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User-Controlled Electrical Energy Consumption towards Optimized Usage of Electricity Infrastructure

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Abstract— **The paper is describing dynamic intelligent technique enabling sharing communication network resources through the internet to achieve controlled electrical energy consumption. The scheme is an endeavour towards achieving a Dynamic Smart Grid environment, which allows the users take deliberate and timely decision to reduce/curtail electrical loads when system contingencies arise. This implies the development and implementation of a dynamic intelligent energy management system, which allows the user to withdraw electrical energy in a conscious, responsible and cost-effective manner. The paper describes customers demand-side response (DSR) in form of an economic load model, which represents the changes of the customer's demand with respect to changing of electricity price level. The scheme is enabling electricity end-users to be engaged in solving the peak-load problem by deliberately (on own decision, command and at own premises) by curtailing or shifting load, thus sharing in moderating those peaks. The methodology could be considered a parallel intervention to supplier Smart-Gris technologies aiming to achieve a final national goal of moderated electricity demand throughout the year. The ultimate goal of the scheme is to achieve flattening the curve of electrical consumption to achieve optimized economics of electricity infrastructure. The described system improves the use of energy consumption around the clock, helps reduced energy price, and better economic operation of electrical energy systems.**

Keywords-components; Smart Grid; Electrical Energy; Demand-Side Response, Electrical Energy Distribution, Internet Communication and Control.

I. Introduction

The traditional user-supplier rapport in the electrical energy market has historically evolved following a strategy implying whenever a load is switched on it is expected to be fulfilled by the supplier at the expected time and quality. Growing electrical demands followed by constantly growing supply led to troubled electrical services manifested by technical and economic deficiencies and alleged critical environmental impacts. Technical and economic difficulties are mainly represented in congestions at peak demands associated with compromised quality (e.g. voltage drop) and high-priced energy. At low-demands e.g. at nights, a resulting low energy cost could be driving power plants to operate at the limits of economic viability. The situation came to an extent at which electrical suppliers, at their end, needed an operating scheme, where they can identify and prioritize demand while users at the other end, needed to be aware of supplier capabilities and network conditions in order to be able of deciding about purchasing electricity at a certain time and price. Recognizing the limits of user-supplier interaction conditions helps achieving improved electrical supply services.

The basic concept of markets as mentioned by [1] pp23, is that buyers (customers) should be able to make a choice of not purchasing if, for example, the price is too high. In order to do that, they must be able to see the price (or some other signal based on cost) and make a judgment on the value of foregoing the purchase at that time. This does not mean they go without, but they may advance or delay the usage.

The scheme is enabling electricity end-users to be engaged in solving the peak-load problem by deliberately (on own decision, command and at own premises) by curtailing or shifting load, thus sharing in moderating those peaks. The methodology could be considered a parallel intervention to supplier Smart-Gris technologies aiming to achieve a final national goal of moderated electricity demand throughout the year. The presented scheme allows electricity users to make use of continuous and simultaneous information communicated to them by the Australian Energy Market Operator [2] through the internet about electricity market conditions helping undertaking information-based decisions. Additionally, it allows users internally manage, control and at times curtail own loads as deemed necessary. The scheme is an endeavor towards achieving a **Smart Grid** where transparency of the market and informed and engaged users are helping achieving an intelligent grid environment. The smart-grid technology will make use of the internet and modern communication systems to minimize the use of energy at times of peak demand around the clock reflecting so the benefit of the user and supplier.

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Expanding the scheme shall lead to improved electrical supply systems characterized mainly by moderate and controlled energy demands and improved system performance. The paper describes a model of a smart-grid system, featured by the following: (1) On-premises energy management control systems to allow curtailment of load during a demand peak event making use of the Australian Energy Market Operator (AEMO)-internet-communicated load profile, (2) monitor the performance of major equipment in order to control on-off switching timing and (3) controls that ensure end-use devices only operate as deemed necessary. Objectives of this work are to achieve reduced peak demand and improved power system supply economics by improving the load factor.

