A Historical Perspective and Business Model for Load Response Aggregation Based on Priority Service

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Abstract

We review early technologies and experiments in the 1980's for implementing demand response. We argue that while new smart grid technologies are cheaper and provide more functionality the barrier to demand response implementation at the retail level lies in the development of business models that will incentivize customer participation on the retail side and facilitate integration of the aggregate responses into the wholesale market. We then describe such a model that is based on the concept of priority service where customer can choose different levels of interruption for segments of their loads which they can reallocate at will within the household. We review the theory of efficient pricing of such service along with alternative implementation forms. We then illustrate by means of an example the potential economic gains of such an approach.

1. Introduction

New metering and control technologies being introduced under the umbrella of the "Smart Grid" make demand response mobilization in the power grid viable from an economic and technical perspective. However, from a methodological perspective the key ideas in this area date back to the 1980's. In their Seminal paper [1] Schweppe et. al. describe the concept of Homeostatic Control which articulates a vision that encompasses most of the demand response concepts currently embraced as part of a smart grid. In particular they state "Homeostatic Utility Control is an overall concept which tries to maintain an internal equilibrium between supply and demand. Equilibrating forces are obtained over longer time scales (5 minutes and up) by economic principles through an Energy Marketplace using time-varying spot prices.". In a subsequent paper [2] Gellings describes a "load control system for residential and small commercial buildings [that] limits consumption during peak demand periods and is set by the customer according to a rate agreements with the utility. It will prevent appliances such as dryers or water heaters from operating simultaneously if their combined load exceeds the maximum allowed. The translator interprets meter data for the logic circuitry, which controls appliances through the communicator."

In [3] Arthur Rosenfeld, a pioneer in energy efficiency area and his coauthors describe the experimental credit and load management system (CALMS) in the UK and its underlying technology and economics.

Load management programs have been implemented during the 1980's in various systems in the US and abroad. For instance EDF implemented a three level tariff (Red, Green and Blue) using a relatively simple technology that would signal to customers by means of a colored light indicator which tariff is active. In its June 17, 1985 issue Electric Utility Week published an article describing the Massachusetts Department of Public Utility (DPU) ruling requiring that Boston Edison offer interruptible rates to all its customers by October 1, that year which will offer a "menu of prices, with the lower prices having longer and more frequent interruptions than the higher prices". In [4] Gorzaeinik describes a thermostatic load control program implemented at OG&E which employed a "temperature activated load controller that senses outside air temperature to control customer air conditioning units by reducing the compressor duty cycle to 75%.". Customer willing to install the device received a discount on their monthly bill. Interruptible service tarrifs with different levels of demand charges and energy charges with corresponding levels of curtailment frequency and notification were implemented by PG&E under Tariff E20 that was offered to industrial and commercial customers. Southern California Edison (SCE) offered several innovative load management programs to industrial commercial and residential customers. Figure 1 shows an interruptible service program with a menu of service options which was offered to customers with load over 500MW.

SCE also offered an air conditioners cycling program that offered several options for the percentage reduction in the compressor duty cycle and

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compensated customers according to the selected option and the size of the air conditioners as shown in Figure 2. The program was widely promoted using the actor George Burns as a spokesman. In its proposal to the CPUC SCE targeted 65,000 installations of the air conditioner cycling controller by 1984 which would have provided 130MW of load relief in case of a system shortage.

Figure 1: Interruptible Tariff Offered by SCE to Customers with Load Exceeding 500MW

Interruptible Schedules

Monthly Billing Credits	I-2	I-3	I-4
10-minute rate	\$3.10/kW	\$1.50/kW	\$1.00/kW
30-minute rate	2.60/kW	1.00/kW	.50/kW
2-hour rate	—	.50/kW	.00/kW
Additional if interrupted during month		3.00/kW	2.50/kW

The number of periods of interruption will not exceed an average of 15 times or 180 hours per calendar year over a five-year period (except for Schedule I-4, which is for one year).

