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Optimise Energy Cost for Air Conditioning based on the Market Price under Demand Side Response Model

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ABSTRACT

The increasing contribution of air conditioning (AC) to energy consumption has received considerable attention in the past and will continue to do so in the coming years, from Indonesian government, state electricity company and consumers. Managing demand on the electricity system in peak sessions is the most direct way to address the AC peak demand issue. The aim of this research is to developed a consumer demand side response (DSR) model to assist both electricity consumers/aggregator and electricity provider to minimise energy cost if peak price occured in the peak season. The proposed model allows consumers to independently and proactively manage air conditioning load through an aggregator. This research examines how the control system applies DSR model if a price spike may occur at 18.00 during one hour. The results indicate, consumer and aggregator could gain collective benefits when the consumer controls the air conditioning under the DSR program. The model was tested in Makassar City South Sulawesi considering to the caharacteristic of the room and air conditioning in a residential house.

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1. INTRODUCTION

DSR as described by [1] can be defined as the changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity or other incentives over time. [2] describes DSR as a tariff or program established to motivate change in electric consumption by customers in response to change in the price of electricity over time. Further on, DSR programs provide means for utilities to reduce the power consumption and save energy, maximize utilizing the current capacity of the distribution system infrastructure, reducing or eliminating the need for building new lines and expanding the system as described by [3].

The benefits of DSR programs apply to consumers and to electricity providers collectively. Some advantages are: increased economic efficiency of electricity infrastructure, enhanced reliability of the system, relief of power congestions and transmission constraints, reduced energy price, and mitigated potential market power [4]. DSR, as an integral part of the smart grid, is a cost-effective, rapidly deployable resource that provides benefits to utility companies and customers [5]. DSR can help reduce peak demand and therefore reduce spot price volatility [6]. DSR participation would help electricity power markets operate in a more efficient way [7]. The seven overall categories of the benefits of a DSR program are: economic, pricing, risk management and reliability, market efficiency impacts, lower cost electric system and service, customer service, and environmental benefits [8].

From the consumer perspective, applying DSR program will assist consumer to obtain benefit through minimised energy cost without reducing their total usage of power. Curtailing or shifting energy consumption is also an effective way for consumers to avoid expensive costs and reduce their electricity bill. This advantage is not just to the consumer but also to the utility company, as implementing a DSR program can abate the wholesale electricity market price because of the reduction of the demand. As a result, the expensive generation unit will be reduced [9], [10]. In addition, one of the other advantages of DSR in the pricing area is that it mitigates price volatility and hedges cost reductions.

To implement DSR model, consumer is required to enrol as a member of a group controlled by an aggregator. To be exposed to electricity market price, small-consumers need an aggregator to communicate and negotiate the electricity market price and network overload. The small consumer is only able to register in the electricity market through the aggregator [11]. Any change in the electricity usage for the small-consumer is based on the information from the aggregator. As a result, aggregators keep and maintain communication between market operator and consumers.

The membership composition of aggregator can be a loosely defined group based on the geographical area, institutional consumer e.g. school or university, small-industrial consumer, farm consumer, etc. Each group has unique advantages or disadvantages. However, the benefit for aggregation model is the opportunity for small consumer (called residents) and small businesses to save money on their electric bills by exposure to the electricity market. If the electrical power is supplied from a renewable energy source, there are also opportunities for helping the environment as the group could purchased 100% renewable energy for its electric aggregation program. Another benefit is that by negotiating on behalf of all residents and small businesses, the aggregator can obtain favourable contract provisions.

In this research, to participate in DSR program every consumer can be at least partly exposed to the electricity market through an aggregator. The consumer can minimise the energy cost for the air conditioning by controlling temperature. In this case, aggregators need to work very closely with consumers to look at their overall energy consumption and load shape, help them understand how much load can be dropped and at what times. Curtailment plans are thus tailored to aggregator who is financially rewarded for both the commitment to dropping load, and actual load curtailment as well as when consumer applying pre-cooling method. The level of payment may also depend on the frequency and length of the DSR period.

2. DEEMAND SIDE RESPONSE MODEL

Many different economic models are used to represent DSR. DSR programs are divided into two basic categories, namely: time-based programs, and incentive-based programs [12]. The specific types of time-based programs are: time of use (TOU), real-time pricing (RTP) and critical peak pricing (CPP) [13]; while the specific types of incentive-based programs consist of direct load control (DLC), interruptible/curtailable (I/C), demand bidding (DB), emergency demand response program (EDRP), capacity market (CAP) and ancillary service markets (A/S) programs [14]. A brief description of four popular programs – the TOU, RTP, I/C and EDRP model – is provided in the following sections.

