THE VIABILITY OF DYNAMIC PRICING IN STAND ALONE ENERGY SYSTEMS

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ABSTRACT

Recent years have seen the emergence of several high profile Stand-Alone Energy Systems (SAES) in remote/isolated communities. Abundant renewable energy resources, coupled with weak or non-existent energy grid supply infrastructure, mean that such communities are often early adopters of alternative approaches towards the generation, storage and consumption of energy. One such approach which is the subject of much discussion is the ability of energy pricing to promote demand response.

This paper presents a conceptual energy pricing strategy designed to promote demand response in SAES using an adapted reward table algorithm, which uses financial incentives to encourage consumer demand elasticity in order to promote demand flexibility. The results suggest that the pricing strategy presented is capable of effectively promoting demand response in the context of SAES in a way that is both socially and economically viable.

INTRODUCTION

Recent years have seen the emergence of a number of high profile Stand-Alone Energy Systems (SAES) around the world. Such systems are often the earliest adopters of alternative approaches towards the generation, storage and consumption of energy, and as such find themselves at the forefront of research and development in this field [1].

However, SAES projects are faced with a number of significant economic and regulatory challenges, many of which stem from the high cost of system components, in particular energy storage. These factors contribute to a perceived lack of SAES viability, and have limited the deployment of such systems to those areas which are worst served by the existing centralised energy supply model, and as such may be susceptible to security of supply interruptions, or exposed to rising energy prices. These locations - often remote or isolated communities - often have abundant local renewable energy resources, the use of which may be constrained by weak or even non-existent grid infrastructure.

In order to enhance the viability of SAES, accelerate their deployment and develop crucial knowledge and experience of the field, work is needed to increase the socio-economic viability of such systems. This study examines the ability of Demand Response (DR) to contribute towards this, through the use of dynamic energy pricing.

ACHIEVING DEMAND RESPONSE THROUGH DYNAMIC ENERGY PRICING

Demand Response (DR) is a term used to describe a process whereby consumers alter their pattern of energy consumption in response to certain triggers. Conventionally, these triggers are issued by system operators with the primary intention of reducing peak demand. In doing so, operators are able to avoid excessive operation costs, relieve network congestion and better reflect energy market conditions, while the responsive consumer benefits from financial savings.

Arguably the most effective way of achieving DR is by varying the cost of energy (often referred to as dynamic energy pricing). This is based on the principle that consumers will respond to price increases by reducing or deferring their consumption, and take advantage of price decreases by increasing demand during these periods.

Dynamic energy pricing in SAES

The use of dynamic energy pricing strategies in SAES is likely to vary from ‘conventional’ forms of dynamic pricing in a number of key ways. Firstly, the sale of energy within an energy system is conventionally facilitated using an ‘auction’ type negotiation process [2]. This approach is based on two key assumptions; namely that energy consumers wish to minimise the amount they pay for energy and that energy generators wish to maximise their profits by ensuring they receive the best price possible. However, in cases where the consumers and the generators are owned by the same party i.e. the community in/around which they are located (as is the case in many SAES), the latter of these assumptions becomes redundant. The aim in this context is therefore not only to minimise consumer energy costs but to ensure that the negotiation process always converges, so that energy demand cannot exceed energy supply for a given timestep. The negotiation process can therefore be seen as a symmetrical assignment problem.

The second major difference between dynamic pricing in SAES and conventional applications lies in the drivers of the price variations used to prompt DR. Whereas in conventional applications these variations stem primarily from the desire on the part of the network operators to avoid additional operating costs, pricing variations in SAES are likely to be based on the need for system balancing i.e. ensuring that demand does not exceed supply for any given timestep. Renewable energy generation profiles are therefore likely to form the basis for DR triggers in this context.

This alludes to a key theoretical advantage of the use of dynamic pricing in SAES - the ability to improve the correlation between supply and demand. This can potentially contribute towards reducing both the energy storage and generation capacity required within SAES, as well as increasing the levels of renewable energy penetration.

The reward table negotiation method

The use of a reward table negotiation method in the context of energy markets was first presented by Brazier et al.[3], and is representative of a negotiation based distributed optimisation algorithm [4]. It provides a structured negotiation process that takes place between energy suppliers and energy consumers, which is facilitated by a control agent. Following a monotonic concession protocol - which enables bidders to improve their bids as the negotiations proceed but not worsen them - ensures that the process always converges i.e. an agreement is always reached.