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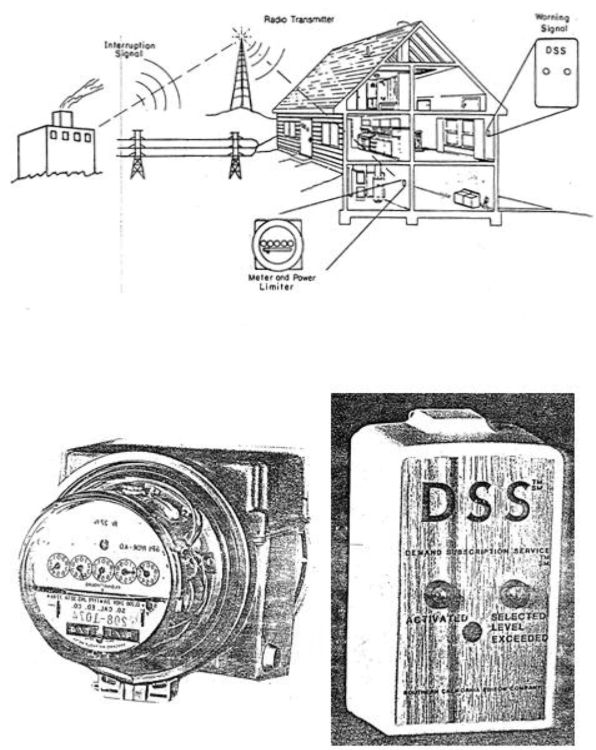
Figure 2: The SCE Air Conditioner Cycling Program.

Another innovative experimental program at SCE which is the foundation of the discussion in this paper was the Demand Subscription program. Under that program customers could subscribe to a fuse size limit to be activated remotely (via radio signal) when the system experiences shortage (with a limit on the frequency and total number of activations). Customers subscribing to the program were offered a monthly rebate based on the difference between their historical load (using a weighted average of annual and monthly peak load) and the subscribed level. Figure 3 illustrate the architecture of the system and the metering and warning units installed at the customer's premises.

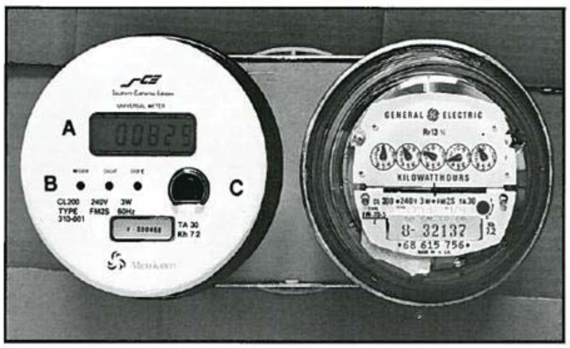
Before activation of the fuse limit, a customer would get a 30 minute warning to reduce load to the subscribed level. Failure to comply resulted in total power loss which could be restored after the appropriate load reduction. The key feature of this approach is allowing the customer a choice such as whether to watch a football game or keep the air conditioner running during a curtailment period, as opposed to the more intrusive load control paradigm where the utility directly controls appliances on the customer side of the meter.

Figure 3: Demand Subscription Service Architecture, Metering and Warning Hardware



In Fall of 1986 SCE also launched its NetComm project whose goal was to install smart meters (see Figure 4) that "will allow Edison to offer a more cost sensitive rate structure and will allow the customers to make price-conscious choices regarding electrical consumption.". Unfortunately most of the demand response initiatives were discontinued or suspended in the early 1990's due to the recession that caused a big drop in electricity demand and a large drop in oil prices and energy prices in general. Metricom which produced the NetComm smart meters ended up using the technology to launch Ricochet the first wireless network service for PCs

Figure 4: The NetComm Smart Meter.