2.1. Time of Use (TOU)

TOU is one of the important demand-side response programs which responds to price and is expected to change the shape of the demand curve [15]. The TOU rate is the most obvious strategy developed for the management of peak demand, and is designed to encourage the consumer to modify their patterns of electricity usage [16]. To apply this type of program, the utility company does not provide rewards or penalties to consumers. To participate, all consumers are required to remove their energy consumption during peak sessions to off-peak sessions as soon as they receive information from the utility company [17]. The type of contract and the rate is fixed for the duration of the contract but depends on the time of the day [18]. Compared to the flat rate contract, some of the risk is shifted from the retailer to the consumer because the consumer has an incentive to consume during periods when the rates are lower.

2.2. Real-Time Pricing

The RTP program gives consumers the ability to access hourly electricity prices that are based on wholesale market prices. These prices vary from hour to hour and day to day according to the actual market price of power. Higher prices are most likely to occur in peak session times (e.g., 11.00-17.00). The consumer can manage the costs with real-time pricing by taking advantage of lower priced hours and conserving electricity during hours when prices are higher [14]. Additionally, the RTP program allows consumers to achieve energy savings by curtailing their marginal use at times when prices are higher and by using more during the off-peak tariff times.

2.3. Emergency Demand-Side Response Program

The EDRP is an energy-efficient program that provides incentives to consumers who can reduce electricity usage for a certain time; this is usually conducted at the time of limited availability of electricity. The EDRP provides participants with significant incentives to reduce load [19]. To participate in this program, all consumers are expected to reduce energy consumption during the events. The program determines which houses must be included in the event to minimise cost and disruption, while alleviating the overload conditions [20]. When asked to curtail, and when their participation has been verified, the consumer is paid as high as $500/MWh [21]. In New York, an emergency demand-side response program allowed participants to be paid for reducing energy consumption upon notice from the New York Independent System Operator (NYISO [22]).

2.4. Interruptible/Curtailable Program

The I/C program has traditionally been one of the most common DSR models used by electric power utility companies. In this type of program, consumers sign an interruptible-load contract with the utility company to reduce their demand at a fixed time during the system's peak load period or at any time requested by the utility company [23]. This service provides incentives/rewards to consumers to participate to curtail electricity demand. The electricity provider sends directives to the consumers for following this program at certain times. The consumers must comply with those directives to curtail their electricity when notified from the utility company or face penalties. For example, the consumers must curtail their electricity consumption starting from 18:00-19:00; those consumers who follow their direction will receive a financial bonus/reward in their electricity bill from the utility company. In California, the incentive of the I/C program was $700/MWh/month in 2001 [24].

In this research, the real time pricing is applied to minimised the energy cost for air conditioning when a peak seson. According to the State Electricity Company (called: PLN) the peak season was occur at 18.00 -21.00. The case study reported in this paper illustrates the optimisation of the air conditioning if a spike may only occur at 18.00 during one hour as well as benefit for the consumer. To applied this system, a single room in residential house is chosen for the case studies considering to the characteristic of the room and the air conditioning. In addition, the temperature data on 12 March 2017 was selected for the outside temperature (To) and the normal price spike during this period was 41.22 $ per MWh and electricity price when spike occur was 90 $ per MWh.

3. RESEARCH METHODOLOGY

Consumers should start to apply the DSR program to optimise the air conditioning as soon as they receive information from the aggregator. Due to the pattern of demand in the peak season, the consumer is required to participate in the DSR program starting from 16:00 to 23:00, two hours before and after peak season. These time were chosen to give more flexibility time to do optimisation. In this research, spike occured at 18.00 during one hour spike. This time was chosen based on the historical data from the electricity state campany that a aprice spike was occured at 18.00. To applied this model, mathematical models for the consumer participant were developed to quantify the economic effect of demand side response. A linear programming based algorithm was developed to determine the optimal solution to achieve energy saving and reduce impact of peak demand.

This model does not provide incentive or penalty to consumers since there is no agreement between both electricity supplier and aggregator or consumer to apply this model. However, consumers will achieve savings by decreasing loads at high priced sessions e.g. applying pre-cooling system to avoid spike price in the critical peak session. Therefore, consumers are able to optimize air conditioning by controlling the temperature room, turn-on the air conditioning when the temperature rises a maximum threshold e.g. 24^{o}C then turn off for the next switching once the temperature drops to be minimum threshold e.g. 20^{o}C. The cycling time of air conditioning is based on the result of temperature optimization.

