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Abstract

We suggest a market design for rapid demand response in electricity markets. The solution consists of remotely controlled switches, meters, forecasting models as well as a flexible auction market to set prices and select endusers job by job. The auction market motivates truth-telling and makes it simple to involve the endusers in advance and to activate demand response immediately.

The collective solution is analyzed and economic simulations are conducted for the case of Kenya. Kenya has been suffering from unreliable electricity supply for many years and companies and households have learned to adjust by investments in backup generators. We focus on turning the many private backup generators into a demand response system.

The economic simulation focuses on possible distortion introduced by various ways of splitting the generated surplus from the demand response system. An auction run instantly as the Transmission System Operator (TSO) requests demand response and the winning endusers are disconnected immediately if the TSO accepts the result of the auction. The endusers are compensated with a uniform auction price job by job and the Aggregator receives part of the surplus.

The simulation captures the nature of the demand response system and reveals that a simple markup contract between the Aggregator and the TSO is sufficiently flexible and little distorting. The simulation also provide a the less intuitive result, that the auction motivates the TSO to offer a high markup contract to the Aggregator to motivate a large pool of demand response. We discuss how this may motivate the alternative owner structure where the Aggregator is a cooperative owned by the endusers themselves.

Keywords: Demand response, auction market, contracts, simulation

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1. Introduction

Balancing demand and supply of electricity on a real time basis is an increasing global challenge. The increasing uptake of uncontrollable renewable energy makes this balancing more challenging and hence requires more flexible consumption or backup production capacity ([15] and [18]). Furthermore, in developing countries economic growth may also be hampered by less developed electricity systems and markets. In this paper, we suggest a market solution for rapid demand response that may be part of the solution whether the problem stems from renewable energy and/or less developed electricity systems.

In particular, we consider the case of Kenya which has both an impressive economic growth and a high degree of renewable energy that makes regulating and balancing of the electricity system more challenging. In Kenya, like many other developing countries, companies and households have learned to adjust to the frequent outages, most prominent by investments in backup generators. Despite very ambitious development plans for the entire electricity system ranging from production to transmission and distribution, trajectories of future demand and supply of electricity suggest potential imbalances in both the short and the long run. Part of the solution for more stable power supply may be increasing Demand Response (DR). In this paper we describe a DR system and market institutions that aim at including DR to reduce on-grid demand in periods with imbalances on the grid. The sources for DR may be the existing off-grid backup generators (which is the primary use case in this paper), intelligent control of cooling and heating systems, street lighting, etc.

The technical solution consists of remotely controlled switches and meters. Together with forecasting systems, the meters can predict the available DR. The installations may be an entire firm (or household) that is backed up by a private generator or partial installations within a firm (or household) that may be disconnected without large consequences for shorter periods of time such as a cooling house.

The suggested market solution is a DR system managed by an Aggregator institution that signs contracts with endusers supplying DR as well as managing the DR as it is requested by the Transmission System Operator (TSO)[1]. The DR contracts work like an option where the enduser sets a minimum compensation and the Aggregator holds and sells the option to the TSO and exercises it on request. To our knowledge, there is no well-established market for DR in Kenya to date. Therefore, we suggest an auction market for pricing the requested DR jobs. The stated minimum compensation levels enter the auction as bids on the incoming DR jobs requested by the TSO. The auction provides incentives for the participants to tell their true minimum compensation a priori, as they sign up for a DR contract. Hereby, the suggested auction allows for optimal price and quantity coordination with limited enduser involvement.

[1] Depending on the way the electricity market is organized, it may also be the Distribution System Operator (DSO) that request DR. In the case of Kenya, as of 2014, Kenya Power is both the TSO and DSO.

The aggregator may be an independent private organization or a public organization (e.g. as an integrated part of Kenya Power). For the most part of the paper, we will consider the Aggregator to be an independent private organization owned by external investors. Later, we consider the case where the Aggregator is owned by the endusers supplying DR.

Based on limited information about the nature of the DR jobs and the endusers, the collective solution is analyzed and an economic simulation is done for the case of Kenya. The economic simulation focuses on the distortion introduced by various ways of pricing the DR as well as the nature of the auction solution. The endusers are compensated by the Aggregator with a uniform price job by job settled by the auction. We analyze three different surplus splitting contracts between the Aggregator and the TSO: A lump sum payment, a fixed price per kWh and a markup price type of contract. While the fixed price contract is too distorting, the simulation indicate that a markup contract is sufficiently flexible. A markup contract is easy to implement and probably the most preferred choice since it requires little a priori negotiation. The simulation also reveals how the competition introduced by the auction market, creates misalignment between the endusers, the Aggregator and the TSO in terms of increasing the pool of endusers. With markup contracts, the TSO may offer the Aggregator a high markup to motivate a large number of endusers, which will result in lower prices for DR. We discuss how this may motivate the alternative owner structure where the Aggregator is a cooperative owned by the endusers themselves.

The outline of the paper is as follows: Section 2 relates the paper to the existing literature and Section 3 introduces the proposed DR system. Section 4 provides the economic institutions and the suggested auction solution. Section 5 introduces the simulation framework and the results are presented in Section 6. Section 7 concludes.

2. Relation to the literature

Adequate, affordable and reliable supply of energy is considered crucial for economic growth and societal development and conversely erratic supply and inadequate infrastructure is a hindrance [5] and [17]. Reliable energy supply is believed to have strong effect on private investment and improves local business competitiveness [1]. Eberhard and Shkaratan [5] uncover that Sub-Saharan Africa countries, one of which is Kenya, face critical power problems including insufficient connectivity, poor reliability and high costs which all together constrain development. However, let alone the generally low access rate, reliability of electricity supply is a daunting problem in economies like Kenya where both scheduled and unplanned outages and power fluctuations are common. According to Eberhard and Shkaratan [5], due to frequent outages and undersupply of electricity, own generation constitutes significant proportion of installed capacity, that leads to the use of costly emergency power. Partly due to erratic functioning of public supply of energy, evidence indicates that in Sub-Saharan Africa own generation (with a recently increasing trend) accounts for 6% of installed capacity, the share ranging up to 20% in low income countries of the region [8]. The overall implication is that unreliable electricity has serious implications some of which are increasing business uncertainty, increased cost of production, reduced competitiveness, lower domestic investment and foreign direct investments, which ultimately retard economic growth and development.