The negotiation process begins with the facilitator identifying the need for an overall reduction in demand for an approaching timestep. This triggers the issue of a reward table to consumers. The reward table consists of a series of reduced consumption values (expressed either as a percentage of the consumer's original demand forecast or in kWhs) each with a corresponding financial reward. Each consumer must then evaluate the rewards on offer and decide which, if any, level of demand reduction they are willing to accept. This decision is then communicated to the facilitator, who then updates the demand forecast accordingly before re-evaluating the need for further demand reduction. Should further reduction be required, a further reward table is issued, this time with the reward levels increased. Each consumer then either chooses to remain with their previous demand level, or agrees to further reduce their demand (note: the monotonic concession protocol prevents consumers from worsening their bids). This process repeats until either the maximum reward level is reached (i.e. the maximum value the facilitator is willing to pay for demand reduction) or the required level of demand reduction is achieved.

The use of the reward table method in SAES

The use of a reward table negotiation process can be regarded as highly suitable for use within the context of SAES. It rewards responsive demand behaviour rather than punishing non-responsive behaviour, i.e. highly responsive consumers are rewarded with a reduction in price as opposed to inflexible consumers being punished with raised prices is considered particularly important. This is due to the fact that it is more likely to result in increased levels of perceived social viability in real world applications, by protecting consumers from the risk of unpredictable and potentially high energy prices, and instead granting them 'safe' access to price reductions.

MODEL DEVELOPMENT

In order to examine the viability of dynamic energy pricing in SAES, it was necessary to develop a model which could be seen as being representative of a typical SAES. This section describes the model development process.

The importance of consumer demand elasticity

The response of consumers to dynamic pricing is a highly complex and phenomenon which is based on a number of social, economic and personal factors [5]. However, the use of a reward table method allows the price elasticity of demand to be used a crude proxy for consumer behaviour.

The literature suggests that demand elasticity is limited when it comes to energy consumption [4], [6]. However, this study posits that consumers served by SAES are likely to have higher levels of demand elasticity, as they are likely to have a greater knowledge of the need for demand flexibility than other consumers, and are likely to be more aware of sustainability issues than grid-connected consumers [1]. It is also considered likely that such consumers would also be willing to accept higher levels of demand flexibility, given that a SAES may to them still represent an improvement on the prevailing centralised energy supply model.

In order to represent the likelihood of significant variation in consumer demand elasticity, the demand data used in the modelling process consists of three different groups, each with differing levels of demand elasticity: low elasticity (representing 30% of the total demand), medium elasticity (50%) and high elasticity (20%). As shown in Table 1, demand elasticity (ε) also varies according to the level of demand reduction in question. This reflects the fact that minor reductions are likely to be more acceptable to consumers than major reductions. These values are based on literature [7] and reflect the short-term nature of the DR involved.

Table 1 - Variation of elasticity with to demand reduction level.

Demand reduction (relative to original forecast)	Price elasticity of demand (ε) values		
	High ε Consumers	Med ε Consumers	Low ε Consumers
0 to 20%	-0.6	-0.54	-0.48
20 to 80%	-0.2	-0.18	-0.16
80 to 100%	-0.067	-0.06	-0.053

Demand elasticity sensitivity analysis

Given the significant levels of uncertainty associated with consumer elasticity, a sensitivity analysis was conducted in order to examine the impact of variations in consumer elasticity levels upon modelling results.

In addition to the elasticity values selected for each of the three main groups mentioned above, another two sets of values were included in the analysis. The first of these represents a uniform 10% increase in elasticity across all groups (the high elasticity scenario), and the second a 10% decrease (the low elasticity scenario).

SAES system sizing using HOMER

In order to accurately quantify the impact of DR on the sizing of SAES when compared to typical demand data, a consistent sizing methodology is required. This is ensured through the use of HOMER modelling software - a tool used in the design and analysis of renewable and hybrid energy systems [8]. HOMER enables a number of sizing options to be analysed for each system component, and uses a sophisticated optimization algorithm to determine the optimum sizing solution.

Energy demand data

The base case energy demand data used in the model represents the electrical load of 100 typical UK domestic demand profiles, with an added diversity of 40%, at a resolution of 1 hour. Demand peaks at around 61.5kW, with a base load of around 8kW. This base case demand profile was then subjected to the reward table negotiation methodology detailed below.

Energy supply and storage

The technologies selected for inclusion in the analysis reflect the likely abundance of renewable energy resources in many existing SAES: wind, photovoltaics and small scale hydro power (it should be noted that only one sizing option was included in the analysis for hydro installations, in order to reflect the likelihood of the resource being dictated by local conditions). Due to the likelihood of its requirement in SAES, diesel generation capacity is also included, as is energy storage provision in the form of batteries.

Reward table algorithm development

The reward table negotiation method was adapted for its application within the context of SAES, with the need for a reward table issue being determined by the (forecasted) balance between demand and supply (which includes the contribution of energy storage) for any given timestep[1].