While today's metering and control technology is cheaper and significant technological advances made since the 1980's enable much more functionality at affordable costs, arguably, technology was never a barrier to implementation of demand response. The focus has been (as now) on demonstration of capability, rather than on development of a business model that will facilitate implementation.

We argue that the key elements to making demand response a reality are: a regulatory framework, Institutional structure and a sustainable business model that will incentivize customer choices at the retail level. Furthermore, such a business model should recognize system operations realities and aggregate retail load response into wholesale products that are useful and competitive in a wholesale market environment. In this paper we will describe such a model that is based on the concepts of efficient rationing and priority service pricing introduced in [5][6][7]. The context has changed since the theoretical development in these references was targeted for a regulated utility implementation as opposed to the current restructured electricity market where the role of load response aggregation has shifted to the private sector. In [8] Chao provides an update of the original priority service concept adapted to the context of a competitive electricity market with a smart grid. The technological capability has also changed dramatically from the simplistic demand subscription framework described above to smart meters that enable a more sophisticated implementation with multiple levels of service, which at the time the original priority concept was introduced was more of a theoretical construct than a readily implementable idea.

The purpose of this paper is to review the basic concept of priority service in an updated market and technological setting. Our goal is to revisit this paradigm as a business model for a load response aggregator whose business is to aggregate retail level demand response into wholesale products that can be offered into the ISO wholesale energy markets.

2. Alternative Demand Response Paradigms.

There are two fundamental approaches to demand side management in electricity service that parallel the classical price vs. quantity control in economic theory. The first approach is to provide real time prices to retail customers who will respond to such prices by adjusting their consumption either directly or through automatic control of household appliances preprogrammed to turn on or off in response to price signals. However, wholesale electricity prices are extremely volatile and in some systems can go down to negative $300/MWh and rise to $3000 per MWh (in ERCOT). Exposing retail customers to such price volatility is politically objectionable since customers do not like and are not used to price uncertainty and while real time price response can be automated it still puts the burden of managing price risk on the customer. Treating electricity as a commodity works well at wholesale level but most retail customers are used to thinking of electricity as a service.

An alternative approach is to provide quality differentiated service based on contracted load control options. Quality differentiated service and optional price plans are common in other service industries (air transportation, cell phone, insurance) and customers have experience with choosing between alternative service contracts. Hence we contend that at the retail level uncertainty in service delivery is preferable to price uncertainty.

A key challenge in mobilizing load response within the smart grid vision is the development of business models and economic paradigms for a utility or third party aggregator to bridge the gap between the wholesale commodity market and retail service. Aggregated retail load control can be offered into the wholesale markets for balancing energy and ancillary services. While there are numerous ways for mobilizing such load response, one may draw a fundamental distinction between direct control of devices and appliances within the household versus load control that rations power to the household but does not reach beyond the meter, leaving the allocation of available power to appliances in the hand of the customer. Such allocation can be done manually or automated with a ZigBee type protocol. Direct control of devices and appliances in the household such as thermostats, air conditioners, water heaters, EV battery chargers is intrusive but may provide faster response that enables higher valued products (e.g. regulation). On the other hand rationing of power to the meter with customer dynamic control of allocation to devices in the home is less intrusive and empowers customers to reflect their changing preferences more accurately while enabling advance commitment to a total load reduction.

In the remainder of this paper we will focus on the later approach and describe an economic framework for product differentiation at the retail end of the electricity supply chain and for pricing of service contracts that are based on service priority. The basic concepts for this design evolved as part of an EPRI project called PRISM (Priority Service Methodology) in the late 1980's [9]. The key elements of the proposed approach are: 1) Market segmentation which recognizes the diversity of preferences among customers and segments of customers' load, 2) Product differentiation that is based on supply cost and value of service. 3) Design of a "menu" of service contracts that will induce matching of products with applications through customer choice. 4) Enable customers to reveal their preferences through their choices.