Eberhard and Shkaratan [5] argue that the main channel through which deficient power infrastructure and unreliable energy supply constrains economic growth is due to its harmful effect on business productivity. For firms, unexpected power outages inflict other costs such as foregone sales and equipment damage, higher maintenance cost, switching costs, restart cost, lost man hour and spoilage of some production over and above the need to have standby power source [2]. Added to the higher cost of operating own generator, these extra costs reduce the quality and competitiveness of products and services undermining the return on investment [12]. In practice, it is not easy to measure and verify costs associated with unexpected blackouts.

Increasing and stochastic demand for electricity, costly investment in infrastructure, environmental concerns, and temporary demand peaks, among others, make it difficult to ensure reliable supply only through supply side interventions. This calls for innovative management of demand side resources [19]. Activating consumers to adjust their electricity consumption behavior through price signals and/or incentivized contracts would improve market efficiency and system reliability besides reducing consumers' power bills ([13], [11] and [7]). Moreover, with active involvement of endusers, demand side management reduces the need for costly spinning reserves [16]. This helps to avoid or postpone the construction of new generation units and grid expansion, and reduces greenhouse gas emissions thereby contributing for environmental and social improvement. Besides, effective load management with smart technologies would reduce transmission and distribution losses.

According to Ramini and Ipakchi [13], a well-designed and correctly implemented DR, promotes market efficiency and operational reliability even with increased profusion of variable generation. For effective implementation of smart demand response, a set of accompanying technical solutions such as smart grids, remote switches, prediction/forecasting models, programmable implements on enduser premises are crucial. Besides the technical solutions, other factors including geography, consumer awareness, market institutions and regulatory environment matter for the success of such programs.

Though advances in communication technology and metering have heightened the potential of demand response, the development of appropriate business model has been a critical challenge in actual implementation and exploitation of this promising load management system [11]. Large scale involvement of endusers in demand management programs can be organized by aggregators [10]. Ikheimo et al [9] identified four main drivers for the increasing demand for DR aggregators: increasing concern for electricity emissions, increasing distributed and variable electricity generation (e.g., wind electricity), increasing role of elec-

[2] See e.g. the UMEME enduser study [6].

tricity, costly nature of electricity generation facilities and cost effectiveness of demand side flexibility compared to supply side response.

Notwithstanding the fact that load aggregation offers several benefits, there is no clear cut agreement in literature as to who does the aggregation in a better way. DR aggregation can be administered by electricity distributor [9]. However, in practice, distributional concerns that the benefits accruing from DR have disproportionately gone to the utilities than consumers, has given rise to new business model relying on a third party Aggregators[3]. Ikheimo et al [9] summarized the main functions of a load aggregator as: to collect customer demand flexibility and provide access to the market and offer resources to market, collect requests and respond to them in an optimal way. From a case study on the Texas electricity market, [4] finds that management of residential air conditioning systems helps to shift peak electricity demand though total electricity consumption was increased due to the program. According to Ikheimo et al [9], a DR system which encourages both automated DR technology and involvement by third party Aggregators will result in efficient, low cost load reductions that are going to be profitable for all stakeholders.

3. The Rapid Demand Response System

The rapid DR system consists of three components:

- A monitoring and prediction system that maps available DR (from the endusers with a DR contract) on the electricity grid.
- Remotely controlled switches that can activate the DR immediately if necessary.
- Market institutions (e.g. contracts and price-setting mechanisms) that provide sufficient incentives for endusers to participate

The DR system is managed by an Aggregator institution that signs contracts with the endusers supplying DR. Meters and switches are installed at the endusers' premises and the consumption profile is estimated using forecasting models. The entire predicted consumption is mapped on a power grid and offered as DR to the TSO on immediately request. The Aggregator may be an independent private organization or a public organization (e.g. as an integrated part of Kenya Power).

An extensive user study carried out as part of the UMEME 24/7 project, indicates that the viable solution is to organize the endusers by a private organization that trades with Kenya Power [6]. The endusers indicate lack of trust in Kenya Power and that the endusers need to negotiate with Kenya Power as a group. Also, Kenya Power indicated the need for an institution to manage

[3] See https://sites.google.com/site/adscsmartgrid/incentive-pricing/demand-response (I cannot open link - most be a better way to ref or different ref)

the collective DR service[4]. Throughout the paper, we therefore consider a supply chain with a private Aggregator that signs contracts with endusers and the TSO.

We will primarily assume that the private Aggregator is investor owned and in parallel discuss the alternative owner structure where the Aggregator is owned collectively by the endusers themselves as a cooperative.

4. The Economic Institutions

We first consider the procurement situation and then introduce the auction market.

4.1. The Procurement Situation

We consider a procurement situation with a TSO that demands DR in kWh (DD) and a number of endusers that Supply DR in kWh (SD). Prior to that, we assume that the Aggregator (or market maker) has signed a framework agreement with N endusers and that the expected DR for each enduser has be constructed and made available by meters and remotely controlled switches. Hereby, we effectively assume that the DR from enduser i is verifiable[5].

More formally, assume that a risk neutral principal (the TSO) seeks to procure y kW DR for a time period of t hours or simply DD kWh[6] from one or more of N risk neutral endusers with a DR contract (this we will refer to as a "job"). The particular job may be local or global meaning that the set of eligible bidders that can actually solve the job may be less than N.

We assume that endusers (the agents) with a DR contract have a backup generator that can produce sufficient electricity to maintain their electricity consumption. We presume that the marginal cost of running a private generator (c^i) is constant but higher than the on-grid price for electricity p^{on}. With a uniform compensation (settled by a uniform price auction job by job) and constant marginal costs, the minimum compensation is independent of the length of the job[7]. We assume throughout the paper that the aim of the enduser is to maximize (expected) surplus from participating in a given job:

$$\pi^i = SD^i(\hat{p} - (c^i - p^{on})) \tag{1}$$

Where SD^i is i's supply of DR in kWh, $\hat{p}$ is the compensation paid to the enduser per kWh and p^{on} is the on-grid price for electricity during a job.

