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Understanding usage patterns of electric kettle and energy saving potential

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HIGHLIGHTS

- Time-of-use analysis to motivate kettle usage and consumption prediction.
- Identification of households whose kettle usage and consumption is outside the norm.
- Mathematical model to estimate water volume from consumed power measurements only.
- Quantification of energy savings if a household uses its kettle more efficiently.
- Kettle usage and demand prediction using an Adaptive Neuro Fuzzy Inference System.

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ABSTRACT

The availability of smart metering and smart appliances enables detecting and characterising appliance use in a household, quantifying energy savings through efficient appliance use and predicting appliance-specific demand from load measurements is possible. With growing electric kettle ownership and usage, lack of any efficiency labelling guidelines for the kettle, slow technological progress in improving kettle efficiency relative to other domestic appliances, and current consumer attitudes, urgent investigation into consumer kettle usage patterns is warranted. From an efficiency point of view, little can be done about the kettle, which is more efficient than other methods of heating water such as the stove top kettle. However, since a majority households use the kettle inefficiently by overfilling, in order to meet energy targets, it is imperative to quantify inefficient usage and predict demand. For the purposes of scalability, we propose tools that depend only on load measurement data for quantifying and visualising kettle usage and energy consumption, assessing energy wastage through overfilling via our proposed electric kettle model, and predicting kettle-specific demand, from which we can estimate potential energy savings in a household and across a housing stock. This is demonstrated using data from a longitudinal study across a sample of 14 UK households for a two-year period.

1. Introduction

An electric kettle is an electrical appliance, that has a self-contained heating unit, for heating water, and automatically switches off when the water reaches boiling point or at a preset temperature below 100 °C. It is thus different to the stove top kettle, which is less energy efficient and takes longer to boil the same volume of water as the electric kettle. In the rest of this paper, we refer to the electric kettle as kettle only.

The kettle is one of the most used appliances in the United Kingdom (UK) as well as the appliance with the highest rates of ownership; according to UKs Department for Environment, Food and Rural Affairs 2006 report [1], 97% of UK households own a kettle. Kettle ownership, and consequently kettle load demand, is also growing worldwide. For example, in Libya, 42% of homes owned a kettle in 2013, compared to 8% five years ago, with an estimated annual energy use of 374 kW h per household [2].

In the UK, more than nine in ten people (90%) use the kettle every day, with 40% doing this five times a day or more. Thus, the kettle has become a key domestic consumer. The 2012 annual electricity consumption of the kettle in the UK was 4489 GW h, which is roughly 34% of the total consumption attributed to cooking [3]. Moreover, the electricity demand from the kettle is increas-

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ing (at the expense of electric ovens and hobs due to changes in cooking practices and increased oven efficiency) and according to [3] will surpass, in the UK, the annual consumption of 5000 GW h by 2030, contributing close to 40% of the overall cooking electricity demand.

Though, overall, a lower consumer when compared to the electric heater or washing machine, the kettle is one of the appliances that has the highest wattage and requires the highest current when switched on [4]. This is evidenced by high spikes, caused by kettle usage, in the otherwise low to medium demand profile of a typical household [5]. Due to the spiky nature of its demand, the kettle can significantly influence electricity generation and the power distribution network, mainly due to the so-called "TV pick-up effect" that manifests itself through significant and synchronised usage of appliances, such as kettles and microwaves, during TV programme breaks [6].

The kettle is also one of the most inefficiently used appliances. In a survey of 86,000 homes in the UK, by the Energy Saving Trust [7], it was found that three-quarters of British households admit to overfilling their kettle when boiling water and are subsequently wasting GBP68 million each year. Similarly, in Libya [2], over 50% claim to overfill their kettle. However, both these statistics are based on interviews, instead of measurements. While kettle usage is generally assumed to be very regular and non-random [4,8], to the best of our knowledge, there has been no in-depth study which analyses patterns of kettle consumption. This is probably because of the assumption that kettle usage is highly routinized, monitoring kettle usage requires consumer engagement, and that the kettle is not considered a candidate for flexible domestic electricity demand [3], and as such, not of high interest to demand response measures.