II. Background

The Australian Energy Market Operator (AEMO) has a big responsibility to provide electricity energy for the all consumers. One of these responsibility is managing power flows across the Australian Capital Territory, New South Wales, Queensland, South Australia, Victoria and Tasmania [3]. In order to achieve the high quality service to all customers in Australia, AEMO send price/demand information to the public every 30 minutes.

Generally, the electricity supply system has three interconnected components: generation, transmission and distribution. Based on data of 31 December 2008, Queensland total electricity generating capacity was 12487 MW [4]. This power generation is used to provide electrical energy to all consumers in the Queensland area: residential, commercial and industrial. However, the amounts of energy produced from various generators depend on market demand, price and availability of sources. In 2008, 81 % percent of electricity came from coal-fired power stations, while 15 percent came from gas and 4 percent came from renewable energy [4].

Most of the power stations are directly connected to the transmission system. The Queensland electricity transmission system is provided by Powerlink that is licensed to operate more than 12,000 kilometres of Queensland high voltage transmission network, transporting electricity from the generators to the distribution networks [5]. The distribution system is carrying electricity from the transmission system to consumers. In Queensland, Energex and ERGON energy distribute electrical energy to the customer. ERGON energy provides several tariff options for end users. For example, Tariff 11 for all domestic consumption 18.843 cent per kWh, while Tariff 31 night rate for all consumption 7.689 cent per kWh and Tariff 33 economy for all consumption 11.319 cent per kWh [6].

Based on the data, total Australian energy consumption grew at an annual rate of 2.6 % for the 25 years to 1997/1998 [7]. Following the 2007- 2008 period, annual electricity consumption in Queensland has grown by over 29 percent or approximately 10,500 GWh making Queensland the second highest consumer of electricity in Australia [8]. This has indicated that Queensland has a significantly greater number of high energy users than any other state with most of these in regional Queensland.

III. Australian Electricity

A. *Australian Electricity Market*

Since the beginning of the 1990s, Australia's electric power industry has undergone a series of structural reforms [9]. One of the electricity reform programs has created the National Electricity Market (NEM), which is responsible for structure, rules and regulations in the delivery of energy to customers [10]. AEMO's responsibilities include wholesale and retail energy market operation, infrastructure and long term market planning demand forecasting data and scenario analysis [11].

To improve governance, and enhance the reliability and sustainability of the State's electricity system, the Australian Government has created a collaborative electricity and gas industry in the form of the AEMO. AEMO commenced operation on 1 July 2009 [11] . Therefore, all roles and responsibilities of the NEMMCO have been transitioned to the Australian Energy Market Operator. In Queensland, the electricity industry was restructured on 1 July 1998 to prepare the industry for participation in the competitive NEM [10]. The reform was done because of the high levels of energy demand and the rates of population growth in Queensland every year.

The Market structure of NEMMCO / AEMO can be presented in figure 1 below.

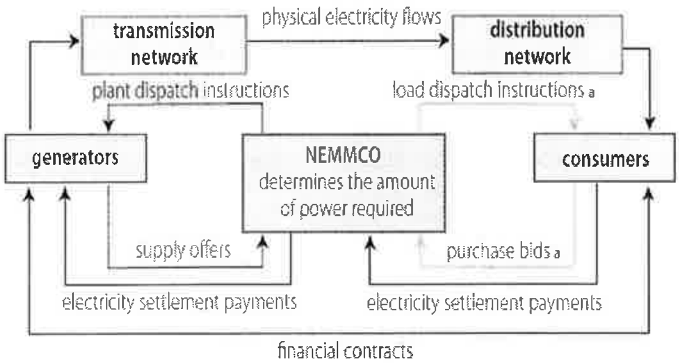

Figure 1 The Market structure of NEMMCO/AEMO [12]

Electricity demand growth is a main problem in relation to the population increase in Queensland State for the foreseeable future. This demand growth is expected to continue with an estimated population growth every year. Figure 2 below show an example of an actual energy demand/price situation in Queensland. The price curve follows the demand curve closely, reflecting the fact that generators at lowest operating cost are in fact providing base load power, twenty four hours a day, while peak loads exceeding the base load are usually covered by the more expensive plants, for shorter period [13]. Electricity prices are typically at their lowest level at night following the low demand during off-peak session. Prices are rising based on the peak session in the morning and the evening.

