REAL TIME DEMAND RESPONSE USING RENEWABLE ENERGY RESOURCES AND ENERGY STORAGE IN SMART CONSUMERS

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ABSTRACT

There is a pressing need to accelerate the development of low-carbon energy technologies in order to address the global challenges of energy safety, climate changes and economic growth. Smart grids are particularly important as they enable several other low-carbon energy technologies, including electric vehicles, variable renewable energy sources and demand response. This paper describes an optimization model to adjust the hourly load level of a given consumer in response to hourly electricity prices with consideration of renewable energy resources and energy storage.

The objective of the model is to minimize the energy cost of the consumer. Price uncertainty and uncertainties in making prediction about solar PV and wind power generation are modeled through robust optimization techniques. The model materializes into a simple linear programming algorithm that can be easily integrated in the Energy Management System of a household or a small business. A simple bidirectional communication device between the power supplier and the consumer enables the implementation of the proposed model. Simulations results confirm the performance of the proposed model.

INTRODUCTION

Our current electric grid was devised more than 100 years ago when electricity needs were simple. Power generation was localized and built around communities as most houses had only a few light bulbs and maybe a radio. The grid was created simply for utilities to push energy out to consumers' homes. This limited, one- way communication makes it difficult for the grid to respond to the ever-changing and rising energy demands of the 21st century.

A smart grid [1] is a next generation power network using IT technologies. It delivers power from suppliers to consumers using two-way communications, which leads to energy efficiency and grid reliability enhancement. It basically has the capability to sense grid conditions, measure power, and control appliances with two-way communications to power generation, transmission, distribution and consumer parts of the power grid. This makes it possible for the consumer to dynamically respond to changes in energy consumption, demand and grid condition. For example, when the power is low-cost, the user can allow the smart grid to turn on certain home appliances such as washing machines that can run at arbitrary hours, but at peak times it could turn off the appliances to reduce demand which is known as demand response. Smart grid also has the capability of integrating renewable energy such as solar and wind power [2].

Environmental problems coupled with high oil prices and also increasing government support is driving to enhance renewable energy consumption and commercialization. Therefore, smart grid is being promoted by many governments as a way of solving energy independence and environmental issues.

There are wide variety of demand response programs along with benefits and challenges of implementation and economic modeling of them [3], [4], [5], and [6].

One of the contributions of the current study is proposing a real time pricing (RTP) scheme and consists of providing a simple optimization model that allows a consumer to adapt its hourly load level in response to hourly electricity prices with considering of renewable energy sources and energy storage. Two-way communication between the consumer and the supplier is considered. This algorithm can be easily embedded into the energy management system (EMS) of a household or a small business and make it possible to achieve maximum utility by the consumer.

To the best of our knowledge, no similar real-time demand response model under uncertainty with considering of renewable energy sources and storage has been proposed in the technical literature.

The rest of the paper is organized as follows. The proposed model is describes in the next section. After that, the implementation of the model is explained. Then, we provide and discuss results from a case study and the conclusion is at the last section.

DEMAND RESPONSE MODEL

The main notation used throughout the paper is stated below for quick reference. Other symbols are defined as required throughout the paper.

d_k	Consumer demand at the beginning of hour k.
e_{day}	Minimum daily consumption required by the consumer.
e_k	Energy consumption in hour k.
r^U/r^D	Up/down demand ramping limit.
$u_k(.)$	Consumer utility in hour k.
λ_k	Energy price in hour k.

A superscript a/min/max affecting any of the symbols above indicates actual/minimum/maximum value.

Robust Model

In the proposed model, the power supplier provides the consumer willing to participate in the demand response program with hourly electricity prices based on the technical issues of the grid, energy price in the market and consumer usage data. The consumer equipped with a Micro Turbine, PV panel and energy storage receives predictions on the amount of solar radiation and wind speed from the meteorological organization (see Fig. 1). This data is automatically received by an energy box (E-box). Wind speed and solar radiation predictions are presented for the next 24 hours. The precise amounts of renewable energy sources for each hour is available 10 minutes before the hour. This information is based on wind speed and the amount of solar radiation automatically received from the meteorological organization. The price uncertainty is considered via robust optimization, because robust optimization is particularly suited to address uncertain, but bounded parameters [6]. Due to existing uncertainty, robust optimization techniques are employed [7] to make predictions about PV power, wind power and electricity price. Consequently, consumers will be able to determine about their energy consumption for each hour based on changes in the price and the amount of energy produced by renewable energy sources.