Specifically, the proposed design assumes a tariff structure consisting of a demand charge based on connection size to the distribution network (in KW) and an energy charge for KWh consumed. While such tariff structures are not prevalent today, the proliferation of distributed resources such as solar panels that enable households to offset their energy bills while free riding their connectivity to the grid will eventually necessitate some form of connection charge. Within this tariff structure it is possible to segment a customer's connection to the distribution system according to levels of curtailment risk as illustrated in Figure 5. For instance a customer may subscribe to 2KW that will only be curtailed in emergency condition and will be subject to the highest connection charge, another 4KW curtail able no more than 5 hours per year with a lower connection charge and so on.

Under this paradigm, an aggregator would assemble a portfolio of curtailable service contracts with different curtailment frequency as shown in Figure 6. Of course the actual amount of energy relief resulting from calling a customers' curtailment depends on his actual energy use at that time so an aggregator will need to develop some statistical yield curves that will relate the curtailable contract portfolio to the energy relief it can offer in the wholesale market. In the following section we will use a stylized example to illustrate the design of curtailable service contracts that can implement the concepts discussed above.

Figure 5: Customer's Load Segmentation

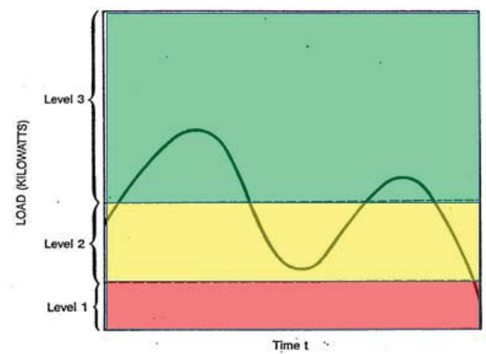
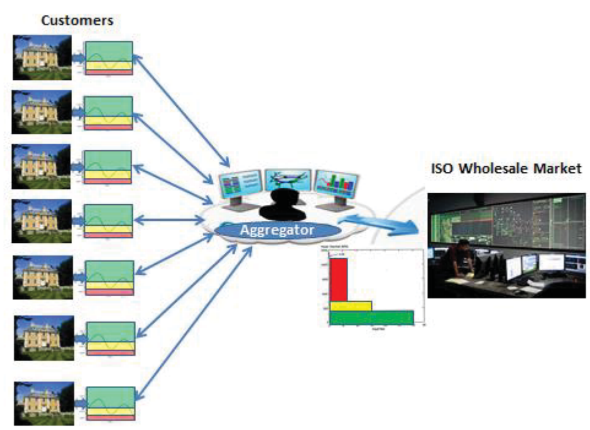


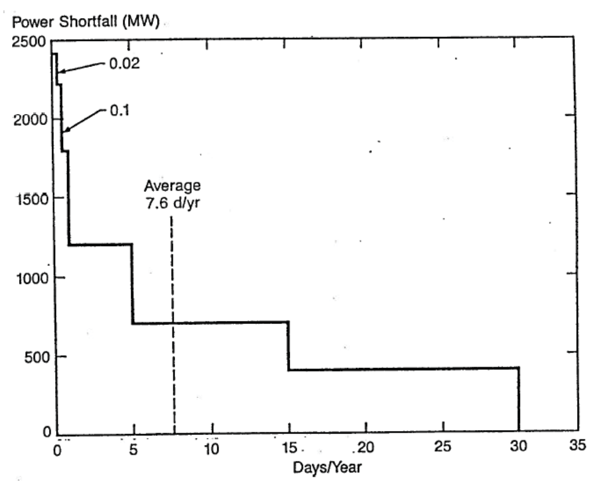
Figure 6: Aggregation of Customers' Load Segments into a Wholesale Load Relief Profile



