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A real-life assessment on the effect of smart appliances for shifting households' electricity demand

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HIGHLIGHTS

- Households shift demand of the washing machine away from the evening peak.
- Households do their laundry more often when electricity is locally produced.
- Users of automation shifted most demand.

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ABSTRACT

Today's major developments in the production and demand of electricity in domestic areas make it increasingly important that domestic electricity demand can respond to the availability of electricity. Energy management systems and smart appliances can facilitate this by supporting the user to shift electricity demand of appliances to moments in time when electricity is abundantly available. However, the benefits resulting from domestic demand response depend on household acceptance and behaviour change. This paper explores the real electricity demand shift of households in time and the role of smart appliances to bring about this shift. A longitudinal study was conducted among Dutch households over a period of one year. The households received a dynamic electricity tariff, an energy management system and a smart washing machine. Results show that households shift their usage of the smart washing machine mostly to the day when the sun is shining and electricity is produced by their own solar panels. Households who regularly used automation of the smart washing machine, which implicates that the use of the washing machine is automatically shifted to time periods where electricity supply is abundantly available, were more likely to shift their electricity usage. Furthermore, during the course of one year, the results remained stable, indicating a structural shift in demand.

1. Introduction

The aim of this research is to investigate if households can shift their electricity demand to times when electricity is abundantly available. Research on this topic is becoming more valuable because electricity demand and supply in domestic areas are expected to undergo two major developments in the coming decades. First of all, the amount of distributed renewable electricity generation will increase, for example, due to the growing number of installed photovoltaic (PV) panels. Second, there will be a significant increase in electricity demand, due to an expected widespread introduction of new energy efficient technologies, such as electric vehicles and heat pumps. These developments pose great challenges to the traditional power system, in which supply follows demand entirely.

Smart grids are proposed as a potential solution to facilitate the affordable introduction of cleaner electricity producing and consuming technologies. Many researchers have mathematically assessed the potential size and value of different concepts of demand response in residential areas by which vast benefits for different actors are postulated using several scenarios (e.g. [1–5]). Consequently, the value of demand response for improving system efficiency is well established. However, the effects of smart grids strongly depend on the successful implementation of demand response programs. Based on Darby and McKenna [6], we define demand response as a household action (automated, manual, or both) due to which electricity use is shifted in time in response to

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a price signal or other stimuli. This can result in more efficient usage of the available sustainable electricity, like self-consumption of on-site PV electricity [7] and peak demand reductions (e.g. [5]). An example of a price signal that several countries have in place is a day- and night pricing scheme. In this scheme, electricity is cheaper during the night, when demand is low. Another example of a price signal, which is upcoming, is that self-consumption of on-site PV is encouraged financially in some countries [7]. For these households it is financially interesting to consume the electricity at the same moment as when it is produced by the household's solar panels.

Automation through smart appliances has been proposed as a promising strategy for households to shift their electricity demand in time depending on price signals. Smart appliances can operate (semi-) autonomous and can thereby support users to automatically select the most desirable moment in time for consuming electricity. Prior research has investigated the effects of smart appliances on demand response by developing statistical models and simulations [7–11]. However, these models are based on assumptions with respect to the demand responsiveness of households and there is a lot of insecurity about households' willingness and ability to shift electricity demand in time [12]. In this respect, scholars have acknowledged that scientific research on the actual, everyday behaviour of households interacting with smart appliances is lacking [13]. The present research addresses this gap in the literature. Specifically, we contribute to the literature by investigating in a real-life setting the factual demand response that was achieved by a large group of Dutch households while interacting with a smart washing machine over one year. Households were also equipped with PV panels, an Energy Management System (EMS), and a dynamic tariff. The EMS gave easy to interpret feed forward on the dynamic tariff and feedback on electricity demand, to increase demand response [12,14]. To the best of our knowledge, this is the first quantitative study on households using smart appliances to achieve a shift in electricity demand, that evaluates self-consumption of on-site PV electricity and peak demand and the effect of automation to bring about that shift.