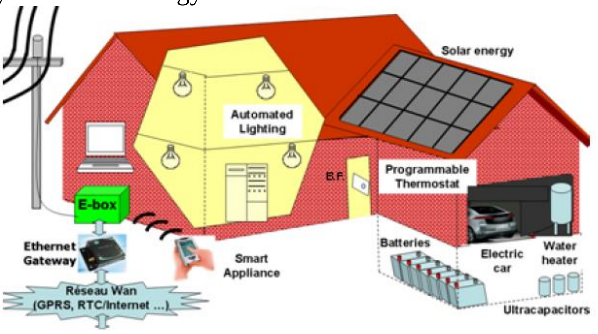

Fig. 1. Smart consumer [4]

The linear programming problem can be formulated in the following equation:

$$minimize\ (\lambda_t^a e_t - u_t(e_{total_t}) + \sum_{h=1}^{24-t}[\lambda_{t+h}^{min} e_{t+h} - u_{t+h}(e_{total_t+h})] + \beta\Gamma_1 + \sum_{h=1}^{24-t}\xi_{t+h} + EC \times \Gamma_2 \sum_{h=1}^{24-t} Aux_{t+h})$$

In the above objective function, e_t is the amount of energy that purchased from the energy supplier in hour t (e.g., 10 min prior to the current hour), e_{total} is the amount of energy that consumed (including the amount of energy is purchased from the energy supplier, energy that is produced from wind and PV and also the energy that is stored and released from energy storage in hour t). In addition, $u_t(.)$ is the utility of the consumer from the energy consumption (e_{total_t}). As mentioned, λ_t^a is the energy price in hour t and λ_{t+h}^{min} is the minimum prediction of electricity prices in hour t+h [6]. Variables such as β, ξ_{t+h} and Aux_{t+h} are auxiliary variables of robust optimization. Moreover, τ_1 and τ_2 are parameters that controls the level of robustness in the objective function, and may be adjusted continually in the interval [0, 24-t]. EC is a parameter that converts the power to the cost.

Model Constraints

Constraints of this model are as described in the following:

$$e_{total\_t} = (e_t + wind_t^a + PV_t^a - e_{sto_t}) \quad (1)$$

In the above constraint, wind_t and PV_t are the amount of energy produced by a wind turbine and solar panel in hour t, respectively. Also e_{stor_t} is the energy stored or released from the energy storage in hour t.

$$e_{total_t+h} - (e_{t+h} + wind_{t+h}^{min} + PV_{t+h}^{min} - e_{sto_t+h}) \le Aux_{t+h}, \forall h = 1,2,\ldots,24-t \quad (2)$$

$$e_{sto_t+h} = e_{store_t+h} - e_{gen_t+h}, \quad \forall h = 0,1,2,\ldots,24-t \quad (3)$$

$$SOC_{t+h+1} = SOC_{t+h} + e_{sto_t+h}, \quad \forall h = 0,1,2,\ldots,24-t \quad (4)$$

$$U^{stor\_t+h} + U^{gen\_t+h} \le 1, \quad \forall h = 0,1,2,\ldots,24-t \quad (5)$$

$$e_{store\_t+h} \le 3 \times U^{stor\_t+h} \quad \forall h = 0,1,2,\ldots,24-t \quad (6)$$

$$e_{gen\_t+h} \le 3 \times U^{gen\_t+h} \quad \forall h = 0,1,2,\ldots,24-t \quad (7)$$

$$SOC_{t+h} \le 7 \quad \forall h = 0,1,2,\ldots,24-t \quad (8)$$

$$e_{total\_t+h} = \frac{d_{t+h} + d_{t+h+1}}{2} \quad h = 0,\ldots,24-t \quad (9)$$

$$d_{t+h} - d_{t+h+1} \le r^D \quad h = 0,\ldots,24-t \quad (10)$$

$$d_{t+h+1} - d_{t+h} \le r^U \quad h = 0,\ldots,24-t \quad (11)$$

$$d_{t+h+1}^{min} \le d_{t+h+1} \le d_{t+h+1}^{max} \quad h = 0,\ldots,24-t \quad (12)$$

$$\sum_{h=1}^{t-1} e_{total\_h} + e_{total\_t} + \sum_{h=1}^{24-t} e_{total\_t+h} \ge e_{day} \quad (13)$$

$$\beta + \xi_{t+h} \ge (\lambda_{t+h}^{max} - \lambda_{t+h}^{min})y_{t+h} \quad h = 1,\ldots,24-t \quad (14)$$

