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Experimental determination of demand side management potential of wet appliances in the Netherlands

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HIGHLIGHTS

- Experimental determination of residential peak shift potential of wet appliances.
- Shifting demand results in peak reduction of 10%.
- Photovoltaic self consumption accounts for 6% demand reduction.

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ABSTRACT

The potential of demand side management (DSM) of wet appliances (washing machine, dishwasher and tumble dryer) in households with photovoltaic (PV) systems is studied experimentally focusing on evening peak demand reduction and increase in PV self-consumption. In a sample of 100 Dutch households the electricity demand is monitored for one year at high time resolution. It is found that the dishwasher has the best DSM potential, with a median average peak reduction potential up to 35 W per household on average for all appliances, while PV self-consumption for the median household can be increased with 68 kWh/year per appliance. The tumble dryer and washing machine's potentials are 30 W and 25 W per household, respectively, for the mean average peak reduction, and 38 kWh and 28 kWh, respectively, per household per year for increase in PV self-consumption per appliance. Further, the median peak reduction potential of a single group of wet appliances ranges from 1% to 5% of the power demand in peak hours, while combined they could add up to 10% of the total peak. The median increase in PV self-consumption is in the range between 1.5% and 4% for separate appliances, while the median total could provide an increase up to 129 kWh per household per year if a household possesses and utilizes the potential of all appliances, which is about 6% of the annual household demand. In conclusion, DSM potential for wet appliances is limited.

1. Introduction

1.1. Renewables in the electricity grid

The deployment of photovoltaic (PV) solar energy in the past decades has led to an impressive 227 GWp installed capacity worldwide at the end of 2015 [1], covering 1.3% of the world's annual electricity demand. This growth is expected and targeted to grow to values surpassing the terawatt level. In the Netherlands, PV systems are predominantly installed in residential areas on the roofs of privately owned homes. This will lead to a shift in the electricity supply chain from centralized high-power fossil fueled power plants to a decentralized bidirectional power flow electricity system. The inherent intermittent power generated by PV due to day–night and seasonal sequences, and cloud effects poses a challenge, as demand from households with PV is not following the generated PV power. This mismatch in production of solar energy and electricity demand is a grave concern of distribution system operators (DSOs) and utilities, since electricity demand and supply have to be balanced at all times.

These problems could be addressed on the one hand by shifting the load of appliances to other times of the day in order to reduce peak power demand and on the other hand by optimizing PV self-consumption, i.e. by using the generated solar power directly in the household. The latter objective is not only attractive for grid

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operators and utilities, but also for the end users, especially in situations where net metering is not in force. This could be organized using smart energy management systems, usually referred to as smart grids. A smart grid can be defined as 'a set of software and hardware tools capable of routing power more efficiently, thus reducing the need for excess capacity' [2]. This effectively means that a smart grid is a local grid connecting several households, which will attempt to most efficiently match supply and demand by utilizing energy storage facilities such as electric vehicles and shifting demand load to a time where there is excess energy supply from for example solar panels. Smart grids may be quite complex because of these abilities and a lot of research is being conducted into the potential of smart grids to incorporate different energy sources, storage systems and users in relation to demand side management (DSM) and user acceptance [3–22].

1.2. Demand side management

A smart grid should be able to employ demand side management. DSM refers to the ability of consumers, manually and/or automatically, to respond to a signal by adjusting electricity demand to facilitate a better matching of supply and demand [8,19]. This signal can be a price signal, e.g., a dynamic electricity price, or a power mismatch signal, e.g., excess PV supply. A number of studies exist that specifically focus on DSM in residential areas. For example, various authors have reported on the development of algorithms to calculate the potential of demand side management [13,20]. Others have studied the potential of households to shift their behavior [14,23,24]. More recent studies have focused on investigating the shifting potential in real-life settings by providing households with smart appliances and studying their actual behavior [15,18,25]. Muratori et al. [21] found that the specific design of dynamic price programmes has significant effect on the potential for peak shifting of households. Also, government policies in the UK have been successful to improve DSM in the industry and residential sector [26].

