Real-Time Demand Response Model

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OUTLINE

- **Introduction to Demand Response**
- Problem Statement and Motivation
- Proposed Demand Response Model
- Implementation Details
- Experimental Results
- Critiques and Discussion

DEMAND RESPONSE

- Consumers [industrial, residential or individual] have the ability to manage the power usage.
  - Factories may use standby generators.
  - Office buildings can adjust lighting/cooling.
- Demand Response is the management of electricity consumption at consumer end in response to the supply conditions.
- Essentially, it refers to the mechanisms used to encourage consumers to reduce demand during peak times. [Economic demand response]

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PROBLEM STATEMENT

- Objective: Maximizing utility for consumers.
- Input: Hourly electricity prices and history data about previous prices and decisions.
- Output: Adjusted hourly load level in response to prices.
- Motivation:
  - Ability of smart grid to facilitate bidirectional communication.
  - Energy cost savings.

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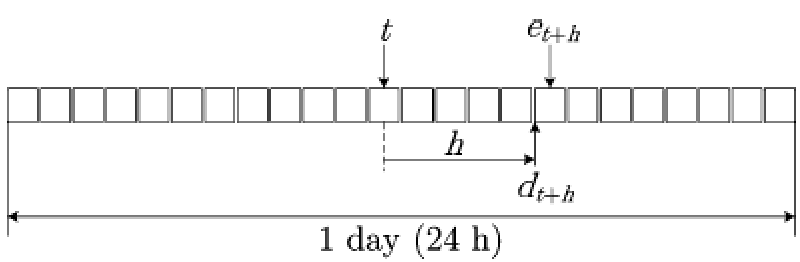
NOMENCLATURE

- d_k – consumer demand at beginning of hour k.
- e_{day} – minimum daily consumption required by 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.
- t – current hour

REQUIREMENTS

- Information related to hourly energy consumptions, and demand levels for initial t-1 hours is known.
- Price of electricity for the current hour t is communicated to the consumer.
- Consumer demand at the beginning of hour t is known.
- Load profile for entire day needs to be provided.
- Model has been developed for 24-h span.



INITIAL MODEL

$$\text{Minimize}_{\{e_{t+h}, h=0,\ldots,24-t\}\cup\{d_{t+h}, h=1,\ldots,25-t\}}$$

$$\lambda_t^a e_t - u_t(e_t) + \sum_{h=1}^{24-t} [\{\lambda_{t+h}\} e_{t+h} - u_{t+h}(e_{t+h})] \quad (1a)$$

subject to:

$$\sum_{h=1}^{t-1} e_h^a + e_t + \sum_{h=1}^{24-t} e_{t+h} \geq e_{\text{day}} \quad (1b)$$

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

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

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

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

INITIAL MODEL

Energy consumption for remaining hours [t,t+1..]

Consumer demand for remaining hours [t+1,t+2..]

Minimize $_{\{e_{t+h}, h=0,\ldots,24-t\} \cup \{d_{t+h}, h=1,\ldots,25-t\}}$

$$\lambda_t^a e_t - u_t(e_t) + \sum_{h=1}^{24-t} \left[\{\lambda_{t+h}\} e_{t+h} - u_{t+h}(e_{t+h})\right] \qquad (1a)$$

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Actual price for consumption in hour t

Consumer Utility for hour t

For remaining hours

subject to:

$$\sum_{h=1}^{t-1} e_h^a + e_t + \sum_{h=1}^{24-t} e_{t+h} \geq e_{\text{day}} \quad (1b)$$

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$$\lambda_t^a e_t - u_t(e_t) + \sum_{h=1}^{24-t} \left[\{\lambda_{t+h}\} e_{t+h} - u_{t+h}(e_{t+h}) \right] \quad \text{(1a)}$$

For remaining hours

subject to:

Consumer Utility for hour t

$$\sum_{h=1}^{t-1} e_h^a + e_t + \sum_{h=1}^{24-t} e_{t+h} \geq e_{\text{day}} \quad \text{(1b)}$$

Lower limit on daily energy consumption

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

$$d_{t+h} - d_{t+h+1} \leq r^{\mathrm{D}}, \quad h = 0, \ldots, 24-t \quad \text{(1d)}$$

$$d_{t+h+1} - d_{t+h} \leq r^{\mathrm{U}}, \quad h = 0, \ldots, 24-t \quad \text{(1e)}$$