$$\xi_{t+h} \ge 0 \quad h = 1,\ldots,24-t \quad (15)$$

$$y_{t+h} \ge 0 \quad h = 1,\ldots,24-t \quad (16)$$

$$\beta \ge 0 \quad (17)$$

$$e_{t+h} \le y_{t+h} \quad h = 1,\ldots,24-t \quad (18)$$

In the constraint (3) e_{sto_t+h} , e_{store_t+h} and e_{gen_t+h} are the energy that exchanged, stored and released with/from the energy storage in hour t+h, respectively. Variables U^{stor_t+h} and U^{gen_t+h} are binary variables that indicate the storage statues and generation of the energy storage. Since the energy storage is only able to be in one of the statues (storage or generation) at a time, considering the constraint (5) is necessary. Constraints (6) and (7) show the energy storage which is able to store or release 3MWh in one hour. Constraint (8) indicates the capacity of the energy storage. Other constraints, (9)-(18), are similar to [6].

SIMULATION RESULTS

In order to illustrate the possibility and efficiency of the proposed model, it was implemented in a small commercial consumer, equipped with a two-way communication**,** small renewable power generation unit and energy storage. Data for the considered commercial consumer and data price is provided in [6]. These data correspond to the energy prices of the Spanish area of the electricity market of the Iberian Peninsula on Monday July 5, 2010.

The power capacity of the micro turbine and PV are 2MW and 1MW, respectively. Moreover, the consumer equipped with the energy storage that its capacity is 7 MWh. This energy storage is able to exchange 3 MWh in every hour. The hourly profile of wind and solar PV energy are given in Table I and Table II. The second column provides the actual power generation, while the third and fourth columns contain the lower and upper bounds of power generation for each hour, respectively.

EC is a parameter that converts the power to cost and its value is considered 50 $/MWh. This parameter takes values in the price intervals. However every other value can be considered, upper values indicate more importance of uncertainties modeling in the objective function and vice versa. The model is solved using CPLEX 11.2.1under GAMS.

Table I. Power generation from wind turbine

t	$wind_{t+h}^{a}$	$wind_{t+h}^{min}$	$wind_{t+h}^{max}$
1	0.45	0.375	0.485
2	0.525	0.5	0.575
3	0.55	0.51	0.575
4	0.56	0.515	0.6
5	0.55	0.51	0.625
6	0.45	0.43	0.48
7	0.425	0.425	0.45
8	0.45	0.44	0.475
9	0.5	0.475	0.55
10	0.49	0.46	0.515
11	0.49	0.46	0.515
12	0.4	0.375	0.43
13	0.44	0.4	0.465
14	0.45	0.475	0.49
15	0.5	0.46	0.525
16	0.525	0.5	0.55
17	0.525	0.5	0.55
18	0.55	0.525	0.6
19	0.56	0.53	0.58
20	0.575	0.55	0.625
21	0.575	0.55	0.625
22	0.6	0.551	0.625
23	0.625	0.6	0.65
24	0.65	0.61	0.675

Table II. Power generation from PV

t	pv_{t+h}^{a}	pv_{t+h}^{min}	pv_{t+h}^{max}
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0.05	0.04	0.6
8	0.1	0.85	0.105
9	0.2	0.185	0.21
10	0.3	0.275	0.31
11	0.425	0.4	0.45
12	0.5	0.45	0.575
13	0.65	0.625	0.69
14	0.6	0.55	0.625
15	0.5	0.46	0.525
16	0.4	0.375	0.43
17	0.275	0.24	0.3
18	0.15	0.13	0.115
19	0.07	0.06	0.075
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0
24	0	0	0

Figure 2 shows the energy consumption profile corresponding to the optimal value of τ [6] for the two considered alternatives (with renewable energy sources and without them). Note that however energy consumption has greatly increased per hour, the utility of the consumer has increased. The energy cost in every hour for the two considered alternatives is illustrated in Fig. 3. This figure shows that hourly energy cost is significantly reduced; therefore utility of the consumer is greatly increased. Finally, we compare total energy consumption for both alternatives in 24 hour. The results obtained from this comparison are listed in Table III.

Negative costs in table III and figure 3 indicate the utility. As the results show, despite increased energy consumption during the day, the cost of energy consumption is significantly reduced. One reason for this reduction in energy costs is the use of renewable energy sources instead of buying power from the power grid. Another is the use of energy storage which has a significant role in managing consumption, in the hours when electricity price is lower or there is more energy, so a section of the energy is stored for later use when we need it. Results indicate that the energy cost is significantly reduced during the day resulting in increased profits. This increase in profits can compensate the cost of purchasing and installing renewable sources and storage devices.