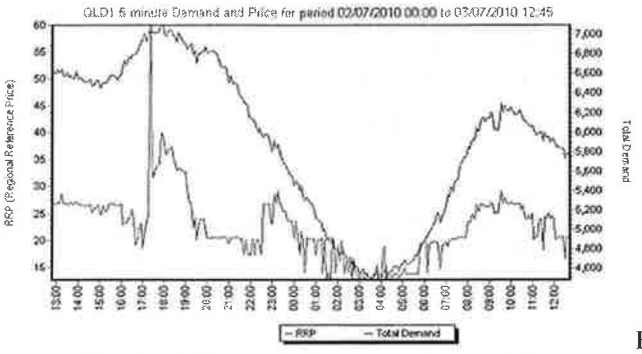

Figure 2 Wholesale Electricity Price and Demand for a Typical Day in Queensland on 2nd-3rd July 2010 as broadcasted by the AEMO [2]

Figure 3 demonstrates the fluctuation of electricity price in Queensland from May 2008 to May 2010. This graph illustrates that the average of electricity price during that time is in the range of \$50/MWh. However, the excessive prices exceeded \$500/MWh. This indicated that the excessive prices occur regularly in all states on the interconnected power network [14]. Therefore, the customer must bear the additional cost for managing these extreme prices.

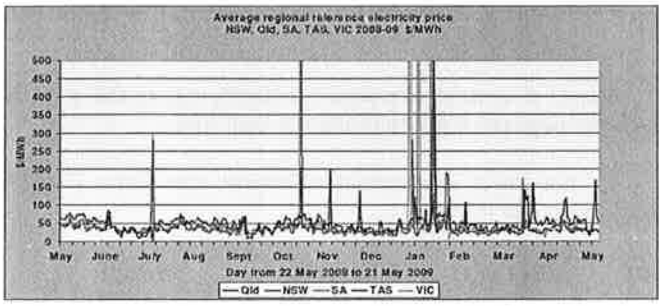

Figure 3 Fluctuation of Electricity Price in Queensland [14]

B. Demand Side Response under Smart Grid Technology

The smart grid system is an expression for contemporary electrical energy supply system that allows appropriate demand-side-response to control the electricity usage by innovative technology. A dynamic demand-side-response smart technique is presented, applicable in a transparent electricity market where end-users are enabled to use actual information about market situations through the internet and are acting upon controlling own demand [15]. The system is using computer-controlled switches, which enable users to control electricity usage based on the electricity price/demand information from the AEMO.

The benefits of a demand response program return on users and electricity providers. Some advantages for the utility are: increased economic efficiency of a deregulated electricity market, enhanced reliability, relief of congestions and transmission constraints, reduction in price volatility, and mitigation of potential market power [16]. In addition, DSR provides means for users to reduce the power consumption, saving energy and optimizing energy consumption [17]. Therefore, implementation of DSR programs is expected to improve economic efficiency in the wholesale electricity market.

C. Demand Side Response Model

Many different models are used in Demand Side Response program planning. In the report of the strategic plan of the International Energy Agency (IEA) [18], DSR is divided into two basic categories, namely, the time based program and the incentives based program. According to [19] the specific types of time based program are: time of use (TOU), real time pricing (RTP) and critical peak pricing; While the specific types of incentive based program consist of direct load control (DLC), Interruptible/curtailable (I/C), demand bidding (DB), emergency demand response (EDRP), capacity market (CAP) and ancillary service markets (A/S) programs.