Constraint on load variability

$$d_{t+h+1}^{\min} \leq d_{t+h+1} \leq d_{t+h+1}^{\max}, \quad h = 0, \ldots, 24-t. \quad \text{(1f)}$$

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Actual price for consumption in hour t

Consumer Utility for hour t

For remaining hours

subject to:

$$\sum_{h=1}^{t-1} e_h^a + e_t + \sum_{h=1}^{24-t} e_{t+h} \geq e_{\text{day}} \quad \text{(1b)}$$

Lower limit on daily energy consumption

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

Approximation of energy usage with respect to demand

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

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

Constraint on load variability

$$d_{t+h+1}^{\min} \leq d_{t+h+1} \leq d_{t+h+1}^{\max}, \quad h = 0, \ldots, 24-t. \quad \text{(1f)}$$

Bounds for consumer demand at beginning of each hour

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$$\text{Minimize}_{\{e_{t+h}, h=0,\dots,24-t\} \cup \{d_{t+h}, h=1,\dots,25-t\}}$$

$$\lambda_t^a e_t - u_t(e_t) + \sum_{h=1}^{24-t} [\{\lambda_{t+h}\} e_{t+h} - u_{t+h}(e_{t+h})] \qquad \text{(1a)}$$

?????

subject to:

$$\sum_{h=1}^{t-1} e_h^a + e_t + \sum_{h=1}^{24-t} e_{t+h} \geq e_{\text{day}} \qquad \text{(1b)}$$

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Energy consumption for remaining hours [t,t+1..]

Consumer demand for remaining hours [t+1,t+2..]

Actual price for consumption in hour t

Consumer Utility for hour t

For remaining hours

Lower limit on daily energy consumption

Approximation of energy usage with respect to demand

Constraint on load variability

Bounds for consumer demand at beginning of each hour

ROBUST MODEL

Minimize

$$\lambda_t^a e_t - u_t(e_t) + \sum_{h=1}^{24-t} \left[\lambda_{t+h}^{\min} e_{t+h} - u_{t+h}(e_{t+h})\right]$$

$$+ \beta\Gamma + \sum_{h=1}^{24-t} \xi_{t+h} \tag{2a}$$

subject to:

$$\text{Constraints (1b)–(1f)} \tag{2b}$$

$$\beta + \xi_{t+h} \geq \left(\lambda_{t+h}^{\max} - \lambda_{t+h}^{\min}\right) y_{t+h}, \quad h = 1, \ldots, 24 - t \tag{2c}$$

$$\xi_{t+h} \geq 0, \quad h = 1, \ldots, 24 - t \tag{2d}$$

$$y_{t+h} \geq 0, \quad h = 1, \ldots, 24 - t \tag{2e}$$

$$\beta \geq 0 \tag{2f}$$

$$e_{t+h} \leq y_{t+h}, \quad h = 1, \ldots, 24 - t. \tag{2g}$$

ROBUST MODEL

Predicting price of electricity for remaining hours.

Minimize

$$\lambda_t^a e_t - u_t(e_t) + \sum_{h=1}^{24-t} \left[\lambda_{t+h}^{\min} e_{t+h} - u_{t+h}(e_{t+h})\right]$$

$$+ \beta\Gamma + \sum_{h=1}^{24-t} \xi_{t+h} \quad (2a)$$

subject to:

Constraints (1b)–(1f) (2b)

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$$\xi_{t+h} \geq 0, \quad h = 1, \ldots, 24 - t \quad (2d)$$

$$y_{t+h} \geq 0, \quad h = 1, \ldots, 24 - t \quad (2e)$$

$$\beta \geq 0 \quad (2f)$$

$$e_{t+h} \leq y_{t+h}, \quad h = 1, \ldots, 24 - t. \quad (2g)$$

Non negativity of decision variables

ROBUST MODEL

Minimize

$$\lambda_t^a e_t - u_t(e_t) + \sum_{h=1}^{24-t} \left[\lambda_{t+h}^{\min} e_{t+h} - u_{t+h}(e_{t+h})\right] + \beta\Gamma + \sum_{h=1}^{24-t} \xi_{t+h} \tag{2a}$$

subject to:

$$\text{Constraints (1b)–(1f)} \tag{2b}$$

$$\beta + \xi_{t+h} \geq (\lambda_{t+h}^{\max} - \lambda_{t+h}^{\min})\, y_{t+h}, \quad h = 1, \ldots, 24-t \tag{2c}$$

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$$y_{t+h} \geq 0, \quad h = 1, \ldots, 24-t \tag{2e}$$

$$\beta \geq 0 \tag{2f}$$

$$e_{t+h} \leq y_{t+h}, \quad h = 1, \ldots, 24-t. \tag{2g}$$

Predicting price of electricity for remaining hours.