[4] Note that the suggested organization does not prevent the Aggregator from having Kenya Power to handle the actual billing based on information from the Aggregator, as suggested by some of the interviewed stakeholders [6].

[5] Manipulation of the consumption profile seems unlikely or equivalently assume that trustworthy metering can be costlessly enforced e.g. by a harsh penalty for deviations.

[6] The length of the job (t) is not known a priori.

[7] The UMEME enduser study support this assumption for jobs of a duration of a few hours [6]. For a job of longer duration, the operation costs may increase.

By assumption, DR is verifiable for each enduser i. Thus, possible strategic manipulations by the endusers only regard the cost, and the signal from each agent i is a quantity-price bid, (y^i, x^i), with the interpretation that if agent i is disconnected, the system demand load will drop with y^i kW if enduser i is paid at least x^i per kWh. By assumption, the endusers consume the same amount of electricity whether he is selected to startup his own generator or stays on-grid, therefore, the minimum price-bid is the difference between the on-grid price of electricity p^{on} and the private cost c^i.[8]

The Aggregator signs a contract with the TSO (the principal) that state a price $\hat{p}^{TSO}$ per kWh of DR. We consider three different pricing schemes (or surplus splitting contracts):

Lumpsum contract: The Aggregator and the TSO negotiate a lump sum payment a priori and TSO pays the uniform price settled by the auction, $\hat{p}^{TSO} = \hat{p}$.

Markup contract: The Aggregator and the TSO negotiate a percentage markup (α) to paid on top of the uniform price settled by the auction, $\hat{p}^{TSO} = (1+\alpha)\hat{p}$.

Fixed price contract: The Aggregator and the TSO negotiates a fixed price $(\bar{p})$ per kWh, $\hat{p}^{TSO} = \bar{p}$.

In all cases the Aggregator compensates the enduser with uniform price settled by the auction. Hereby, we assume throughout the paper that the aim of the Aggregator is to maximize (expected) surplus from a given job:

$$\pi^{Aggregator} = \sum_{i \in \tilde{n}} SD^i(\hat{p}^{TSO} - \hat{p}) \tag{2}$$

where SD^i is i's supply of DR in kWh and $\tilde{n}$ is the endusers that won the auction and then compensated with $\hat{p}$ per kWh.

Finally, the objective of the TSO (the principal) is to maximize (expected) surplus from a given job:

$$\pi^{TSO} = \sum_{i \in \tilde{n}} SD^i(\bar{p}^{TSO} - \hat{p}^{TSO}) \tag{3}$$

where SD^i is i's supply of DR in kWh and $\tilde{n}$ is the endusers that won the auction and then compensated with $\hat{p}$ per kWh. The TSO accepts only DR if $\bar{p}^{TSO} \geq \hat{p}^{TSO}$.

The TSO's request is a quantity-price bid, $(y^{TSO}, \bar{p}^{TSO})$, with the interpretation that the TSO's willingness to pay is $\bar{p}^{TSO}$ for a drop in system demand of at least y^{TSO} kW.

[8] Assuming that the auction promotes truth-telling as argued below, the optimal bidding depends on the on-grid price and the cost of operating the backup generator. In practice the on-grid price is observable and most likely fixed during a job and one may allow the endusers to express their required compensation hour by hour as known from power exchanges.

4.2. The auction market

Multi-unit auctions are widely used on electricity markets both for physical as well as financial electricity related products. The central component of a typical electricity market involves a double auction that mediate between multiple buyers and sellers. However, with a single buyer (the TSO) representing the supply side one-sided auction is the most relevant auction institution.

The literature on one-sided multi-unit auctions distinguishes between uniform price auctions and discriminatory auctions. In the former, all trade is done at the same price whereas in the later buyers pay the price they bid for each quantity. In particular the use of discriminatory prices in the US treasury auctions has been widely discussed in literature. The literature tends to favor uniform price auctions. However, when market power is introduced, multi-unit uniform price auctions do not have the same truth revealing properties as single-unit second price auction [2]. In a uniform price auction the bidders can use their market power to reduce the price on the auction by reducing their demand.

In a DR auction the quantity is the expected drop in electricity consumption. Meters monitor endusers' consumption and the estimated consumption profile is the quantity entering the auction. Therefore, any strategic demand reduction requires manipulation of the consumption profile, which requires persistent deviation from otherwise optimal consumption (assuming trustworthy meters and estimation of consumption profiles). This rules out strategic bidding and makes the endusers de facto price takers.

In an optimal multi-unit auction, each participant is given the opportunity to submit multiple bids for buying or/and multiple asks for selling in order to communicate a complete demand or supply scheme[9]. In case of DR, it might be that an enduser will switch-off the entire firm or just a subset of the firm's installations which may impact the required minimal compensation. Also, the minimal compensation may change from hour to hour do to changes in costs of operating the backup generator at different capacity levels.

Formally, consider a one-sided uniform price auction with a large number of endusers each submit a well-defined supply scheme represented by a set of quantity-price bids $(y_1, x_1), (y_2, x_2), \ldots, (y_L, x_L)$. Where y_l is the DR enduser i offers for sale at x_l. In this general representation, the supply scheme consists of L bids, one for each of the L possible bid prices. The supply scheme is assumed to be monotone in the price. That is, for any two prices p_h and p_l where $p_h \leq p_l$ we have $y_h \leq y_l$, i.e., a seller will supply at least the same when the price increases.

On the other side of the market the TSO requests DR by submitting a single price-quantity bid $(y^{TSO}, \bar{p}^{TSO})$, where y^{TSO} is the minimum quantity required to solve the imbalance and $\bar{p}^{TSO}$ is the maximal price that the TSO is willing to pay. The TSO's reservation price is bounded by the cost of alternative ways to solve the imbalance e.g. by disconnecting parts of the grid or increase the production of electricity one way or the other.