In this paper, we will describe some categories of these models, such as: the interruptible/curtailable (I/C), the emergency demand response program (EDRP) and time of use program (TOU) model. Figure 4 describes those models:

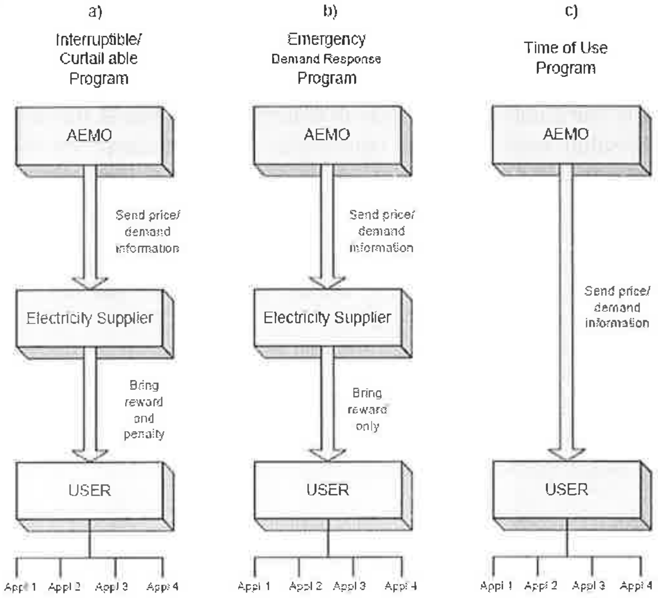

Figure 4 Models of Interruptible/Curtailable (I/C), Emergency Demand Response (EDRP) and Time Of Use (TOU) Programs

Demand-Side Response programs are able to move a portion of the inflated electricity load during peak sessions to lower load periods, Figure 5.

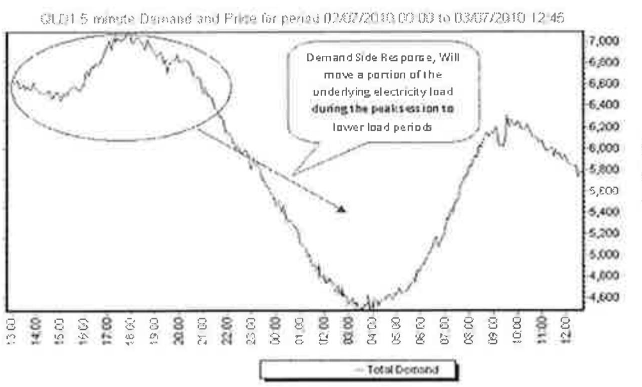

Figure 5 Demand Side Response Programs provide the ability to move loads from peak to low sessions; data from the Australian Energy Market Operator AEMO [2]

a). Interruptible/Curtailable Program (I/C)

The interruptible/curtailable service provides incentives/ rewords to encourage customers who are participating to curtail electricity demand. The electricity provider sends directives to the user for following this program at certain times. The user must obey those directives to curtail their electricity when being notified from the utility. For example: the customer must curtail their electricity consumption starting from 6:00 pm – 7:00 pm. Those customers who are following will get a financial bonus/reword to their electricity bill from the utility. In California the incentive of I/C program was $700 /MWh/Month in 2001 [20]. However, in case the customer decides not to follow those directives, they will get penalties.

b). Emergency Demand Response Program (EDRP)

EDRP is energy-efficient program that provide incentive to customer who can reduce the burden on the electricity usage for a certain time, this is usually conducted at the time of limited availability of electricity. To participate on this program, all customers are expected to reduce their energy consumption during the events. The typical payment are $350-$500/MWh of curtailed demand [21]. However, utility have requested voluntary curtailments from customer during system emergencies in the past [21]. Hence, the provider did not pay customer for these curtailments.