Control Variable which Signifies effect of price deviation

Dual variables of initial model

Auxiliary variable for formulating equivalence

Non negativity of decision variables

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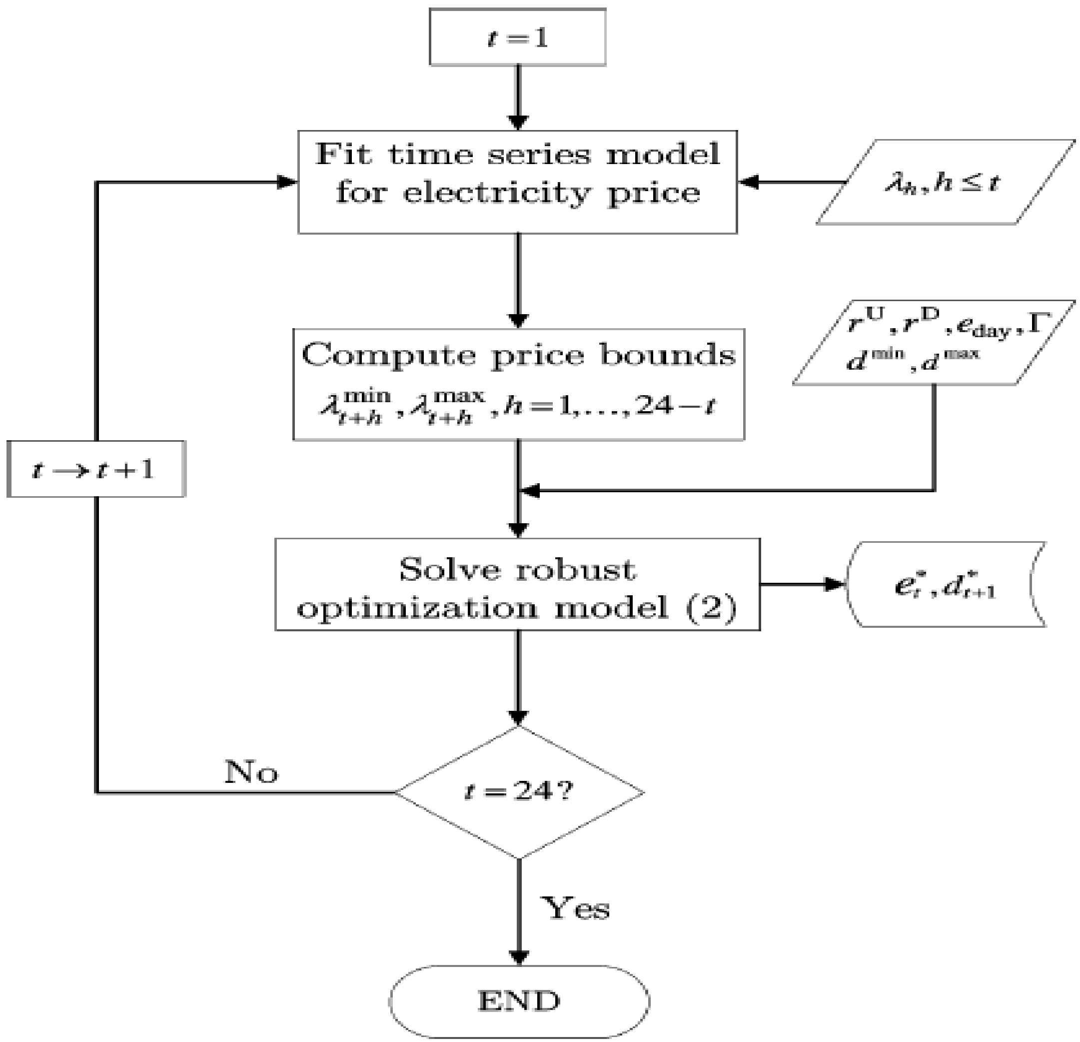
ROLLING WINDOW CRITERION

- The price for current hour is transmitted to the consumer (10 minutes) prior to the current hour.
- Energy consumption in current hour and demand at the beginning of next hour is estimated by solving ‘robust model’. The information is transmitted to supplier (5 minutes) prior to the current hour.
- These two steps are repeated every hour for the entire day.