[9]For a detailed discussion of the importance of allowing multiple bids and asks, see [3]

Now the aggregated supply is found by summing up the supply for each feasible market clearing price. Let n be the number of endusers (sellers) that can potentially be activated during a DR event and j be the associated counter. For any market clearing price p_l, $l = 1, 2, \ldots, L$, the aggregated supply is $AS_{p_l} = \sum_{j=1}^{n} y_l^j$.

We will assume that the imbalance problem is solved only if the full request is meet. Therefore the market clearing price is the lowest price that ensure the smallest positive excess supply, where excess supply is defined as $Z_{p_l} = AS_{p_l} - y^{TSO}, \forall l = 1, 2, \ldots, L$. All trades are executed at the uniform market clearing price $\hat{p} = \arg\min_{p_l, l=1,2,\ldots,L}\{Z_{p_l} \mid Z_{p_l} > 0\}$.

Since the sellers have committed to supply DR at prices exceeding their respective stated minimum compensations and since meters and remotely controlled switches have been installed, the DR can be delivered immediately.

The auction rules:

Step 0: The endusers submit quantity-price bids (y^i, x^i) stating the minimum compensation (x^i) required to disconnect i and the DR in kW (y^i).

Step 1: The TSO requests y^{TSO} kW for an unknown period of t hours.

Step 2: The $n \in N$ endusers that can solve the job enters the auction automatically.

Step 3: The Aggregator solve the uniform price auction and settle the smallest uniform price $\hat{p}$ that result in the smallest excess supply of DR relative to the requested y^{TSO} kW.

Step 4: The Aggregator computes the $\hat{p}^{TSO}$ and the TSO accepts all offers below $\bar{p}^{TSO}$

Step 5: The selected endusers are disconnected for a period of t hours.

Step 6: The selected endusers are compensated with $\hat{p}$ per kWh for all $y^i \cdot t$ kWh at the end of the job.

This auction market turn the traditional intraday auction market (or capacity market) upside down by pre-organizing the DR capacity and make it accessible and hereby allowing the TSO to request jobs i.e. run an instant auction to solve an incoming job.

This approach has similarities with different auction markets such as the so-called AdWords auctions (also known as position auctions) where the prices for sponsored links primarily on Google and Yahoo are settled by an instant auction as a user clicks on a sponsored link, see e.g. [14]. Like AdWords auctions, the endusers submit preferences in advance and an auction is conducted instantaneously as the TSO requests DR. The incentives to bid truthfully together with the simple operational cost structure of running a generator, makes it possible to articulate preference a priori in a simple and manageable way.

As explained earlier, the system does not allow the endusers to exercise any market power for multiple reasons: 1) the quantity is a consumption profile estimated over a longer period of time, 2) there is a larger number of endusers, 3) the endusers may randomly participate in many different auctions (jobs). For these reasons we assume that the endusers' minimum compensation (x^i) is equal to their reservation price (p^i).

On the other side of the market, the TSO is the only buyer of DR and as such a monopsonist. Nevertheless, we argue that this natural market power is not a problem for the suggested market design. If the TSO successfully utilizes its market power, then the social welfare decreases. Therefore, the TSO as social planner has no incentives to exercise market power. On the other hand, if the TSO maximizes its private profit, reducing the requested DR may reduce the market clearing price. In principle, the TSO may iteratively change the requested DR and exploring different market clearing prices. However, the very reason for requesting DR is to solve a critical problem, therefore, it is unlikely that the TSO will exercise its market power and buy less. If the TSO has a cheaper alternative, then that is of course preferred to the TSO and reflected in the TSO's reservation price ($\bar{p}^{TSO}$).

5. The simulation framework

Based on the market solution presented in Section 4 we now introduce a simulation framework that allows us to analyze the economic outcome. The primary focus is the nature of the suggested auction market and the choice of the surplus-spitting between the three players; the endusers, the Aggregator and the TSO. The absolute magnitude of the numbers merely serves as a first indication of value added by the suggested DR system.

The applied simulation compensates for the lack of detailed information about the two primary inputs: 1) the distribution and nature of the DR jobs and 2) the distribution and nature of the available DR. Aggregated information about overall system demand, literature studies as well as collected information from two rounds of user surveys in Kenya are used to set likely priors in order to randomize and simulate various scenarios [6].

The simulation captures "a day" divided into h periods ($h = \{1, 2, 3, 4\}$), which reflects the system demand presented in appendix A:

- $h = 1$ low demand (22:30 to 4:30)
- $h = 2$ increasing demand (4:30 to 9:30)
- $h = 3$ high demand (9:30 to 18:30)
- $h = 1$ peak demand (18:30 to 22:30)

The simulation considers a single DR job in each of the h periods with a duration of one hour. Hereby, the simulation mimick a day consisting of 4 jobs of one hour each. To derive yearly numbers, this "simulated day" is simply multiplied by 50. These numbers are supported by Enterprise Surveys conducted by the World Bank in 2007 and 2013[10]. The survey from 2007, reports on average seven power outages in a typical month in Kenya with average duration of 3.1 hours. The more recent survey from 2013 reports a modest reduction in the number of average electrical outages. However, the average duration of outage in a typical month has rised to 4.9 hours. This was also reflected in about 86.7% (3% in 2007 to 5.6% in 2013) increase in loss due to outages as a percentage of annual sales. Relative to the statistics from the 2007 survey, proportion of firms having or sharing a generator has rised by about 74.77% (from 32.5% to 56.8%) in 2013. In both enterprise surveys unreliable electricity was remarked as a major impediment for large firms relative to small and medium sized firms. Perhaps because many businesses have heavily invested in backup generators, the percentage of firms identifying electricity as a major constraint has declined by about 41% (38.9% in 2007 to 22.9% in 2013).

