ARTICLE IN PRESS

Energy Research & Social Science xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Energy Research & Social Science

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

Original research article

Green lift: Exploring the demand response potential of elevators in Danish buildings

Sergi Rotger-Griful[a], Rune Hylsberg Jacobsen[a,*], Robert S. Brewer[b], Mia Kruse Rasmussen[c]

[a] *Department of Engineering, Aarhus University, Denmark*
[b] *Department of Computer Science, Aarhus University, Denmark*
[c] *The Alexandra Institute, Aarhus, Denmark*

A R T I C L E I N F O

Keywords:
Demand response
Elevator
Energy awareness
Behavioural change

A B S T R A C T

Demand response can be applied in a smart grid scenario to promote renewable energy integration by regulating the electricity consumption to match the available renewable production. Buildings are relevant demand response sources for consuming significant amounts of electricity. This paper presents *Green Lift*, an intervention that explores the demand response potential of indirectly controlling elevators in buildings. *Green Lift* aims at changing the elevator usage by providing information on “good” and “bad” times to take the elevator, from a CO_2 emissions intensity perspective. This is accomplished by installing LEDs beside the elevator doors, linked with real-time CO_2 information: the LEDs flash red when electricity produced is CO_2 intense and green otherwise. During a one-month field trial, we tested *Green Lift* in a 12-storey Danish student dormitory. Combining quantitative and qualitative analysis in an interdisciplinary approach, we observed that more people chose the stairwell over the elevator. However, there was no significant reduction in the elevator electricity consumption. Interviews with the residents revealed that the concept of shifting energy consumption was hard to comprehend. We concluded that the studied elevator is not a good source of flexible consumption and we discuss the implications of these results to elevators in other environments.

1. Introduction

Renewable Energy Sources (RESs) are clean sources of energy that have a much lower environmental impact than Conventional Energy Sources (CESs), which are based on fossil fuels. In the transition towards more sustainable societies, ambitious targets have been established for the amount of energy that should be produced from RESs. The European Union (EU) requires its member states to fulfil at least 20% of their total energy needs with renewables by 2020 [1]. Denmark has established plans with higher ambitions with a 50% production from wind turbines. The Danish Transmission System Operator (TSO) announced that 2015 was a record-breaking year for RES production in the electricity supply. Danish wind turbines generated what corresponds to 42% of the country yearly electricity consumption. In fact, for 1460 h of the year in major parts of the country, wind power supplied more electricity than the total consumption [2].

To meet energy demands requires a mix of both RES and Conventional Energy Source (CES). The generation of RES varies in accordance with the changes over time in weather conditions e.g., wind speed and solar irradiation. Therefore the CO_2 emission intensity arising from electricity generation is varying over time with this mix; being higher in cases where CES-generation is dominating and lower in periods where RESs are producing. Another dominating factor for the CO_2 emission intensity relates to the international import and export of electricity.

In the Danish power grid, there is a correlation of up to 93% between CO_2 emission intensity and RES generation (see Table 1 for more details). The CO_2 emission intensity is, therefore, a good indicator of periods when electricity is originated from RES.

The increasing integration of intermittent RES fosters the need for more flexibility in the consumption. Flexible consumption is usually sought from buildings because they account for a large amount of the total electricity consumption. In the United States (US), it is estimated that 75% of the total electricity is consumed in buildings [3], while in Denmark 66% of electricity is used in such facilities [4]. In this context, demand response seeks flexible consumption to adapt the demand side to the production side. This is done by exploiting the flexibility potential in daily work processes and operations thus enabling a consumption shift [5].

* Corresponding author.
E-mail address: rhj@eng.au.dk (R.H. Jacobsen).

http://dx.doi.org/10.1016/j.erss.2017.04.011
Received 13 August 2016; Received in revised form 9 April 2017; Accepted 18 April 2017
2214-6296/

Table 1
Correlation between wind and solar generation (RES generation) and CO_2 emission intensity in Denmark for each month in 2014 and 2015. Although the correlation is negative, numbers are shown in positive values for clarity. Data provided by Energinet.dk.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
2014	0.80	0.82	0.89	0.82	0.65	0.82	0.69	0.91	0.81	0.82	0.83	0.93
2015	0.92	0.86	0.83	0.77	0.68	0.60	0.59	0.50	0.72	0.60	0.62	0.84

Shifting of energy consumption differs significantly from curtailment of consumption. Shifting requires people and electronic devices to postpone their operation in time but without the need to reduce the total consumption, whereas curtailment reduces the total consumption [6]. A shift in energy consumption can result from *direct* as well as *indirect* control. Direct load control utilises Information and Communication Technology (ICT) to decide and actuate electronic devices in a timely manner. In contrast, indirect control empowers the human by providing a signal when it is preferred to consume energy and stimulates a behavioural change. However, changing behaviour and hence exploiting a flexibility potential is a very challenging task that requires an interdisciplinary effort. As stated by Levi [7]: "The real problems with demand response comes when utilities try to operate the customer like a power plant. What you get is another ineffective effort with limited potential and an even shorter life".