3. An Illustrative Example of Priority Service Pricing and Contract Design.

We begin with a target profile of load relief for an aggregator characterized in terms of a cumulative distribution describing the time duration during which the aggregator can provide load relief above a certain level (MW). For simplicity we will assume in our example that duration is measured in days and load relief levels are discrete. The assumed target profile is illustrated in Figure 7 below. According to this profile the aggregator aims to supply (in expectation) to the wholesale market 0.02 day of 2400 MW load reduction, 0.1 day of 2200 MW load reduction, 1 day of 1800 MW load reduction, 5 days of 1200 MW load reduction 15 days of 700 MW load reduction and 30 days of 300MW load reduction. This load reduction target distribution may be based on an annual price duration curve and revenue objectives of the aggregator but we will take it as given for the purpose of this paper. We note that if the total load served by the aggregator was 2400MW and the target load reduction profile was implemented through random curtailment of load it would result in an average curtailment of 7.6 days per year for every MW served. Our objective, however, is to implement the load reduction through voluntarily selected contracts from a menu of service contract offerings.

Figure 7: Aggregator's Target Load Reduction Profile



In particular let us assume that the aggregator offers a menu of service contracts that specify an annual demand charge per MW peak load and a corresponding curtailment probability as given in Table 1 below.

Table 1: Contract Menu

Curt. Days/Yr.	0.02	0.1	1	5	15	30
$/kW/Yr.	84	72	48	30	12	0

The load is characterized by eight heterogeneous market segments each consisting of 300MW distributed among three categories of curtailment cost as shown in Table 2 below.

For the purpose of designing the contract menu it is only necessary to know the distribution of load with respect to the cost of curtailment reflected by the last two columns in Table 2. However, the distribution

Table 2: Demand Characterization

	Customer Type								Total MW	Interruption Cost ($/kW)
	1	2	3	4	5	6	7	8		
MW of Demand	100	—	—	100	—	—	—	—	200	200
	—	—	100	100	100	100	—	—	400	50
	100	100	100	—	—	100	100	100	600	10
	—	100	—	100	100	—	100	100	500	3
	—	100	100	—	—	100	—	100	400	1
	100	—	—	—	100	—	100	—	300	0.5

across customer types will enable us to illustrate customer self-selection benefits. In particular we assume that given a menu of contracts each customer will assign each MW of load to the contract that will minimize the expected total cost consisting of the demand charge plus the curtailment cost, The sum of these two cost components for each type of load (as characterized by the curtailment cost) and each contract selection is shown in Table 3. We note that the contract menu was designed so that the least cost is achieved on the diagonal of Table 3 which induces the desired assignment of load type to contracts.

Table 3: Assignment of Contracts to Load Types

BASIS FOR SELECTING PREFERRED SERVICE OPTION
Minimize (service charge + expected interruption cost)/kW

	Expected No. of Interruptions per Year					
$ Cost/kW interrupted	0.02	0.1	1	5	15	30
200	(88)	92	248	1030	3012	6000
50	85	(77)	98	280	762	1500
10	84.2	73	(58)	98	162	300
3	84.1	72.3	51	(45)	57	90
1	84.0	72.1	49	35	(27)	30
0.50	84.0	72.05	48.5	32.5	19.5	(15)

Customers' selections ◯

The result of the optimal assignment of load types to contracts is summarized in Table 4 which shows that the number of MW assigned to each curtailment frequency exactly matches the aggregator's target profile for load reduction.

Table 5 shows the welfare implication of contract self-selection, for each customer category versus a uniform price, revenue neutral default implementation where the load reduction profile is achieved through random load curtailment. We observe that each customer type is better off with priority pricing in terms of total cost, although some end up paying more in demand charges than they would have under uniform pricing and random curtailment.

Table 4: Assignment of Load Types to Curtailment Frequency through Self-selection.