On the household level, a theoretical study of a household integrated into a system with large renewable penetration in Turkey showed that a yearly reduction in cost of electricity of 3% would be possible if DSM was applied [27]. In a set of single family buildings in Sweden with 3–9 kWp PV system per building it was shown that up to 200 kWh increase in self-consumption would be possible annually with DSM [28].

In a top-down research into the DSM potential of various European countries, it was found that the Netherlands would be able to change 4.36% of their energy demand with a slight effort, while a total of 12.68% of the demand could be changed with a large effort [29].

1.3. Appliances suitable for demand side management

Clearly, not all household electricity demand can be easily adjusted, as power demand for appliances such as TV-sets and computers is often bound to specific times of use, impeding the possibilities for DSM. Other appliances do not provide enough power demand or energy use to add up to a significant DSM potential, such as printers and radios [30]. Appliances that are used to cool products (cold appliances: freezers and refrigerators), often display relative high energy demand highly dispersed over the day [31], but DSM potential of cold appliances may be limited due to cooling demands.

A group of appliances that may show a high DSM potential are the wet appliances (washing machine, tumble dryer, dishwasher). With their share of electricity use of 17%, they come second in electricity use as consumer electronics represent 22% [31,32]. These appliances embody both high energy use as well as high power demands, and allow for adjusting time of use. In an ideal case, inhabitants would fill these appliances and the smart grid software would interact with these appliances to control the time at which they have to start their operation. A case study in Belgium with a large sample of households showed that demand reduction using wet appliances is not only dependent on their electricity demand but also on the willingness of households to actively apply demand response [32]. The study concludes that demand reduction potential is about 21 W per household on average per year. A study using automated approaches showed relatively high DSM potential [25], while another simulation study showed only limited DSM potential [33]. Although automated approaches are expected to be more and more used in future, the present paper focuses on the potential of *manual* rescheduling of cycles using actual *measured* data instead of simulations and will try to identify what the energetic benefits are from such a scenario. Manual rescheduling will not require high investments and households have more influence on the rescheduling, which is likely to result in easier introduction of DSM in households, however dependent on willingness to adapt behavior [32]. Note that in the area that is used in this research, no smart appliances were installed.

This research will focus on the DSM potential of wet appliances in the sub-urban district Nieuwland in the city of Amersfoort in the Netherlands. This district is home to 500 small (0.8–4.4 kWp) PV systems installed in 1999–2001 totaling 1.3 MWp [34]. One hundred households participate in a demand measurement scheme in which up to 5 appliances per household are monitored at 10-s time resolution. Availability of such a detailed unique dataset is a prerequisite for a proper experimental analysis. This study contributes to a better understanding of the energetic role of wet appliances in current households, as well as their potential for load shifting and photovoltaic self-consumption.

This paper is further organized as follows. Section 2 provides background on PV, DSM, and demand profiles of wet appliances and Dutch household demand profiles. Section 3 details the methodology used. Analysis of results is presented in Section 4, and these are discussed in Section 5. Section 6 closes the paper with conclusions.

2. Background

2.1. PV and DSM

DSM can have multiple benefits for multiple actors in the electricity system. For the Distribution System Operator (DSO) the benefits would lie in the ability of dynamically changing demand to prevent congestion and (too) large peaks in the power flowing through the network cables. While in the last decades the peak moments were mainly during evening hours due to increased demand, large-scale incorporation of PV systems into the electricity grid leads to a peak moments around midday. For a residential district with a large amount of PV systems, a sunny spring or summer day could thus result in higher negative power flow than the positive power flow on a dark winter evening, resulting in higher demands of the electricity grid, which may lead to required investments in grid extension. By curtailing PV systems, grid investment can be reduced albeit with a negative consequence for PV owners in that their economic benefits will be lower. At the end of the afternoon, the reduction in PV power coincides with an increase in household consumption. Thus, high ramp rates need to be dealt with. DSM can be a solution by reducing peak demand, thereby decreasing the ramp rate. Pöyry delineated the usefulness of DSM for grid operators along a total of five dimensions [35]. These dimensions as well as the application of these dimensions to wet appliances are given in Table 1. It was reported that 5%–15% reduction in peak demand