For each of the four periods a different set of upper and lower bounds about the jobs and the endusers to solve them is settled. The TSO's Demand for DR (DD) is measured in MWh[11] and the associated reservation price $\bar{p}^{TSO}$ are independently drawn from a uniform distribution according to Table 1. Likewise, the endusers' supply of DR (SD) and the associated minimum bidding price p^i is independently drawn from a uniform distribution as shown in Table 1.

The simulation capture different scenarios for the total number of endusers $N = \{50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600\}$ that hold DR contract with the Aggregator[12]. To reflect the situation that not all of the N endusers would be needed to solve a given job, n endusers that can solve a given job is selected as follows:

- In 50% of all cases $n = N$ (a global imbalance problem)
- In 50% of all cases n is selected as a fraction reflecting the relative size of the job as follow (a local imbalance problem):
  - If $DD^h/DD^{h,max} < 0.25$ then $n \in U(0.05N; 0.195N)$ for $h = \{1, 2, 3, 4\}$
  - If $0.25 \leq DD^h/DDh, max < 0.25$ then $n \in U(0.05N0.195N)$ for $h = \{1, 2, 3, 4\}$

[10] In number of outage hours the rough estimate of 50 times the simulated 4 jobs, is approximately 29% less than the results in the 2007 World Bank survey. The UMEME project has not been able to collect more precise numbers on the actual outages.

[11] The time period for a given DR job (t) is left out since all simulated jobs last one hour each.

[12] Current statistics shows that as of 2014, there are a total of about 126,000 businesses registered in Kenya with annual business entry rate of about 5% (http://www.tradingeconomics.com/kenya/total-businesses-registered-number-wb-data.html). The 2007 World Bank Enterprise Survey reports that about 65.7% of manufacturing firms included in the survey own or share backup generators and the similar 2013 Enterprise Survey reports a significant increase in the number of firm having backup generators in general. On this basis we assume that it is reasonable to consider 600 firms signing a DR contract with the Aggregator.

– If $0.5 \leq DD^h/DD^{h,max} < 0.75$ then $n \in U(0.15N0.75N)$ for $h = \{1, 2, 3, 4\}$

– If $0.75 \leq DD^h/DD^{h,max} < 1$ then $n \in U(0.4N; N)$ for $h = \{1, 2, 3, 4\}$

In each simulation round 4 jobs are drawn (one for each of the h periods) and the n endusers that can help solving the job is created.

Table 1: Simulation framework

Scenarios		Jobs TSO)	Endusers
LOW	Quantities	$DD^{h=1} \in U(0.01; 10)$	$SD^{h=1} \in U(0.01; 0.4)$
		$DD^{h=2} \in U(0.01; 20)$	$SD^{h=2} \in U(0.01; 0.6)$
		$DD^{h=3} \in U(0.01; 35)$	$SD^{h=3} \in U(0.01; 0.8)$
		$DD^{h=4} \in U(0.01; 50)$	$SD^{h=4} \in U(0.01; 1)$
	Prices	$p^{TSO,h=1} \in U(8; 32)$	$p^{i,h=1} \in U(5; 30)$
		$p^{TSO,h=2} \in U(8; 32)$	$p^{i,h=2} \in U(5; 30)$
		$p^{TSO,h=3} \in U(10; 40)$	$p^{i,h=3} \in U(5; 30)$
		$p^{TSO,h=4} \in U(10; 40)$	$p^{i,h=4} \in U(5; 30)$
MEDIUM	Quantities	$DD^{h=1} \in U(0.01; 10)$	$SD^{h=1} \in U(0.01; 0.4)$
		$DD^{h=2} \in U(0.01; 20)$	$SD^{h=2} \in U(0.01; 0.6)$
		$DD^{h=3} \in U(0.01; 75)$	$SD^{h=3} \in U(0.01; 0.8)$
		$DD^{h=4} \in U(0.01; 100)$	$SD^{h=4} \in U(0.01; 1)$
	Prices	$p^{TSO,h=1} \in U(8; 32)$	$p^{i,h=1} \in U(5; 30)$
		$p^{TSO,h=2} \in U(8; 32)$	$p^{i,h=2} \in U(5; 30)$
		$p^{TSO,h=3} \in U(10; 40)$	$p^{i,h=3} \in U(5; 30)$
		$p^{TSO,h=4} \in U(10; 50)$	$p^{i,h=4} \in U(5; 30)$
HIGH	Quantities	$DD^{h=1} \in U(0.01; 30)$	$SD^{h=1} \in U(0.01; 0.4)$
		$DD^{h=2} \in U(0.01; 70)$	$SD^{h=2} \in U(0.01; 0.6)$
		$DD^{h=3} \in U(0.01; 110)$	$SD^{h=3} \in U(0.01; 0.8)$
		$DD^{h=4} \in U(0.01; 150)$	$SD^{h=4} \in U(0.01; 1)$
	Prices	$p^{TSO,h=1} \in U(8; 32)$	$p^{i,h=1} \in U(5; 30)$
		$p^{TSO,h=2} \in U(8; 32)$	$p^{i,h=2} \in U(5; 30)$
		$p^{TSO,h=3} \in U(10; 40)$	$p^{i,h=3} \in U(5; 30)$
		$p^{TSO,h=4} \in U(10; 50)$	$p^{i,h=4} \in U(5; 30)$

Figure 1 below illustrates a simulation round. It starts by drawing a job (y^{TSO} MW DR requested by the TSO), then the n endusers that can solve the job is drawn (y^i MW DR and the minimum reservation price p^i) and the TSO's reservation price ($\bar{p}^{TSO}$) is drawn. With this input in place, the auction is solved with respect to the job, the available DR and the TSO's reservation price. Since the contract that splits the surplus between the Aggregator and the TSO influences the price that the TSO meet, it also influences the outcome of the auction. To capture this, a simulation round computes different auctions results reflecting the three different types of surplus splitting contracts.