Interruption cost $/kW interrupted	200	50	10	3	1	0.5
Interruptions per year selected	0.02	0.1	1	5	15	30
Total MW selecting that level	200	400	600	500	400	300
Interruptible MW at that frequency	2400	2200	1800	1200	700	300

Table 5: Total Customer Cost Comparison of Self-Selection vs. Uniform Price with Random Curtailment

With Random Outages ($ millions)

	Customer Type							
	1	2	3	4	5	6	7	8
Charge/yr	11.8	11.8	11.8	11.8	11.8	11.8	11.8	11.8
Shortage (cost/yr)	160.0	10.6	46.4	192.3	40.7	46.4	10.3	10.6
Total (cost/yr)	171.8	22.4	58.1	204.1	52.4	58.1	22.0	22.4

With Service Reliability Menu ($ millions)

	Customer Type							
	1	2	3	4	5	6	7	8
Charge/yr	13.2	9.0	13.2	18.6	10.2	13.2	7.8	9.0
Shortage (cost/yr)	2.9	4.0	3.0	2.4	3.5	3.0	4.0	4.0
Total (cost/yr)	16.1	13.0	16.2	21.0	13.7	16.2	11.8	13.0

4. Tariff Design

The efficiency gains demonstrated in the above illustrative example hinge on the design of a contract menu and pricing that will induce efficient self-selection of service priority by customers. Such pricing follows the general principles of mechanism design theory. Specifically, we first determine the optimal assignment of supply probability to the curtailment cost of each MW load and then we determine the price for each supply probability level that will induce the desired assignment through customer self-selection.

Let v denote the customer valuation of an energy demand unit which is also assumed to be the curtailment cost for that unit. Let $D(v)$ represent the demand function denoting the total load served by the aggregator with valuation exceeding v and suppose that the aggregator's target curtailment function is given by $F(L)$ denoting the probability of serving L load unit or more (i.e. $1\text{-}F(L)$ is the probability of curtailing the L^{th} MW of load). Under an efficient rationing scheme, load units should be served in order of decreasing valuation. Hence, the probability $r(v)$ that a unit load with valuation v will be served under the aggregator's target load reduction profile is $r(v)=F(D(v))$. Our objective is to determine a price $p(r)$ denoting the unit demand charge for service probability r that will induce customer self-selection so that a load unit with valuation v self-selects the efficient supply probability level $r(v)$ or curtailment probability $1\text{-}r(v)$ where $r(v)=F(D(v))$.

According to mechanism design theory, customer selection must meet optimality and individual rationality conditions which can be formulated as:

$$r(v) = Arg\,\underset{r}{Max}[0, \{r \cdot v - p(r)\}]$$

First order necessary condition for this self-selection problem are:

$$\frac{dp}{dr} = v$$

$$v \cdot r - p(r) \geq 0$$

Which upon integration yield:

$$dp(v) = v \cdot dr(v)$$

$$p(v) = p_0 + \int_0^v u dr(u)$$

where p_0 is a free integration constant that can be set so as to meet other design objective such as a total revenue constraint. The price function $p(r)$ can be extracted by removing the unobserved parameter v from the two parametric functions $p(v)$ and $r(v)=F(D(v))$.

Figure 8 provides a graphical illustration of the above calculation. Specifically the striped area represents the price that will be paid by a unit of demand with valuation u under the optimal tariff design.

The total expected value of service (given that such a unit will be served with probability $r(u)$ is $u \cdot r(u)$. which is the area of the entire rectangle. Hence the white area represents the consumer surplus obtained by a load unit with valuation u.

The free parameter v_0 which determines p_0 is the threshold valuation that will be served. In other words load units with valuation below v_0 are voluntarily excluded, i.e., they will not take the contract since their corresponding consumer surplus is negative. The aggregator can select the level of exclusion depending on its revenue target or other objectives.

In the above derivation we assumed a continuum of contract options. In practical implementation, however we can offer a discrete number of contracts by segmenting the service probability function *r(v)* as shown in Figure 9.

Figure 8: Graphical Representation of the Price Formula.

