Energy and Buildings 88 (2015) 193–202

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

# Empirical variation in 24-h profiles of delivered power for a sample of UK dwellings: Implications for evaluating energy savings

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ARTICLE INFO

*Article history:*
Received 28 August 2014
Received in revised form
25 November 2014
Accepted 29 November 2014
Available online 5 December 2014

*Keywords:*
Energy demand
Residential sector
Energy efficiency
Peak power demand

ABSTRACT

Improved methods for quantifying energy savings in buildings need to be supported by empirical measures rather than modeled estimates of future annual energy demand. This paper uses power temperature gradient (PTG, W/K), or the slope of power demand in response to changes in external air temperature; first, to categorise dwelling energy performance from daily energy data (when 0–15 °C outside); second, to investigate variations in 24-h profiles of delivered power. Estimates of PTG were obtained from 567 UK dwellings with 118,000 days of gas and electricity data. From a multivariable regression model, PTG was predicted by dwelling characteristics (number of bedrooms, number of floors, dwelling type, and dwelling age category (all $p < 0.001$)) but not by number of occupants. When dwellings were grouped into quintiles of PTG, mean PTG had threefold increase from the first to fifth quintile (188 to 563 W/K, respectively). This was reflected in 24-h profiles of delivered power (30 min intervals): at 0 °C, each 100 W/K decline in PTG corresponded to ~2.5 kW decline in mean morning and evening peak power. Using PTG to estimate reductions in peak power as equivalent 'negawatts' reframes potential benefits of energy efficiency retrofits and for grid resilience.



## 1. Introduction and background

The IEA has posited energy efficiency, conventionally defined as *using less energy to deliver the same or better levels of service or amenity*, as 'the first fuel' and in so doing has both underscored the priority placed on energy demand savings and their equivalence with generation from renewables or other zero-carbon energy sources [1]. This need to re-frame the concept of energy efficiency addresses the historical separation between energy supply and demand that has tended to distort the focus of energy research and policy development. With the evolving development of the 'smart grid', such a dichotomy appears untenable in the context of the integrated approach needed to manage and maintain a dynamic energy system with an increasing percentage of intermittent and distributed generation from renewables. Moreover, the building sector has been identified as not only making a key contribution to energy efficiency gains to meet carbon emission reductions, but as a central component in the development of smart grids, for instance with time sensitive tariffs and controls to manage demand peaks as well as on-site generation and storage. As a result there has been increasing research interest in understanding the 24-h profile of residential energy demand and the potential for shaving or shifting peak demand, such as with control systems [2] and time-varying tariffs [3]. Far less is understood about the variation in 24-h energy demand across the residential sector and the influence of energy efficiency on peak demand, with previous research mainly focussed on exemplar dwellings [4].

Quantifying the energy saved in a building that is specifically due to energy efficiency interventions, and hence to estimate equivalent 'negawatts' generated remains challenging [5,6]. First, while much of the policy on energy efficiency is focussed on the thermal performance of the building shell and heating system efficiency (for example, as mandated by building codes), categorising dwelling energy performance typically is based on annual consumption. Even if 'normalised' for floor space, annual consumption comprises a high degree of heterogeneity due to a range of factors, including diurnal patterns of dwelling operation, seasonal variations, and external factors such as changes in energy price from year to year. These factors can act to confound the impact of improvements in the building fabric or heating system efficiency.

Second, the use of normative models to predict annual energy demand in either absolute or relative terms remains problematic [7]. For instance, assumptions for thermal performance parameters are often used in energy demand models, such as for wall

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http://dx.doi.org/10.1016/j.enbuild.2014.11.075

construction or heating system efficiency, whereas measured in situ values may be missing or inaccurate. These models also assume standard operational conditions within dwellings, for instance in the profile of daily heating and indoor temperature settings. Whereas, a range of social factors, such as occupancy heating practices or heating requirements are often not collected in energy surveys. Evidence suggests that models typically tend to overestimate the annual energy demand of older 'energy inefficient' dwellings and underestimate it for newer efficient dwellings [8].

These issues of estimating changes in energy demand before and after intervention are compounded in retrofit programmes, such as under the Green Deal in the UK, where the options and financing for retrofits are based on estimated savings in annual energy demand [9]. Policymakers have increasingly recognised the need to strengthen the evidence base and improve methods for quantifying reductions in energy demand. Unfortunately, limited empirical evidence has been available from large-scale field studies with sub-annual energy data. Moreover these datasets still pose considerable analytical issues, for instance establishing straightforward empirically based metrics on the relative energy performance of a dwelling, particularly with less than annual energy data and in the absence of detailed information available about the building or occupant characteristics.