Based on the model above, there are some equations which can be used by consumers to calculate the changing of the electricity price, demand, incentive and costumer benefits associated with the implementation of DSR based on some previous work reported in [19, 22].

c). Time Of Use Program

This program does not provide incentive or penalty to customers. Participant can arrange their electricity consumption based on the information of electricity price from the utility. Usually the electricity price will be high during peak load, and will be low at the off-peak session. Users are able to choose and decide on some appliances for use at a particular time. For example: using air conditioning at off-peak sessions and light in peak session. Customers can avoid the use of some equipment during in peak session and operate during in off-peak time.

d). Calculation of the savings in electricity expenditure

In [20, 22], the following approach is used to calculate the savings in electricity expenditure based on price, demand, incentives and costumer benefits associated with the pertinent DSR program used.

The change in energy consumption $\Delta d\ (t)$ at the time t when the user changes demand from $d_o(t)$ *to* $d(t)$ *is:*

$$\Delta d\ (t) = do(t) - d(t) \quad (1)$$

For participating in the DSR program, the total incentives $P(\Delta d(t))$, when $A(t)$ is paid as incentive to the costumer at the time t for each kWh load reduction, as the following:

$$P(\Delta d(t)) = A(t).\Delta d(t) \quad (2)$$

To account the total penalty $PEN \cdot \Delta d(t)$ when the consumer does not commit to the obligations as a member of the DSR program, when $pen(t)$ is the penalty per kWh at the time t and $D(t)$ is the DSR program contract level of consumption in kWh, will be accounted as the following:

$$PEN(\Delta d(t)) = pen(t).\{D(t) - [do(t) - d(t)]\} \quad (3)$$

The contract could be mentioning a benefit from joining the action so that e.g. $B(d(t))$ is the customer income during that period from the use of d(t) kWh and at the same time the customer could be receiving additional incentives $P(\Delta d(t))$ as described in eq.(2). The cost of the consumed electricity and any penalty for not following the program, if applicable, will be deducted from the income as the following:

$$S = B(d(t)) + P(\Delta d(t)) - d(t).r(t) - PEN(\Delta d(t)) \quad (4)$$

where, S is total customer's benefit; $r(t)$ is the rate the customer pays per kWh electricity at that time.

To maximize the customer benefit the slope ∂S/∂d(t) should be equal to zero, so:

$$\frac{\partial S}{\partial d(t)} = \frac{\partial B(d(t))}{\partial(t)} + \frac{\partial P(\Delta d(t))}{\partial d(t)} - r(t) - \frac{\partial PEN}{\partial d(t)} = 0 \quad (5)$$

This leads to:

$$\frac{\partial B(d(t))}{\partial d(t)} = r(t) + A\ (t) + pen(t) \quad (6)$$

The benefit function most often used is the quadratic benefit function [22]:

$$B(d(t)) = Bo(t) + ro(t)[d(t) - do(t)] \left\{1 + \frac{[d(t) - do(t)]}{2\ \beta\ (t)do(t)}\right\} \quad (7)$$

$B_o(t)$: Benefit when $d(t) = d_o\ (t)$ ($)
$r_o(t)$: nominal rate for electricity consumption ($/kWh)
$\beta(t)$: Elasticity parameter

$$\beta(t,h) = -\frac{ro(h)}{do(t)}.\frac{\partial d(t)}{\partial r(h)} \quad (8)$$

The elasticity parameter is a unit-less factor indicating how strong the energy demand depends on the price of energy, i.e.

the effect the price has to determine the magnitude/quantity of demand. The multiplier $\frac{ro(t)}{do(t)}$ helps transforming the parameter into a unit less factor by referring to initial known conditions.