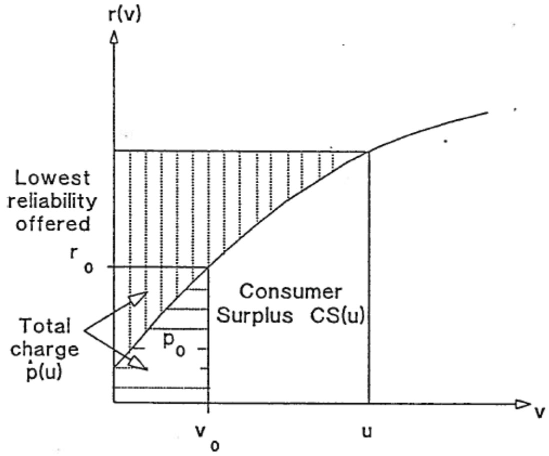
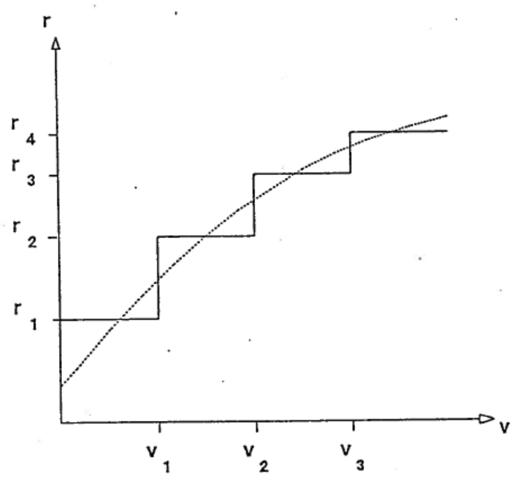


Figure 9: Offering Discrete Service Contracts



Under such an arrangement load types will be lumped into valuation ranges and served randomly within each such range. Such discretization results in some inefficiency but it can be shown [5] that the efficiency losses go down as the square of the number of contract types used. In other words, 2 contracts will capture 75% of the efficiency gains and three contracts capture 90% of the efficiency gains.

5. Alternative Implementations of Priority Service Contracts

Priority based contracts can be implemented in different forms. In the above discussion we described a pricing mechanism that imposes a demand charge on each load unit based on the selected probability of service or frequency of curtailment under this paradigm customers will segment their subscribed load into priorities choosing the number of KW they wish to assign to each priority. Their bill will then consist of an appropriate monthly demand subscription charge based on their priority selections and a uniform energy cost for the energy they consume across all priority levels.

An alternative tariff structure could impose a different energy charge for energy consumed under each priority which prorates the demand subscription fee over expected energy consumption in each priority. The main difference between the two approaches described above is a shift in risk associated with demand subscription revenue to the aggregator but the derivation is equivalent to what was shown above.

There are also different ways to characterize service priority either as a probability of service or as a cutoff wholesale price which when exceeded load units assigned to that threshold level are curtailed.

Priority service contracts can also be defined as a priority insurance policy under which a customer selects a compensation level to be paid for each insured load unit and pays an insurance premium that is monotonically increasing with the level of compensation. The aggregator has the incentive to curtail load so as to minimize compensation payments and thus will implement a priority service mechanism. It can be shown that under this approach it is optimal for customers to insure each load unit for a compensation that exactly equals the valuation of the unit. The insurance premium can be easily determined from the priority service prices derived above.

Another interesting way to interpret and structure priority service contracts is to view load curtailment by the aggregator as the exercise of a call option sold to the aggregator by the customer on every unit of load. A call option is characterized by a strike price which is the wholesale price at which the holder of the option (i.e., the aggregator) can recall (i.e., interrupt) the contracted load unit. The customer can choose the strike price and receives the "option premium" as a reduction in rate against his electricity bill for consumption of energy at the forward energy price. Under this mechanism, often called callable forward contract, it is optimal for the customer to select a strike price for the call option that equals to his valuation of each load unit and it is optimal for the aggregator to exercise the option by curtailing the load unit when the wholesale spot price exceeds the option strike price. This call option approach for implementing priority service was first described in [10] and is illustrated in Figure 10 below. The callable forward framework has been generalized in [11] to include pricing of an early notification of pending curtailment.