To achieve this goal, an optimization package such as MATLAB allows the user to optimize this objective function within operational constraints such as a permitted temperature range. Therefore, the optimization problem can then be represented as minimizing energy cost (Z), or mathematically[25]:

$$Z(t) = \int_{t=1}^{t=n} [(C(t)\ dt \tag{1}$$

$$Z(t) = \int_{t=1}^{t=n} [(S(t) . P(t). D(t). U(t))\ dt\ ] \tag{2}$$

Subject to constraints [26, 27]:

$$\frac{dT}{dt} = \frac{Q.\ A.(T_o(t) - T(t))}{H} - \frac{B.U(t)}{H} \quad (3)$$

where:

Z = Minimised energy cost (A$)
S = Electricity price (A$/kWh)
P = Rating power of AC (kW)
D = Duration time for operating AC during a day (hours)
U = Continuous time binary variable (1 or 0)
Q = Heat transfer coefficient from floor walls and ceiling (W/m^2 ^{o}C)
B = Heat transmission from the AC (W)
A = Total area (m^2)
H = Heat capacity of the room (J/ ^{o}C)
To = Temperature outside (^{o}C)
Tt = Temperature inside the room at time t (^{o}C)
n = interval time t (hour)

4. NUMERICAL RESULTS

In this simulation, the maximum and minimum permitted temperatures of 24^{o}C and 20^{o}C were chosen. There are 18 switch edges characterizing the switching decisions, from this we can compute the energy cost for the air conditioning. The numerical minimization was applied to find to set of edges which satisfy the constraints and provide minimum cost. The process is required to do optimisation of the cost. The energy cost was calculated when the air conditioning was on, and the cost was zero when the air conditioning was off. This method continued until the time of operating the air conditioning had expired. To make the temperature comfortable for the consumer, the room temperature was only allowed to be between maximum and minimum temperature. This means the temperature was not allowed to reach the maximum and minimum permitted temperatures. For the purpose of the simulation, the starting point temperature of 23^{o}C was chosen with the air conditioning status off. Figure 1 and Table 1 summarises the parameters of the typical room and the air conditioning used in this optimisation.

Table 1. Parameter of the Room A used in this Analysis

No	Parameters	Unit	Value
1	Heat transfer coefficient from floor wall and ceiling (Q)	0.8	W/m^2 ^{o}C
2	Total area (A) (4.8 m x 3 m)	14.4	m^2
3	Heat capacity of the room (H)	20	J/ ^{o}C
4	Heat transfer from the air conditioning (B)	900	W
5	Reference of temperature	23	^{o}C
6	Hysteresis	2	^{o}C
7	Maximum temperature	25	^{o}C
8	Minimum temperature	20	^{o}C
9	Rating power of air conditioning (P)	0.5	kW
10	Number of switch change events	18	

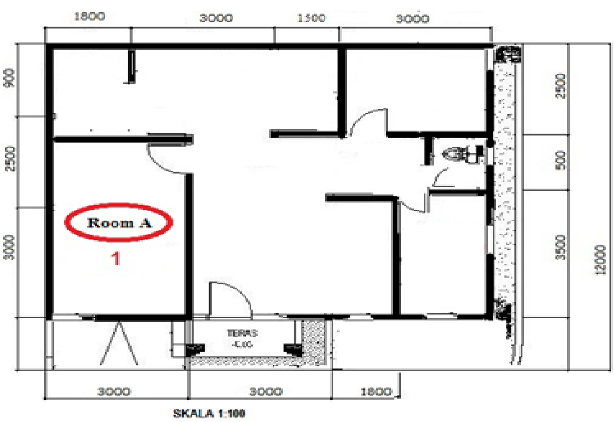

Figure 1. Computer Graphics View of the House (Up-View)

Figure 1 indicated the building of example room used in this research. The building under study in this research are low consumption single family house. In this case a single room (called Room A) was chosen with built using material standard for residential house in Makassar city-Indonesia.

4.1. Market Cost as a Function of a Price Spike Without DSR Program

The typical operation of air conditioning is continuous without DSR model. In this case the consumer did not consider a price spike. The starting point of 22°C was chosen with the air conditioning status OFF. The minimum and maximum temperature were 20°C to 24°C. As discussed previously that the air conditioning was turned off once the temperature dropped to the selected minimum temperature. In contrast, the air conditioning was turned on once the temperature rose to the selected maximum. Figure 2 below illustrates the cycling temperature and market cost if a spike mya occur at 18.00.