In this paper, we propose a mechanism for indirect demand response shifting in large buildings by exposing to the occupants an energy metric signal derived from the mix of RES and CES used for electricity generation. We explore this mechanism in the context of elevator usage in a field trial that we call the *Green Lift*. However, the mechanism could also be extended to other areas. Our research provides the foundation for analysing demand response for interventions that consider consumer involvement. This includes a proposal on how to define a good baseline, which is a complex problem in demand response system design. Furthermore, we offer a rarely addressed interdisciplinary analysis of our experimental results combining quantitative and qualitative aspects of energy demand flexibility. It should be noted that this work is not a full-fledged behavioural study but rather a technical feasibility investigation with both a technical and behavioural analysis.

The paper is organized as follows: Section 2 introduces related work with emphasis on energy awareness and the potential of consumption shifting. In Sections 3 and 4, we introduce the conceptual and the experimental design of the *Green Lift* intervention, respectively. The subsequent analysis is divided into a baseline study in Section 5 and a validation of the intervention in Section 6. Finally, we end the paper with a discussion in Section 7 and our conclusions in Section 8.

2. Related work

2.1. Building level demand response

Demand response is usually provided through demand response programs in which the electricity consumer signs up with the electricity provider or a Curtailment Service Provider (CSP). These programs usually fall into two different categories: price-based programs, where the consumer receives a varying electricity tariff encouraging electricity usage in cheaper time periods, and event-based programs, where the program administrator directly requests specific power changes [8]. Generally, price-based programs use indirect control to shift electricity usage, while event-based programs use direct control.

Energy Management Systems (EMS) within buildings can enable demand response provision from different electricity consumption devices. Heating, Ventilating and Air Conditioning (HVAC) systems in large buildings have been widely studied for their large demand response potential [9–11]. These systems consume a large amount of energy and at the same time, provide a service that can be stored within the building (i.e., thermal capacity). Lighting systems are another common target of demand response programs [12]. The lights within a building can be dimmed or switched off in certain time periods without causing major discomfort. Buildings have other electricity loads that can be controlled for demand response purposes and fall in a miscellaneous category [12]. This category includes plug-loads like smart appliances or electrical vehicles [13], but also common systems like circulation pumps and elevators. It has been suggested in [12] that if a building has several elevators, some of them could be directly shut down during a demand response event.

2.2. Energy awareness displays

A variety of techniques have been tried to moderate residential energy shifting, such as informational displays of grid CO_2 emissions [14], time of use pricing [15], smart meters and appliances that can be scheduled to run at certain times [16,17]. Appliances and infrastructure components like laundry machines, dishwashers and ventilation systems have been demonstrated under external smart grid control [18]. These mechanisms often require some kind of display and complex interactions with the electricity consumers.

The most common manner to display information is using dashboards with various types of data shown on a screen [16,19–24], but there are also other visualisation solutions. For example, a clock displaying a green energy availability forecast [19], a power cord that shows the instantaneous electricity passed through it by changing the illumination intensity of the cord [25], or even a small bear figure to be placed nearby appliances that illuminates aiming at communicating environmental issues within a household [26].

The information being displayed ranges from electricity consumed [19,20], electricity prices forecast [16] and a renewable electricity production forecast [19]. This information is usually presented using plots [16,24,23], but also using green/amber/red colour coding thus emulating traffic lights [16,20,19]. In [19], the authors describe a system similar to the one presented: a watch, composed by two gauges, that displays information to the consumer aiming at shifting their electricity usage. The outer gauge shows the green power availability forecast using a green/amber/red colour code, while the inner gauge shows the current electricity consumption with the same colour coding. Similarly, the energy company E.ON provides a smart energy display together with their smart meters [20]. This display is used to provide a wider range of information and also uses a light that flashes green when the household is using a low level of electricity, amber if the level is medium and red if the level is high. These three levels are different for each household and are learned by the smart meter over time.

2.3. Behavioural change: shifting energy and practices

A considerable amount of research has been conducted on using feedback to encourage residential electricity users to reduce their electricity use, with some moderate success [27–29]. However, some problems have been identified with feedback, including problems with engagement over the long term after the novelty has worn off [30–32].

Convincing residential consumers to shift their electricity use to off-peak times is even more challenging than curtailment. This is due to the additional complexities of demand response, because users must first understand the demand response concept, they must be provided with