By differentiating the above equation and solving for $\frac{\partial B(d(t))}{\partial d(t)}$ and substituting the result in (6)

$$r(t) + A(t) + pen(t) = ro(t)\left\{1 + \frac{d(t) - do(t)}{\beta(t)\, do(t)}\right\} \quad (9)$$

When the customer is participating in a DSR program, the customer consumption $d(t)$ for a maximized benefit can be calculated from equation (9) as the following:

$$d(t) = do(t) \cdot \{1 + \beta(t,t) \cdot ([r(t) - ro(t) + A(t) + pen(t)) / ro(t)\} \quad (10)$$

The multi period model is summing the total energy demand *d(t)* over one day as the following:

$$1 + \sum_{h=1}^{24} [\beta(t,h).\left(\frac{[r(h) - ro(h) + A(h) + pen(h))}{ro(h)}\right)] \quad (11)$$

It should be noted that the I/C program implies rewards and penalties, whereas the EDRP involves only rewards and the TOU neither rewards nor penalties, see Fig. 3.

Because the technique presented in this work is designed to be installed and operated at the user premises all the above mentioned DSR schemes are applicable.

At this initial stage, this research will be representing a TOU program, where users on flat-rate tariffs are reaping financial benefits just from reducing energy consumptions at certain times a day; usually averting peak-load periods. Customers on different tariff, where energy prices differ with day time and national load peak/valley conditions (e.g. night tariffs), they can be reaping financial benefits also from shifting loads from day- to night-times, where electricity is cheaper.

IV. METHODOLOGY

This research addresses the problem of excessive electrical energy usage and peak demand based on electricity demand-price information in Eastern and Southern Australia. This scheme will enable electricity users to shift or curtail loads in order to avoid peak demand. Time of Use (TOU) service is used to develop the model. In order to achieve the aim and objective of this research, a multi media model will be developed, assisted by the Linux operation system, in order to allow individual users to effectively and continuously apply the scheme.

To control electricity demand this scheme uses computer-controlled-solid-state switches, a router and an internet relay. The relay is programmed to receive and act upon information received about AEMO electricity demand/price conditions on the internet. Figure 6 illustrates a simple model application, where four appliances are controlled remotely over an internet network through four solid-state switches.

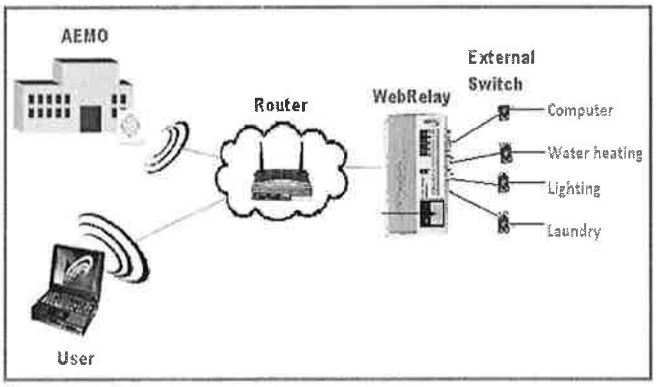

Figure 6 Controlled Scenarios

Consumers use the home computer to set-up their preferences for appliance profile usage and priorities. The profile of appliances identifies when an appliance is run and at what time. Pursuant to the order, household appliances that have been linked with a switch can be operated based on the previously set-up time. Table 1 illustrates an example of an appliance profile. All control systems above is implemented by a shell script under a Linux operation system. Figure 7 shows the pseudo code of the controller that is executed with each interaction.

Appliance	Start After	Finish before	Session Time
Computer	08.00 AM	08.00 PM	Peak Session
Water heating	06.00 PM	06.00 AM	Off-peak session
Lighting	06.00 PM	10.00 PM	Off-peak session
Laundry	06.00 AM	10.00 AM	Off-peak session

Table 1 Appliance profile

```
if [$start - $finish];then
  case $name in
        Computer) turn on relay1State=1;;
        Waterheating)turn on relay2State=1;;
        Lighting)turn on relay3State=1;;
        Laundry)turn on relay4State=1;;
        esac
else
   case $name in
        Computer) turn on relay1State=0;;
        Waterheating)turn on relay2State=0;;
        Lighting)turn on relay3State=0;;
        Laundry)turn on relay4State=0;;
        esac
Finish
```

Figure 7 Pseudo Code of The Control Loop

V. ANALYSIS AND RESULTS

In order to evaluate the effect of the proposed scheme on electricity energy saving the electricity price/demand in Queensland for period 2nd – 3rd July 2010 has been used, figure 2. In the following, four scenarios have been formulated to demonstrate the results as presented in Figure 8 and summarized in Table 2.