The first iteration of the negotiation process sees a standard, flat rate pricing level applied. Should the initial demand/supply forecasts predict an overall energy deficit for the coming timestep, the reward table algorithm reduces the price of energy for that timestep by 1% in an attempt to promote DR. The reward table issued to consumers consists of a series of incremental reductions in price relative to the starting flat rate. Each consumer is then free to determine the pricing reduction they require for each of the incremental demand reduction levels. It is anticipated that in reality, an element of automation would be present so as to ensure that consumers were not required to participate directly in the negotiation process every hour. The combined reward table for all three consumer types (based on the elasticity values presented in Table 1) is shown below in Table 2. As the price falls, greater levels of DR will be triggered, with consumers with higher elasticity of demand agreeing to reductions in demand before those with lower elasticity. It is expected that this DR will consist of a combination of demand reduction and load deferral, achieved either via direct consumer action or through automated load control.

Table 2 - Adapted reward table.

Demand relative to original forecast (%)	Required reward level of consumer elasticity groups (price relative to flat rate)		
	High ε	Med ε	Low ε
100%	100.00%	100.00%	100.00%
95%	97.00%	97.30%	97.60%
90%	94.00%	94.60%	95.20%
85%	91.00%	91.90%	92.80%
80%	88.00%	89.20%	90.40%
75%	87.00%	88.30%	89.60%
70%	86.00%	87.40%	88.80%
65%	85.00%	86.50%	88.00%
60%	84.00%	85.60%	87.20%
55%	83.00%	84.70%	86.40%
50%	82.00%	83.80%	85.60%
45%	81.00%	82.90%	84.80%
40%	80.00%	82.00%	84.00%
35%	79.00%	81.10%	83.20%
30%	78.00%	80.20%	82.40%
25%	77.00%	79.30%	81.60%
20%	76.00%	78.40%	80.80%
15%	75.67%	78.10%	80.53%
10%	75.33%	77.80%	80.27%
5%	75.00%	77.50%	80.00%

RESULTS

Before the impact and viability of dynamic pricing can be examined, a base case scenario was developed to provide a means for comparison. This was carried out using HOMER, and featured the standard demand profile described previously. This base case resulted in the specification of a range of renewable generation technologies, as well as a diesel generator. The resulting

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[1] Note: for the purposes of this study, both demand and supply forecasts are assumed to be totally accurate.

energy supply profile was then used to provide the supply data required for the reward table negotiation process, with only the non-dispatchable elements i.e. the renewable generators, included. This reflects that fact that only non-dispatchable generation profiles would be consistent under varying demand scenarios.

The impact of dynamic pricing on demand

The reward table negotiation method was then applied to the base case demand profile so as to introduce DR, with triggers coming from the non-dispatchable supply profile generated previously. This resulted in an overall demand reduction of 4.64%, with the standard flat rate price being applied in 88.8% of timesteps. Figure 1, below, shows the variation in the two demand profiles over the course of a winter week.

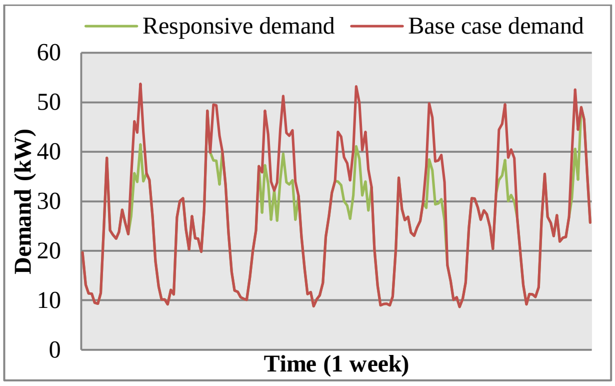

Figure 1 - Base case demand versus responsive demand over a winter week.

The impact of responsive demand on SAES sizing

The newly generated responsive demand profile was then used to replace the base case demand profile in the HOMER model, thus enabling a new SAES sizing solution to be modelled. The results of this simulation (shown in Table 3, below) show a significant decrease in the required levels of both energy storage and diesel generation capacity.

Table 3 - Impact of responsive demand on SAES sizing.

	Base Case	Responsive Demand	% Diff.
PV array (kWp)	1	1	0%
Wind (kW)	10	0	100%
Hydro (fixed at 20kW)	✔	✔	0%
Diesel generator (kW)	26	20	23%
Diesel consumption (litres/year)	2827	2741	3%
Battery storage (No. of 4V batteries)	48	32	33%
Converter size (kW)	25	20	20%

These results reflect the improved correlation between demand and supply profiles achieved by the introduction of the dynamic pricing strategy. The reductions made represent a significant decrease in the overall cost of the system, both in terms of initial purchase costs and of operating and maintenance costs.