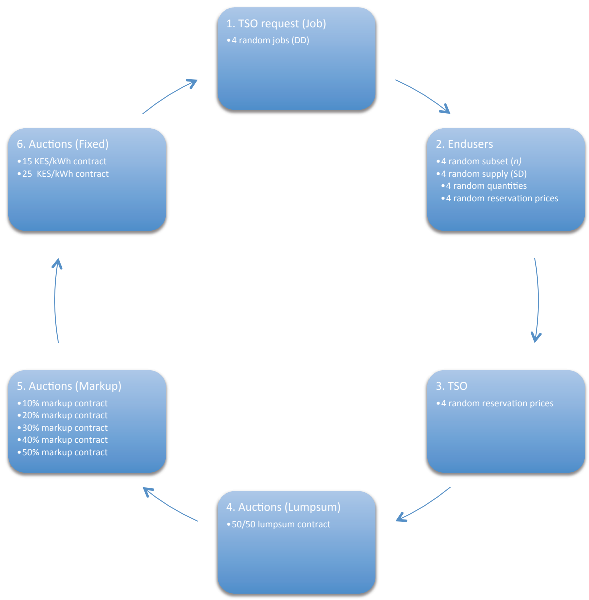

Figure 1: A simulation round with results from the 8 different surplus splitting contracts and the $h = 4$ different periods.

6. The simulation results

In this section we present selected sets of simulation results. As mentioned above, the simulated results are multiplied by 50, as a best guess to reach yearly numbers. All monetary numbers are reported in Kenyan Shillings (KES)[13].

The simulation captures the nature of the incoming DR jobs and how these jobs are priced with the suggested auction market. On one hand, the absolute numbers are only a rough indication of the potential surplus that can be generated by the DR system. On the other hand, the numbers provide insights into the nature of the DR system and the potential distortion from various contracts with the TSO as well as competition between the endusers created by the auction market.

The following set of results have been computed for the 3 main scenarios (Low, Medium and High):

Solved jobs: The average percentage of requests by the TSO meet 100% by the DR system.

Quantity of DR: The average number of MWh of DR bought by the TSO.

[13]By November 12. 2013, one US dollar equals 85.75 KES.

Surplus generated: The average surplus to the 3 players involved in the DR program plus the sum of the surplus from the endusers and the Aggregator (the Coop).

Number of endusers activated: The average number of endusers with a DR contract that has been activated during a DR job.

All results depend on the choice of surplus-splitting contract between the Aggregator and the TSO. The above set of results were computed for 3 types of contracts (in total 8 different contracts):

Lump sum contract: A non-distorting 50/50 surplus splitting contract.

Markup contract: 5 different markup contracts that leave the Aggregator with respectively 10, 20, 30 , 40 or 50 % of the market clearing price on the auction.

Fixed price contract: Two fixed price contracts that fix the price paid by the TSO to 15 or 25 KES/kWh.

In the following we provide a selected set of these results.

The first observation is that the fixed price contracts are not sufficiently flexible to handle the changing nature of the incoming DR jobs as well as the diversity of endusers that may solve the jobs. Too high fixed prices make the TSO accept less DR and too low fixed prices leave the Aggregator with a deficit.

While the lump sum contract avoids distortion, it requires a difficult negotiation about the size of the actual lump sum paid to the Aggregator prior to the realization. We assume that the surplus to the TSO given the market clearing prices settled by the auction, is split 50/50 between the TSO and the Aggregator. This is clearly a very strong assumption not least because the TSOs reservation price is private information and that the TSO has no incentives to share this information. In a repeated negotiation about the size of the lump sum payment, the TSO will learn the price of DR by the auction market unlike the Aggregator that only observe whether the TSO accept or reject prices and not the actual reservation prices. For these reasons, we will mainly consider the lump sum contract as a benchmark and it appears as such in Figure 2. As one would expect, the percentage of jobs solved with lumpsum contract is consistently higher than that of the other contracts.

The markup contract is sufficiently flexible. Unlike the fixed price contract, the Aggregator is always left with a positive surplus and the distortion is limited though increasing as it follows the market clearing prices settled by the auction market. Relative to a lump sum contract the turnover drops in the high scenario with around 5% in case of 350 contract holders ($N = 350$) and a 10% markup contract. With a 30% markup contract, the turnover drops with 14% relative to a lump sum contract and with 23% for a 50% markup contract. For medium and low scenario these relative numbers are smaller.

In Figure 2 we have the aggregated surplus in 1000 KES for the endusers, the Aggregator and the Coop (the endusers and the Aggregator collectively) as