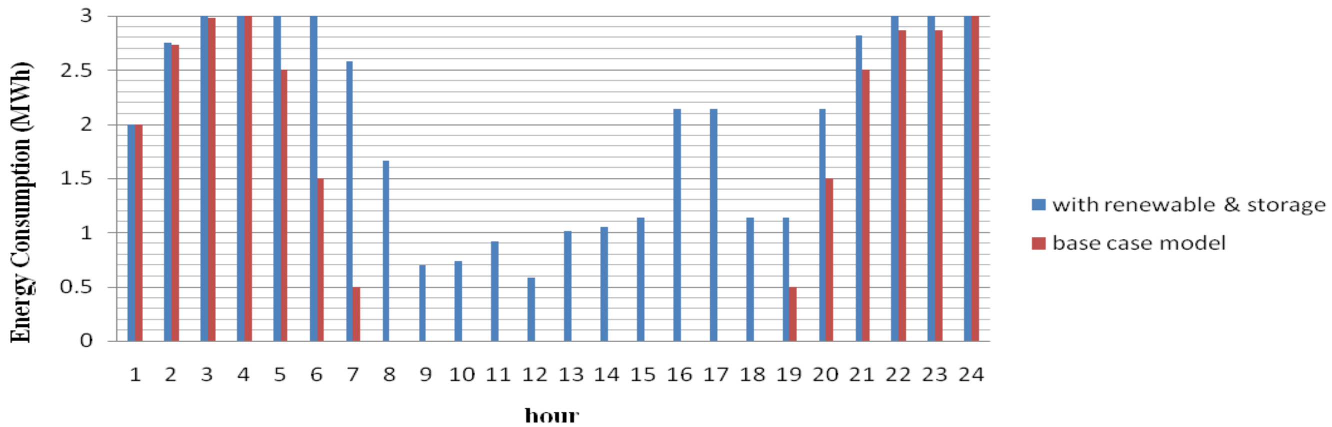

Fig. 2. Hourly Energy Consumption – proposed model considering renewable energy sources& storage and the base case

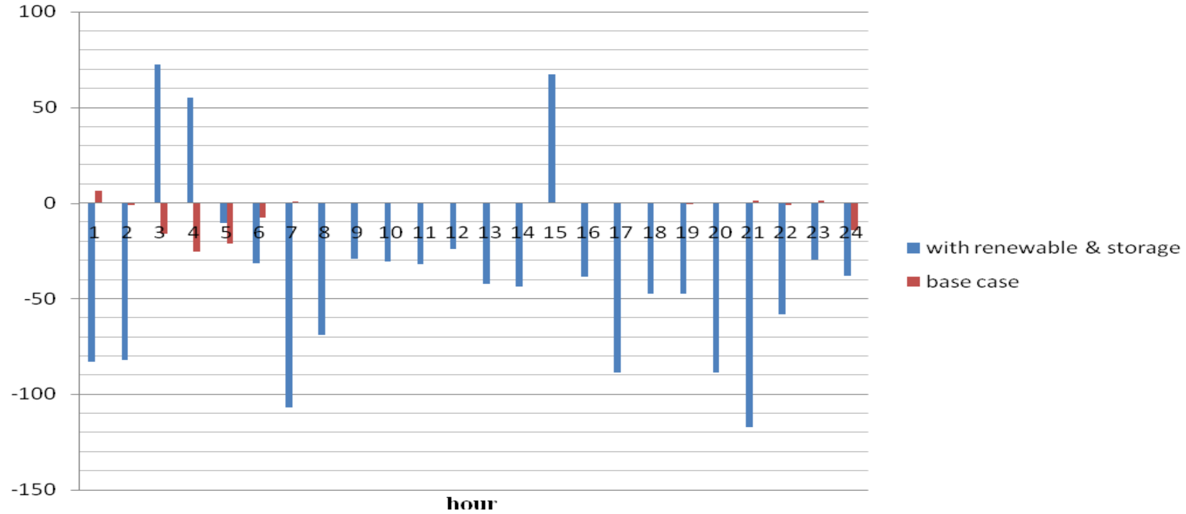

Fig. 3.Hourly Energy Cost – proposed model considering renewable energy sources& storage and the base case

Table III. Comparison between the results of the proposed model and base case

	base case	with renewable &storage
Energy Consumption in a day	28.462	47.654
Energy Cost in a day	-77.074	-944.665

CONCLUSION

This paper provides an optimization model to adjust the hourly load level of a given consumer in response to hourly changing electricity prices with considering of renewable energy sources and energy storage, through bidirectional communication with the electricity supplier. Such algorithm allows maximizing the consumer utility. A case study demonstrates the usefulness of the proposed model to maximize the utility or to reduce the electricity bill of the consumer that integrates the proposed procedure in its EMS.

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