In this optimisation, there are 18 switch edges to compute the energy cost for air conditioning. If S_s is the electricity price when a spike occurs, C_s is the market cost for spike cases, then the total market cost for the spike case (MC_1) is determined by the following Equation:

$$MC_1(t) = \int_{t=1}^{t=n} [\, C_s(t) \;\; dt\,] \tag{4}$$

$$MC_1(t) = \int_{t=1}^{t=n} [(\, S_s(t) \,.\, P(t).\, D(t).\, U(t)) \;\; dt\,] \tag{5}$$

Equations (1) to (5) were used to compute the results of simulation without DSR program when one hour spike may occur at 18.00, as shown in Figure 2 and Table 2.

Table 2. Total Market Cost Without DSR Program

	One Hour Spike (MC_1)
Total Market Cost ($)	7.54

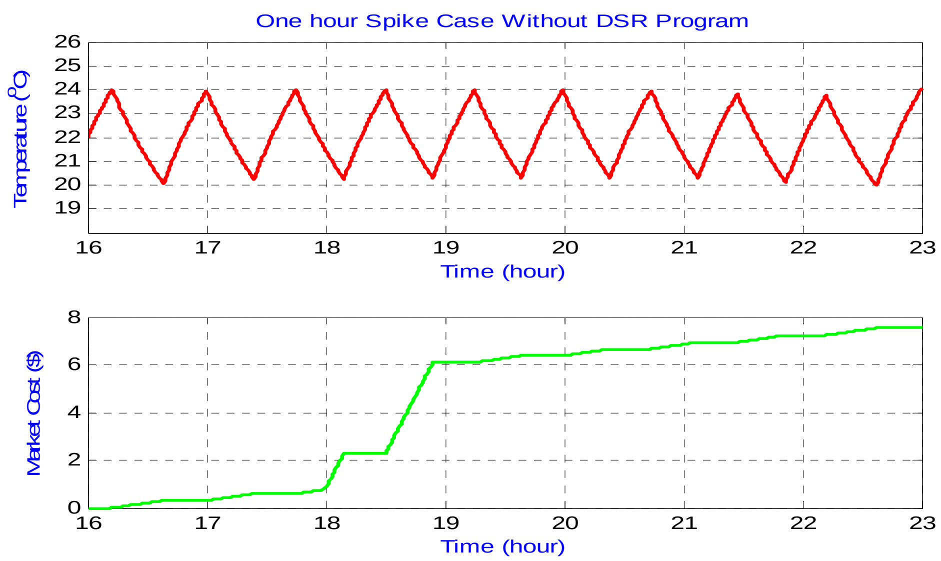

Figure 2. Cycling temperature and market cost without DSR Program

As shown in Figure 2, the calculation of the electricity cost during this period was based on the air conditioning status. The electricity cost increased when the temperature was being reduced by having the air conditioning on. However, there was no electricity cost when the air conditioning was off or electricity costs were not calculated when the air conditioning was off. The electricity cost calculation started from switch number 1 to number 2. Then, the air-conditioning was turned off again between switch numbers 2 to 3, when the electricity cost is zero. The type of operation was continuous for all switching and all times. The consumer/aggregator pays the cost according to the normal price before and after a spike happens. The price spike was only calculated when the spike happened at 18.00 during one hour.

4.2. Market Cost as a Function of a Price Spike Under DSR Program

In this optimisation, the maximum and minimum temperatures were 25°C and 19°C. Temperature starting of 22°C was chosen. Under DSR program the cycling temperature room was longer than without DSR program. This is to give more option and more flexibility for the optimisation. Under the DSR program, the control system applied the pre-cooling method to avoid high costs when a spike happens. Similar to the previously described method, the air conditioning was turned on once the temperature rose to the maximum permitted temperature. Then, it was turned off when the temperature dropped to the minimum permitted temperature. The control system kept the room temperature between the maximum and minimum permitted temperatures.