Nevertheless, a clear trend in increased kettle usage [2,3], lack of any efficiency labelling guidelines, slow technological progress in improving efficiency (relative to other cooking appliances), and current consumers attitudes (86% of people do not choose kettles based on their features, but on looks to match a kitchen design/already owned products (see [1] and references therein)), all call for urgent investigation into consumer behaviour patterns with respect to kettle usage and energy conservation measures.

In this paper, we test the above assumption of regularity in kettle usage, quantify the actual and predicted contribution of energy consumed by the kettle in a household, and propose a method to determine energy waste from load measurements only. This is supported by a longitudinal study comprising a sample of 14 UK houses, of different occupancy and age groups (e.g., retirees, working couples, families with children and single occupants), some energy conscious and others not. The timestamped kettle power consumption was collected via an appliance-level smart plug monitor that measures active power every 6–8 s [9]. See [10] for details about the field study.

The main challenge in assessing energy waste due to overfilling the kettle is measuring fill water volumes in a non-intrusive way, since it is impractical to measure and record water volume for every kettle use. This paper overcomes the above problem by measuring the individual kettle consumption (kW h) and estimating the water volume from this measurement using mathematical modelling. In particular, using measurements with different kettle types, a generic mathematical model is built that relates the water volume of a kettle, its consumed power and water temperature.

We demonstrate how power consumption information and time of use information, together with the proposed mathematical model, can reveal a household's behaviour in terms of water overboiling and energy wastage, and identify established routines and usage synchronicity across the monitored households.

Furthermore, we study short-term and long-term load forecasting [11], which is useful for energy feedback, load balancing [12], effective planning and power plant management [13], demand response [14,15] and renewable energy systems and energy storage design [16]. Since consumers directly interact with appliances, appliance-level load forecasting is particularly challenging [14] as it depends on human behaviour, which is often stochastic and unpredictable. Moreover, energy efficiency measures and utility programs affect forecasting which is often a challenge to account for [17]. Adopting the established Adaptive Neuro Fuzzy Inference System (ANFIS) [18] prediction tool, we show that kettle usage and energy consumption can accurately be predicted, short- and long-term. Using this knowledge, we show how we can predict potential annual energy savings per household and for an entire housing stock if energy saving measures were taken.

In summary, the key contributions of the paper are:

- Time-of-use analysis to understand patterns of use and its implications for accurately predicting kettle usage and consumption.
- A method for identifying households whose usage is outside the norm through understanding energy consumption patterns to support energy conservation measures.
- A mathematical model of the kettle that relates water fill levels, consumed power, and change in water temperature to estimate water volume from consumed power measurements only.
- Quantification of energy savings if households use their kettle more efficiently by quantifying overfilling and reboils.
- Kettle usage and demand prediction using an Adaptive Neuro Fuzzy Inference System, which is also used to estimate energy savings for the next year if current patterns of use are maintained.

The paper is organised as follows. First, we discuss related work in the literature in Section 2. In Section 3, we present our findings with respect to temporal and energy usage analysis. In order to quantify energy waste due to overfilling, we describe our proposed modelling approach for estimating water volume and the results of our energy waste analysis in Section 4. Finally, Section 5 describes our prediction of usage and energy consumption methodology and its application to estimating energy savings if households take on board energy conservation measures of not overfilling the kettle.

2. Literature review

In this section, we briefly review prior work. We group the relevant literature into three categories: (1) understanding usage of different domestic appliances; (2) energy usage of the kettle; (3) appliance-level load prediction. Interestingly, despite the fact that the kettle has a non-negligible influence on electricity demand, modelling and forecasting methods to understand and predict demand, as well as calculating energy-wasteful usage, have not been analysed in detail so far for this appliance.

Many empirical studies on consumer attitudes and interactions with energy-consuming appliances have been reported recently, tackling this issue from consumer study [19], human computer interaction (HCI) [20], and energy [21,22] angles. For example, targeting autonomous load shifting, in [21], novel generic probabilistic models for wet-appliance usage are proposed that account for variability of patterns in usage. In [19], based on a longitudinal study in 29 countries, individual user attitudes towards manual and automatic dishwashing is considered, with the conclusion that dishwashers save water considerably more, and providing cleaner dishes with respect to manual dishwashing.

In [20], interactions with domestic appliances are studied through a qualitative longitudinal field-work with a sample of 12 households and an online survey, concluding that consumer beha-