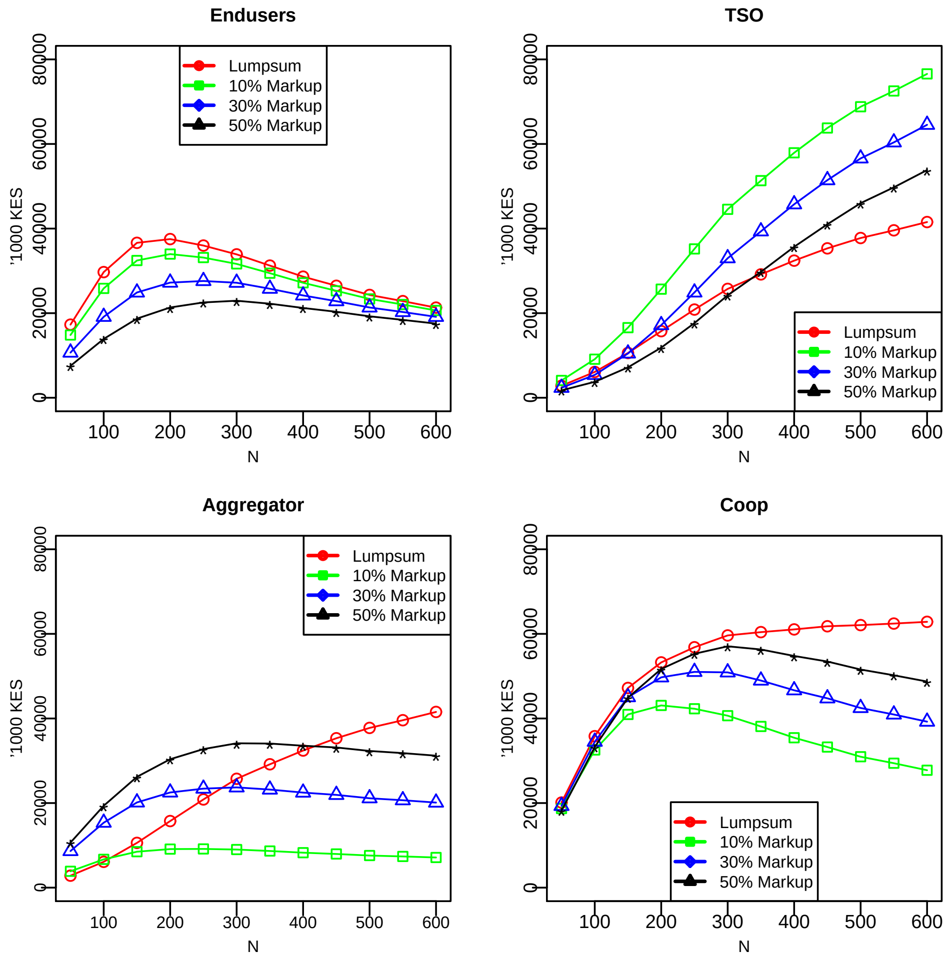

Figure 2: The surplus generated with different surplus splitting contracts, divided into the different economic agents: The endusers, the Aggregator, the Coop (the endusers and the Aggregator collectively) and the TSO.

well as the TSO. The surplus is plotted against N the size of the Aggregator in terms of members with a DR contract. All results are from the medium scenario in Table 1.

Starting with the endusers in Figure 2, the plot clearly show the competition introduced by the auction. For a low number of endusers additional endusers increases the aggregated surplus simply because more auction results are accepted by the TSO and more jobs solved. At some point, the competition between the endusers decreases the aggregated surplus. The auction enhances this competition such that the DR jobs are solved at cheap as possible. The plots also picture the distortion introduced by the different surplus splitting contracts. At the top is the lump sum contract where the TSO is facing the auction price and no distortion is introduced. For the 3 markup contracts, the distortion increases as the TSO is charged an increasing price i.e. the endusers prefer a low markup contract.

For the Aggregator in Figure 2, the plot shows that the surplus from the markup contracts follows the auction prices and that it increases as the markup increases, i.e. the Aggregator prefer a high markup contract. Also, compared with the endusers the preferred number of contract holders is a little larger - the turning point of the curves are a little further to the right. Finally, the lump sum contract indicate that the DR system add additional values beyond 600 members.

The plot for the Coop in Figure 2 combines the endusers and the Aggregator. As illustrated by the plot and discussed further below, the coop will improve the alignment of the three agents. In other words, if the endusers own the Aggregator, the Aggregator and the endusers will jointly prefer a high markup contract.

Finally, the plot for the TSO in Figure 2 illustrates that the DR system add additional values beyond the 600 members. At first, it seems that the TSO would prefer a low markup contract. Though, less intuitive, the TSO may in fact prefer a high markup contract if it results in a larger pool of DR contract holders i.e. a higher N. In Figure 2 we can see that with a 30% markup contract the Aggregator would approximately prefer N=300. Now if N increases to above approximately 375 the Aggregator and the TSO is better off with a 50% markup contract. This however, lowers the surplus to the endusers. If that causes difficulties for the Aggregator in raising the pool of DR contract holders, the TSO may prefer to trade with an Aggregator owned by the endusers as oppose to a privately held Aggregator, to align the incentives and make the auction market drive down the price for DR. In case of a Coop, the TSO and the Coop would prefer a 50% markup for N between approximately 375 and 500. For N above 500 the competition among the endusers drives down the auction price and consequently the markup to a level such that the Aggregator would be better of with the initial 30% markup contract.

As indicated above, it is likely that the TSO and the Aggregator may agree on a high markup contract. In Figure 3 we present the results for the 30% and the 50% markup contract for respectively the medium scenario and the high scenario. The axes are the same but now we plot the aggregated surplus for the different agents in the same plot.

The overall shape of the different curves in Figure 3 is the same in all of the plots but the turning points differ. While Figure tells the same story as in Figure 2 the changes that comes from increasing demand for DR is reflected in the plots. Going from medium to high scenario moves the turning point to the right towards a higher N (a larger pool of DR) for both a 30% and a 50% markup contract. The less intuitive results that the TSO may offer a high markup contract is also reflected in Figure 3, and the Figure shows how this result changes as the demand for DR increases. In high scenario the Aggregator