If S_s is the electricity price when a spike occurs, C_s is the market cost for spike cases, then the total market cost for the spike case (MC_s) is determined by the following Equation:

$$MC_s(t) = \int_{t=1}^{t=n} [\, C_s(t) \;\; dt \,] \quad (6)$$

$$MC_s(t) = \int_{t=1}^{t=n} [(\, S_s(t) \,.\, P(t).\, D(t).\, U(t)) \;\; dt \,] \quad (7)$$

Equations (1) to (3) and (6) and (7) were used to compute the numerical results of optimisation of the air conditioning when one hour spike may occur at 18.00, as shown in Figure 3 and Tables 3

Table 3. Total Market Cost without DSR Program

	Half Hour Spike (MC_s)
Total Market Cost ($)	4.96

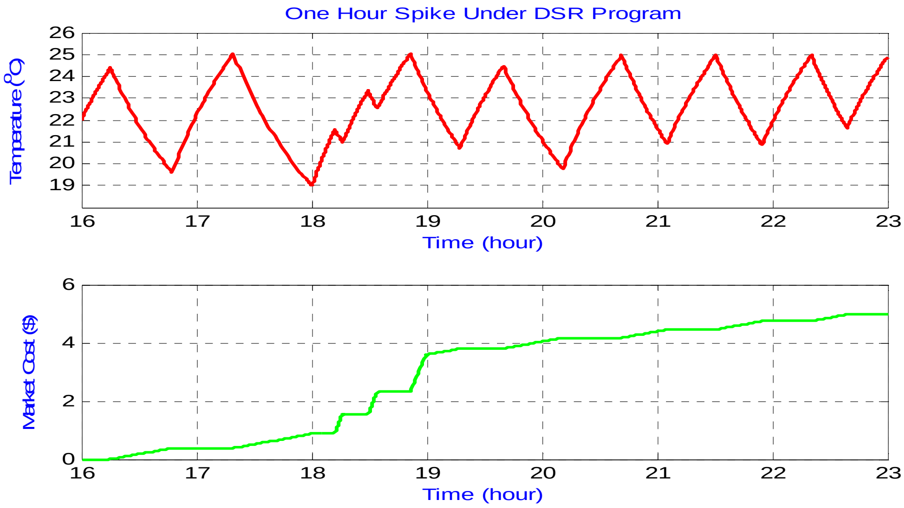

Figure 3. Cycling temperature and market cost under DSR Program

The results reported in Figure 3 indicate that a price spike of one hour may occur at 18.00. The typical operation of the air conditioning was similar to the the optimisation process as discussed above. Under DSR program a pre-cooling method was applied at switch number 4. The temperature during the pre-cooling dropped to 19°C, cooler than the temperature during the spike period. The air conditioning status when the spike started was off. Due to the high cost, the control system turned the air conditioning on only for a short time while the spike happened. The inside room temperatures were under 25°C and above 19°C.

Similar to the process explained above, the cost can be calculated according to the air conditioning status. There was a cost when the air conditioning is on and no cost when the air conditioning was off.

4.3. Benefit of DSR Model

Based on the results of the optimisation reported above, the consumer and aggregator could gain collective benefits when the consumer controls the air conditioning under the DSR program. The collective benefit (CB) is expressed by the following Equation:

$$CB = MC_1 - MC_s \tag{8}$$

The percentage of collective benefit is illustrated by the following Equations:

$$\%\,(\mathrm{CB}) = \frac{\mathrm{CB}\ (\$)}{\mathrm{MC_1}(\$)} \tag{9}$$

Equation (8) and (9) were used to compute the collective benefit. Table 4 summarises the collective benefit for the consumer and aggregator when the consumer applied the DSR program if a spike may only occur at 18.00 during one hour.

Table 4. Collective Benefit if Spike May Only Occur at 18.00

Spike Duration	Without DSR MC_1 ($)	Under DSR TMC_s ($)	Collective Benefit ($)	Collective Benefit (%)
Half Hour Spike	7.54	4.96	2.58	34.22%

It is clear from the results presented in Table 4 that the collective benefits reached by the consumer and aggregator when the DSR program was applied was 2.58 $ (34.22%) for one hour spike case. This indicates that controlling the air conditioning temperature under the DSR program can minimise the energy cost. The pre-cooling method was required to anticipate a price spike in the electricity market if a price spike may only occur in the middle of the day.

5. CONCLUSION

This paper has demonstrated that the proposed DSR model allows consumers to manage and control air conditioning if spike price may occur at 18.00 duirng one hour in the peak season. The model was applied in resdiential house in Makassar City in Indonesia considering to the characteristic of room and air conditioning. This result indicates that, the collective benefit both aggregator and consumer achieved when the consumer applied DSR model to anticipate a price spike in the peak season. In addition, the pre-cooling method is required to applied in DSR model.

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