Scenario 1 In this scenario users are shifting 3051 MWh peak electricity usage occurring between 13:00 pm-21:45 pm towards the time period 21:45 pm-01:30 am when energy demand and prices are low. All participants are suggested to set-up the electricity profile to stop chosen appliance from running during that time. For example, air conditioning, washing machines and dishwashers could be effectively operated at optional times of the day. Achievable savings $213046 per day

Scenario 2 Users are shifting peak demand of 3051 MWh occurring between 13:00 pm-21:45 pm to the period between 01:30 am to 04:00 am. Achievable savings $229435 per day

Scenario 3 Users are shifting peak demand of 3051 MWh occurring between 13:00 pm-21:45 pm to the period between 04:00 am to 06:00 am. Achievable savings $229435 per day

Scenario 4 Users are shifting peak demand of 3051 MWh occurring between 13:00 pm-21:45 pm to the period between 06:00 am to 13:00 pm. No savings in energy cost due to applicable day-time tariffs. However, the scheme was still able to remove congestions out of peak demand areas.

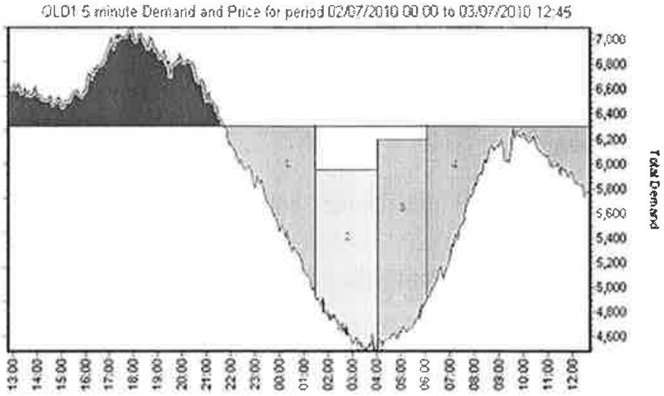

Figure 8 Scenarios 1, 2, 3, and 4

Table 2 summarizes the results of the described scenarios with load reduction, energy consumption, cost of electricity and customer benefit.

Scenario Nr	Time to Curtail load	Time to reconnect load	Load to Curtail (MWh)	Day tariff 18.84 ¢/kWh Energy cost ($)	Night tariff 11.32 ¢/kWh Energy cost ($)	Saving ($)
1	13.00 pm	21:45 pm to 01:30 am	3051	574808	361762	213046
2	to	01:30 am to 04:00 am	3051	574808	345373	229435
3	21.45 pm	04:00 am to 06:00 am	3051	574808	345373	229435
4		06:00 am to 13:00 pm	3051	574808	NA	NA

Table 2 Result of operating scenarios

VI. CONCLUSIONS

The scheme enables consumers to utilize electricity demand-prices information received via the internet allowing them to control energy consumption. Generally, the scheme achieves the following advantages:

- Removed peak demands.
- Reduced energy price volatility.
- Increased grid reliability
- Reduced energy cost/price.
- Optimizing energy consumption.
- Delaying investments in new infrastructure.
- Provides additional capacity more quickly.
- Provides flexibility.
- Lowers likelihood and consequences of outages.
- Averts the use of the most costly-to-run power plants.
- Drives production costs down for all users.
- Achieves large savings at low investment.

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