2. Demand response strategies

Electricity demand shows a pattern over time, which is influenced by natural and social circumstances [15]. For example, households consume more electricity in the winter than in the summer and more in the evening when people come home from work and start using various appliances. Correspondingly, the pattern of electricity production, mostly by solar panels in domestic areas, is mainly caused by natural circumstances. This brings about the problem that people are generally not at home when electricity is locally produced and create a peak demand in the evening, especially during winter. The most common strategies in the electricity sector to encourage households to use available sustainable electricity more efficiently and reduce peak demand are price signals and recently developed smart appliances.

Existing research on the effectiveness of price signals has mainly focussed on peak demand reductions. These studies have reported large deviations in the peak demand reductions that households have achieved [5,16–21]. The deviations can be explained by different factors that cannot be influenced, such as the characteristics of the households. Also, controllable factors like the pricing scheme and the price variety caused deviations. In addition to price signals, prior research has started to discuss smart appliances as a mean to increase the effect of demand response at households [5,18]. Most existing studies (see [5] for an overview) on households' actual demand response effects in combination with smart appliances make use of fully autonomous demand response and aim solely for a peak demand reduction. Utilities can directly lower electricity demand when peak demand is high by remotely interrupting the demand of specific appliances that use electricity (nearly) continuously, such as air-conditioners. This form of automation is referred to as fully autonomous in this article, because the user does not interfere with the process. The user only needs to accept the setting for demand response to allow the utility to shortly interrupt operation. This form of demand response has received much attention, because it is seen as the easy way to reduce the need for expensive reserve capacity. It is often applied in areas with high penetration rates of air-conditioners or electric heating.

Besides such fully autonomous smart appliances, users can shift other forms of electricity demand in time. While short interruptions of demand are mainly interesting to reduce peak demand, a shift of demand can also optimise the efficient use of (own) sustainable electricity production. The usage of wet appliances, such as dishwashers, washing machines and dryers, is in general not very time critical and therefore can be shifted. These appliances are heavy electricity consuming appliances that account for 15% of the total household demand [22], making them interesting for demand response. The user can schedule these appliances him/herself to times at which local electricity is abundantly available. However nowadays, this form of scheduling can also be automated with a semi-autonomous smart appliance. The user defines an ultimate finish time and within this time frame, the smart appliance automatically defines the most appropriate starting time [23,24].

The few studies that have studied household acceptance of such semi-autonomous smart appliances have mostly used questionnaires to explore households' intention to shift the electricity demand of their appliances in time [24–28]. These studies show that the overall attitude towards smart appliances is positive, although respondents do perceive risks concerning safety, loss of control, technical problems and additional costs, and are sceptic about the ecological benefits [26]. Especially, the smart operation of the washing machine is a sensitive issue. Although respondents reported that they were willing to shift operation, they did not want to leave wet laundry in the machine for a longer period of time.

Despite that the time interval for smart operation of the washing machine is thus limited, these preference studies have concluded that households can shift 10–77% of the electricity demand of their washing machine [25,27]. However, when filling in these questionnaires, people respond to descriptions of smart grids, dynamic pricing tariffs, and smart appliances to form attitudes and to estimate their future behaviour. These studies can only provide limited insights in the real-life effects of demand response for households, because many more (often conflicting) factors shape pro-environmental behaviour, so the attitude-behaviour relation is limited [29]. The variance in prior results underline the need to measure the willingness to shift the washing machine in time in a real-life setting by studying actual, everyday behaviour of households.

Two notable exceptions of studies exist that did investigate real-life usage of smart appliances and demand response. The first is a Dutch study, in which households used a smart washing machine for several months to match their electricity demand with the local production of the PV panels [30]. The quantitative analysis of washing machine usage showed that the washing machine was generally turned on during hours in which electricity was locally generated by the installed PV panels [31]. However, this study had several important limitations. First of all, the study used a small sample and all participants were employees of an energy utility, thereby raising doubts about the representativeness of the sample. Second, the study did not include a dynamic tariff, which is assumed to be essential to adopt a demand shift for the majority