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Quantifying economic benefits in the ancillary electricity market for smart appliances in Singapore households

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ABSTRACT

The adoption of smart grid systems has been accelerating around the world, with many pilot projects initiated throughout the developed world. However, there has been a lack of studies quantifying appliance level economic benefits that are available to the end consumers. Through coupling historical market information with an agent based residential load model, this study has quantified the economic benefits of residential smart grid participation in ancillary electricity markets. In this study, we looked at the energy market of Singapore. The regulation and reserve ancillary electricity markets were examined and the associated economic benefits from market participation were assumed to be fully passed on to the consumers. A lesson is that the potential returns for consumer investment in smart appliance technology could be very low. No matter which market that the aggregator participates in, the corresponding credits that a single appliance can earn for the consumer through ancillary markets may not be attractive enough for the consumer. Although there could be other cost saving options such as dynamic electricity prices which could be complementary to such schemes; this result highlights the fact that economic benefits alone may not be attractive enough for smart appliance adoption in the current local policy climate.

1. Introduction

The adoption of smart grid systems has been accelerating around the world, with many pilot projects initiated throughout the developed world. The adoption has been predominantly driven by top down large scale government grant awards, especially in the United States [1]. These projects focus on the upgrading of the transmission infrastructure and metering devices. Households involved in these programs mostly experience just an upgrade of electricity meters and in a subset of these households, an in-house display unit that reports the electricity consumption of these households.

It is not surprising that the most significant benefits that have been proposed in terms of smart grids thus far have focused on the benefits to the system in general—benefits such as peak load shaving, increased stability and robustness to the grid [1,2]. There has been an asymmetrical lack of benefits that are attributable to the end-users of the smart grid [1]. In most instances, the benefits of adopting smart grid technology such as smart meters are not apparent to these households, and more often than not, the households perceive a reduction in benefits by upgrading to these technologies. As such, there has even been resistance from these households on the implementation of these systems [3,4], particularly from perception of reduced privacy and autonomy.

In this study, we set out to do a preliminary investigation on the possible economic benefits that residential consumers can reap through participation in current established electricity markets made possible through smart grid technology. A recurring theme in residential smart grid studies is the implementation of a centralized coordinator among distributed residential users which allow for smarter scheduling of electricity demands with respect to dynamic prices and peak demand [5]. In this paper, we propose an alternative arrangement where the aggregator can manage these distributed loads through participating in secondary electricity markets. Consumers face a flat rate electricity tariff and at the same time can opt to participate in the electricity markets in order to reap economic benefits from smart grids. This is in contrast to traditional assumptions of smart grids where consumers face real time prices.

A possible scenario could be areas where advanced metering devices have been installed but consumers [6] or even regula-

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tors [7] are resistant to real time electricity tariffs. This presents an alternative arrangement that may be implemented together with other electricity tariffs as a complementary add-on, where regulators or utilities can provide real time market signals to consumers to incentivize the shifting or reduction of electricity demand.

One can also easily envision a time varying electricity tariff scheme where consumers allow for some demand management scheduling processes based on time differentiated electricity prices and at the same time participate in primary or reserve markets when the prices are right. The primary focus of this paper, therefore, is to determine the potential benefits of ancillary electricity market participation since these benefits have not been covered by earlier studies. The relative benefits of each smart grid enabled appliance are then quantified for these applications.

2. Existing literature

The literature on smart appliance scheduling is relatively new but growing rapidly. Most of the literature concludes that there are economic benefits that can be reaped from the shifting of appliances from high electricity periods to off peak periods with the combination of reduction of electricity consumption during high periods [8,9]. Several studies have even started considering the comfort of participants as a factor in these smart grid implementations [10–12]. These studies focus on scheduling algorithms and benefits from these processes assuming a certain penetration controllable appliances. There are no discussions on whether these appliances or technologies are attractive to consumers and if consumers are willing to adopt them in the first place.