### 1.1. Data driven approaches

Energy epidemiology provides an alternative way forward as it emphasises data-driven approaches for the analysis of large scale datasets, rather than applying *a priori* assumptions or normative models, to guide policy development [10]. In this paper we reprise the Princeton Scorekeeping method (PRISM) [11] for evaluating measured energy demand that, although adopted widely at the time, has received only occasional reference over subsequent decades from the research and professional community [12]. In part, this may be due to a misplaced emphasis on using PRISM to estimate annual energy demand via heating degree-days. Instead, this study focuses on one component of PRISM: the heating slope parameter obtained from monthly (or more frequent) metering [13]. Here, this concept is redefined as the power temperature gradient (PTG, W/K) using a slightly simplified methodology with daily data (and spanning only the heating season) to obtain the linear relationship between the delivered gas and electricity power and average daily external temperature (illustrated in Fig. 1 and described in more detail in Section 2).

From a steady-state perspective, PTG can be interpreted as a first order empirical metric for the effective rate of heat loss of the building in response to changing external conditions, including through the building shell, ventilation losses, and losses associated with the efficiency of the heating system. Similarly to the heating slope parameter of PRISM, a low PTG implies a low net dwelling heat loss and good energy performance; conversely high PTG indicates poor energy performance. As PTG comprises all metered energy input to the dwelling, it includes changes in incidental or indirect heat gains from other energy uses, such as lighting. PTG does not account, however, for any indirect heating from unmetered energy sources, such as varying solar gains as external temperatures decline. Moreover PTG should not be considered as just reflecting technical performance, but as a socio-technical parameter since it incorporates factors that influence power demand that change with external temperature, which may include the heating practices used by the dwelling occupants (e.g. their thermostat setting and heating system programme) and any energy conservation practices that are adopted to reduce heat losses, such as closing windows and curtains.

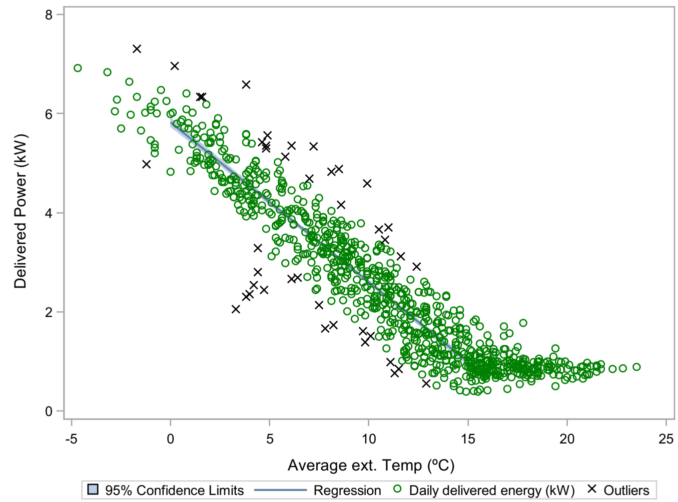


**Fig. 1.** Delivered power (gas and electricity) data from an example dwelling used to calculate PTG (W/K) from the slope of delivered power with respect to daily average external air temperature (0 °C to 15 °C).

### 1.2. Study aims and objectives

This study investigates the use of PTG (W/K) as a simple metric of energy performance in relation to basic building characteristics and social factors, using data on a sub-annual level. It draws on a sub-sample of dwellings with metered 30-min gas and electricity data that were part of large-scale project on smart metering and energy demand by the UK Department of Energy and Climate Change (DECC). Specific objectives are to:

- establish the relationship of PTG to basic dwelling characteristics;
- categorise dwellings according to PTG as a metric of their energy performance;
- examine the difference between 24-h profiles of delivered power for dwellings with different PTG values under various external conditions and hence estimate potential dynamic diurnal energy savings as equivalent 'negawatts' generated.

## 2. Methods

### 2.1. Dwelling sample dataset

From 2007 to 2010 field trials were undertaken in the UK to investigate the effectiveness of various types of interventions that provided householders feedback on their energy use, such as from 'smart meters' that provided real-time display of energy data to comparisons of usage included in regular energy bills. The project was managed by OfGEM on behalf of DECC, with four energy suppliers conducting the studies on over 60,000 households who volunteered, including 18,000 with smart meters [14]. The data used in this study were drawn from one of these field trials conducted by the energy provider EDF and provided to the study. The dataset comprises 592 gas-heated dwellings with at least 80 days of both 30-min gas and electricity data as well as floor area and other basic dwelling and occupant characteristics. As little is known about the selection process of the original sample from EDF customers, or even the response rate, this volunteer sample should not be considered as representative of gas-heated dwellings in the UK residential sector. The final sample of dwellings in the analysis contains more than 300,000 days of gas and electricity consumption between 2008 and 2010, with a varying number of days and different monitoring periods for each dwelling.