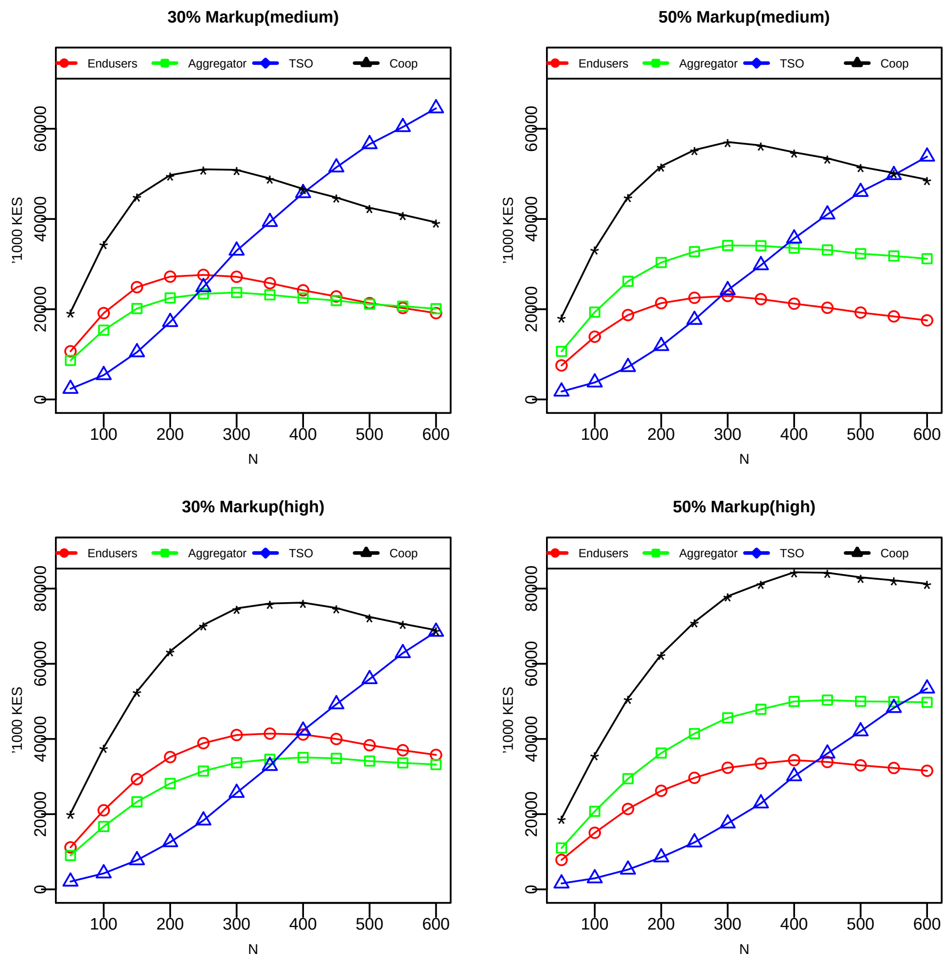

Figure 3: The surplus generated to the players, divided into the two markup contracts: The 30% and the 50% markup in respectively medium and high scenario.

and the TSO may both prefer a 50% markup contract if N increases to more than approximately 500. Also the turning point for the Coop moves to the right towards a higher N as the markup increases from 30 to 50%. Therefore, again if the Aggregator has difficulties in raising the pool of DR contract holders, the TSO may prefer to trade with an Aggregator owned by the endusers as oppose to a privately held Aggregator.

7. Conclusion and discussion

The technological possibility to measure and map available DR and to activate it immediately using remotely controlled switches is the foundation for the suggested DR system. As studies show, the nature of the incoming DR jobs and endusers available to solve these, changes a lot from job to job. This requires the market solution to be as flexible as the technological solution. The suggested market solution makes it easy for the endusers to articulate their preferences in advance and for the TSO to run and activate an auction instantaneously as a job appears.

Although the economic simulation of the market solution, relies on limited data it still capture the nature of the suggest auction solution and the importance of choosing a flexible surplus splitting contract between the Aggregator and the TSO. While a fixed price contract is appealing in terms of communicating prices, it distorts the DR system and leaves many DR jobs unsolved. On the other hand, a lump sum contract maximized the welfare generated by the DR system, however it requires an a priori negotiated splitting of the generated surplus or a trustworthy method to measure the surplus. In either case, it relies on private information about the TSO's reservation price of DR and as such a complex negotiation. Fortunately, the simulation shows that a simple markup contract that allocates a percentage of the otherwise efficient auction prices to the Aggregator is little distorting.

The simulation reveals an interesting nature of the DR system. While the auction drives down the price for DR, the TSO prefers a large number of competing endusers. The Aggregator on the other side receives a markup on top of the decreasing market clearing price. This indicates that the TSO and the Aggregator should be able to settle on a high markup contract in order to motivate the Aggregator to sign more contracts with endusers. However, the resulting lower prices to the endusers may cause tensions as the number of DR contracts increases - both for the endusers that hold a contract and for those that enter a contract. We conclude that this nature may count for a different owner structure of the Aggregator where the endusers get residual income as in a cooperative.

The suggested DR system is well suited to activate available resources like the many backup generators in an economy like Kenya with less developed electricity markets. However, the suggested solution may be used equally well in more developed electricity systems to help solving the challenges from e.g. an increasing uptake of wind power. Buffers such as biogas or a cooling house may function as DR like the backup generators in this paper and be made available for instant pricing and activation with the suggested rapid demand response system.

8. Appendix A

Figure 4 below is a plot of system demand for the period covering 1st July 2011 to 30 th June 2012.

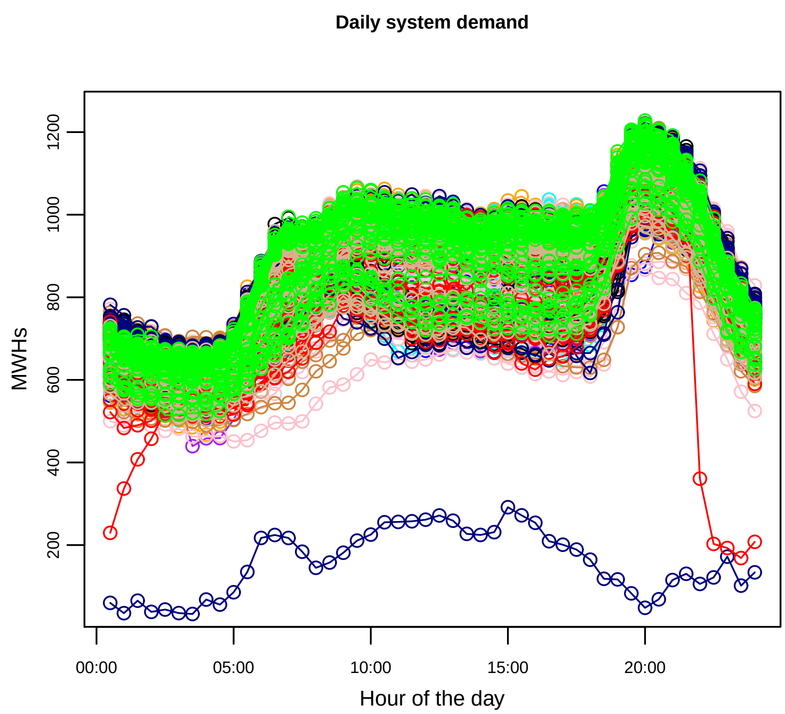

Figure 4: System demand for the period covering 1st July 2011 to 30th June 2012. Source: Kenya Power.

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