Such pricing can be implemented through a callable forward contract with a call option that can be exercised at two points in time "early" and "late" (e.g. with 16 hour notification and 10 minutes notification) with two different strike prices chosen by the customer. Customers are incentivized to select the strike prices so as to match their interruption cost when an early notification is given and when only short notice is given. The contract structure is depicted in Figure 11. The pricing of the "double call option" as a function of the two strike prices and the optimal exercise strategy by the aggregator is described in [11].

Figure 10: Structure and Exercise Policy for a Callable Forward Contract

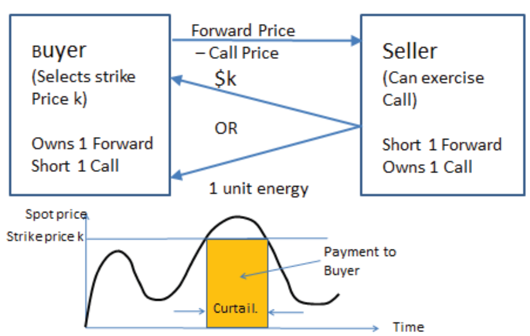
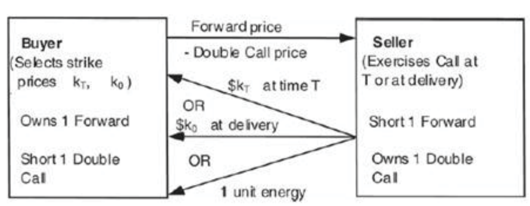


Figure 11: Structure and Exercise Policy for a Callable Forward Contract with Early and Late Call Options



6. Conclusion

Technological developments in metering communications and control make demand response more viable economically and enable rich functionality. However, conceptually, most of the load control concepts being considered to date as part of the smart grid date back to publications and early experimental implementations in early 1980's. We provide a brief historical review of these concepts and experiments and argue that the main hurdle to implementation of demand response has not been technological but rather the lack of adequate business models. Specifically, there is a need for a business model and economic framework for aggregating retail level demand response into wholesale products that can be offered in the ISO markets. We describe such a business model based on the economic concepts of efficient rationing and priority service. The proposed business model supports the idea of creating a firewall at the meter so that a customer's service contract with an aggregator entails control of curtailable power supply to the meter. However, the allocation of the supplied power among alternative devices within the household remains under customer control. We describe alternative contractual agreements that can implement the proposed concept and the pricing of such contracts.

A legitimate question at this point is why the priority service concept didn't succeed in the 1990's and how will new technological advances in metering and control can make this a viable approach. We attribute the declining interest in demand response programs and energy efficiency to the economic conditions in the late 1980's and early 1990's and the drop in energy prices. Cost of high tech metering and control devices was also too high to justify mass deployment of smart meters and two way communications. To the extent that some of the experimental programs were successful in demonstrating the capability to manage load, the integration of such capability into system operation protocols was not well formulated. With regard to demand subscription and priority service, current smart metering and communication technology enable the implementation of multilevel fuses or other means of demand segmentation at reasonable cost.

Furthermore, wireless communication inside the home makes it easy for the customer to schedule and automate the control of appliances so as to meet the contractual obligation with the aggregator, without risking total loss of power as in the original demand subscription implemented by SCE. As to integration of aggregated priority service contracts into system operation, ISO wholesale markets are well suited to accommodate aggregated demand reduction offers. Furthermore, the rapid proliferation of renewables creates a need for flexible resources and aggregated load curtailment is perfectly suited to meet this need.

7. Acknowledgments

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