Empirical results and analysis have also been increasingly published in the literature. California implemented a Critical Peak Pricing (CPP) policy in 2003–2004, allowing for estimation of consumers' responsiveness to peak pricing events [13,14]. A recent study in British Columbia demonstrated the effectiveness of remote load control of consumer loads, where space and water heating loads could be shifted [15]. In Norway, estimated demand response from consumers could reduce peak electricity consumption by 4.8% through control of electric space heating [16].

All the studies above assume that the only price signal that the consumer receives is the wholesale electricity price, or that the consumer can only be involved through the main energy market. In this study, we look at scenarios where the consumers can be involved in the electricity market through ancillary services, thus increasing potential benefits that are available to them. It is proposed that an aggregator agent can combine residential load such that it could be big enough to participate in electricity markets. This would be similar to load interruption schemes as presented in the literature [17–19]. Currently, these schemes are available to large consumers on a voluntary basis, however, results have been mixed with reporting frameworks not consistent across different markets.

There is also a lack of literature with regards to voluntary uptake of smart grid related technologies. [6] Faruqui et al. discussed possible policy actions that are needed to increase such adoption rates and Veldman et al. looked at different scenarios of penetration levels and their impacts on the distribution and transmission network [20]. Exploratory analyses of voluntary adoption of smart grid technologies indicate that consumers are generally positive towards such technologies [21,22]. This study attempts to add to this growing area by quantifying ancillary market economic benefits in the Singapore energy market that can be directly attributable to a set of smart appliances. This would allow for more insights of customer adoption rates of smart grid enabled technologies and policies that could affect them.

3. Study overview

In this study, we adapt a micro level agent based appliance usage model for the Singapore market, and couple the obtained simulation results with historical energy market price data to quantify the expected benefits of demand response for small residential consumers participating in ancillary energy markets.

The residential sector is assumed to face a flat rate electricity tariff, but is able to participate, through an aggregator agent, in the electricity market where they face real time market signals. In this case, it is assumed that the aggregator is able to participate in both the regulation and reserve market. In this system, smart appliances in individual households are assumed to be controllable. An aggregator agent consolidates a large number of individual household such that it is able to provide a controllable load that is significant enough to participate in the electricity market. This aggregator could be defined as needed by the system; for example, a local neighborhood with households that are geographically close to each other. In essence, the controllable loads are then able to participate by acting as a negative load, when an additional quantity of energy is needed in the system, the aggregator can provide such additional energy through the reduction of its own electricity demand, effectively replacing the need to ramp up other conventional generators.

Through price signals from the wholesale market, demand dispatch mechanisms determine demand response actions either through load shifting or load curtailment [23]. In this study, these periods where the aggregator participates in the electricity market would be called demand management (DM) events. The Singapore energy market is assumed as the model for this study. Through this electricity market, the aggregator can gain revenues associated with the spot price of electricity in that particular market. The aggregator can then choose to allocate some portion of these revenues to the individual households.

4. Methodology

The effectiveness of demand management policies depends significantly on the diurnal usage profile of households since the price of generating electricity varies significantly from hour to hour. In order to accurately determine the market potential of household participation, a minute by minute simulation of appliance usage model is developed to determine effective market participation. These profiles are then consolidated to provide market energy demand data which can then be mapped to historical market data of the electricity market to determine participation rates and determine financial benefits. The unit of currency used throughout the study is the Singapore Dollar.

It is further assumed that the required communication infrastructure is in place for households to tap on. For the purpose of this study, it is assumed that the communication infrastructure is fast enough for the required communication signals to be sent to meet all reserve requirements.

4.1. Agent based appliance models

The basic framework of the household model has been discussed in several previous publications [24–29]. In essence, each household is defined as a set of appliances, and in this model, they each own a set of **N** appliances, where a_n represents one unique appliance. The basic appliance model is that of a discrete event model, where for an appliance a_n, the instantaneous power demand, E_n, for its period of operation initiated at time t_s and ending t_f, is represented by,

$$E_n = \begin{cases} S_{n,}, & t < t_s \\ P_n, & t_s \le t \le t_f \\ S_{n,}, & t > t_f \end{cases}$$