rating” refers to a device’s reference power consumption as indicated by the manufacturer.