Sensitivity analysis - consumer demand elasticity

The results of the demand elasticity sensitivity analysis are shown below in Table 4. They show the effect of a 10% variation in consumer demand elasticity levels to be negligible, with a variation in the occurrence of the flat rate pricing level of less than 2%, and a variation in overall demand reduction of 0.4%.

Table 4 - Consumer elasticity scenario comparison.

	Low ε Scenario	Med ε Scenario	High ε Scenario
Overall demand reduction (% of total)	4.64%	4.64%	4.60%
Occurrence of flat rate price (% of total timesteps)	86.49%	87.99%	89.40%
Average price (% of flat rate)	87.31%	88.76%	90.11%

Susceptibility to free-rider behaviour

Observable across all of the results obtained is the apparent susceptibility of this pricing strategy to 'free-rider' behaviour. This is due to the fact that the consumer group with the lowest demand elasticity i.e. those who are less responsive, receive a greater reduction in their average energy price than those in the medium and high elasticity groups. This is shown in Figure 2, which shows the average price for each elasticity group relative to the combined average price, for each of the three overall elasticity scenarios which comprise the sensitivity analysis.

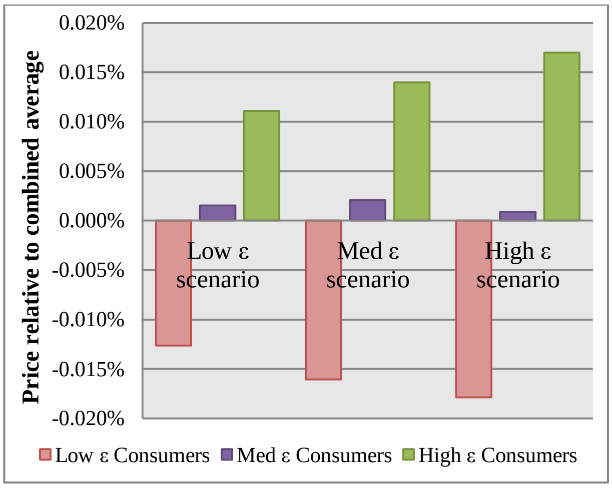

Figure 2 - Price variations in each elasticity scenario, illustrating the susceptibility to free-rider behaviour.

This shows the relative benefit gained by low elasticity consumers increases as overall elasticity levels increase.

DISCUSSION

The results illustrate the effectiveness of the featured dynamic energy pricing strategy (based on a reward table negotiation process adapted for the context) at achieving DR in SAES. The observed DR comes primarily in the form of 'peak shaving' and results in an overall reduction in energy demand, as the model does not explicitly cater for load-shifting.

As these results do not include specific cost data, further analysis is required to establish whether the resulting reduction in revenue from energy sales is likely to outweigh the savings achieved through reduced generation and storage capacity.

The sensitivity analysis has shown the impact of variations in consumer demand elasticity to be lower than anticipated, with the modelled variations having no impact on required generation capacity. However, consumer demand elasticity nevertheless still forms the basis of all dynamic energy pricing strategies.

The susceptibility of the presented strategy to free-rider behaviour, despite being small in magnitude (with a price variation between elasticity groups of less than 0.02%), represents a limitation to the overall viability of such a strategy, in that it can be seen to reward a lack of consumer responsiveness. Game theory would suggest that this could result in a gradual reduction in consumer demand elasticity over time, provided that consumers were aware of the demand elasticity levels of other consumers. This would therefore require careful management in any real-world application.

CONCLUSION

This study has demonstrated the ability of a conceptual dynamic energy pricing strategy (based on an adapted reward table negotiation method) to promote demand response in stand-alone energy systems. This in turn was found to significantly reduce the need for energy storage and fossil-fuel based generation capacity, thus improving the economic and environmental viability of such systems. This approach was also found to yield benefits in terms of social viability, due to the fact that it rewards responsive behaviour rather than punishing non-responsive behaviour.

However, various barriers stand in the way of the real-world deployment of such strategies. In the UK in particular, recent moves to simplify and reduce the number of available energy tariffs offered to consumers indicates the scale of the required shift in attitudes when it comes to demand response and the deployment of dynamic pricing strategies.

Future work will focus on further refinement of the reward table negotiation method and the inclusion of accurate system cost data, which will enable further analysis of the socio-economic viability of dynamic pricing strategies. The addition of an explicit load-shifting capability will also be used to add greater system flexibility. More accurate data regarding consumer demand elasticity data in stand-alone energy systems will also be sought.

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