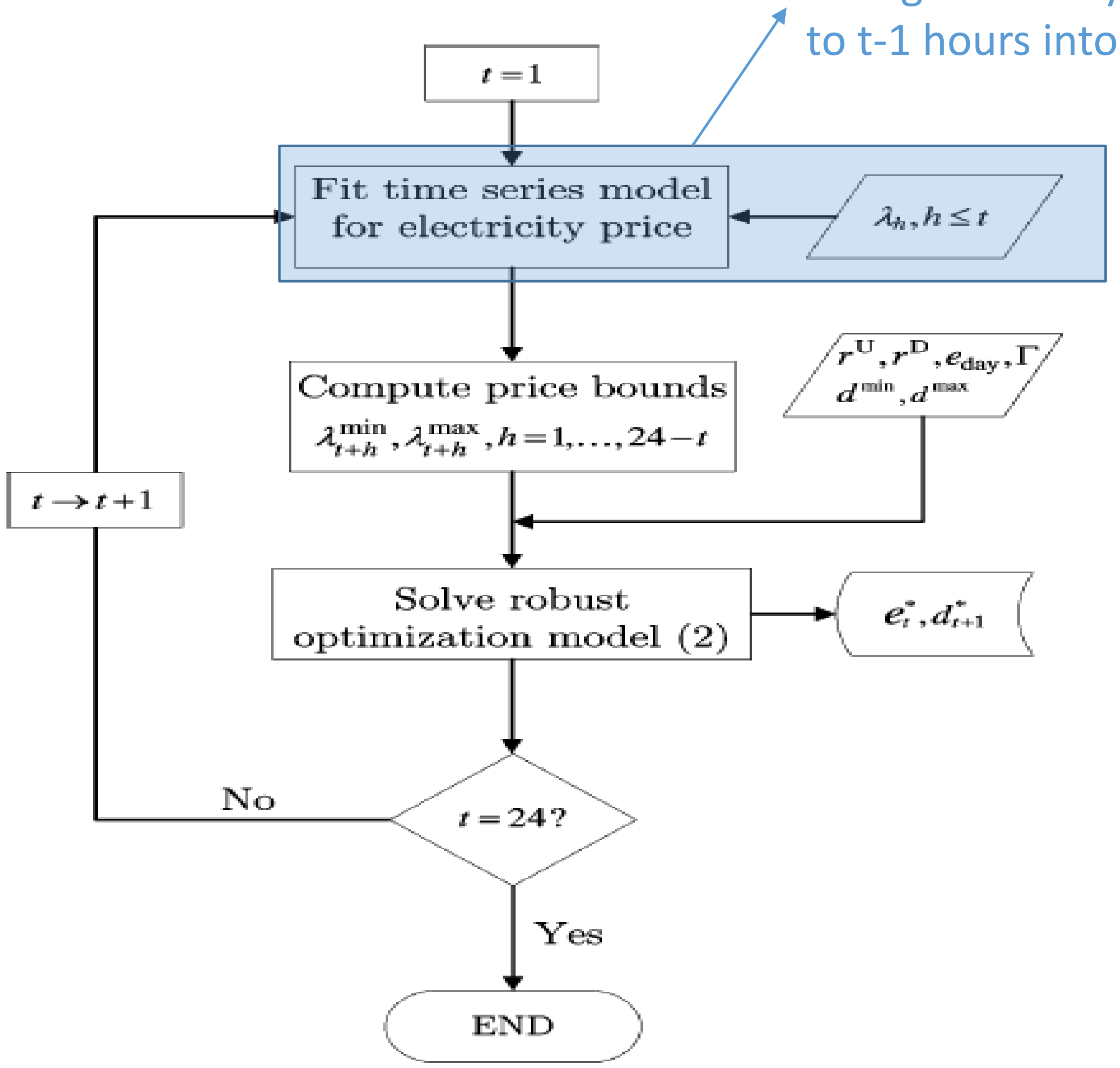
FLOW CHART



$t=1$
Fit time series model for electricity price
$\lambda_h, h \le t$
Compute price bounds
$\lambda_{t+h}^{\min}, \lambda_{t+h}^{\max}, h=1,\ldots,24-t$
$r^{U}, r^{D}, e_{\text{day}}, \Gamma$
$d^{\min}, d^{\max}$
$t \rightarrow t+1$
Solve robust optimization model (2)
e_t^*, d_{t+1}^*
No
$t=24?$
Yes
END

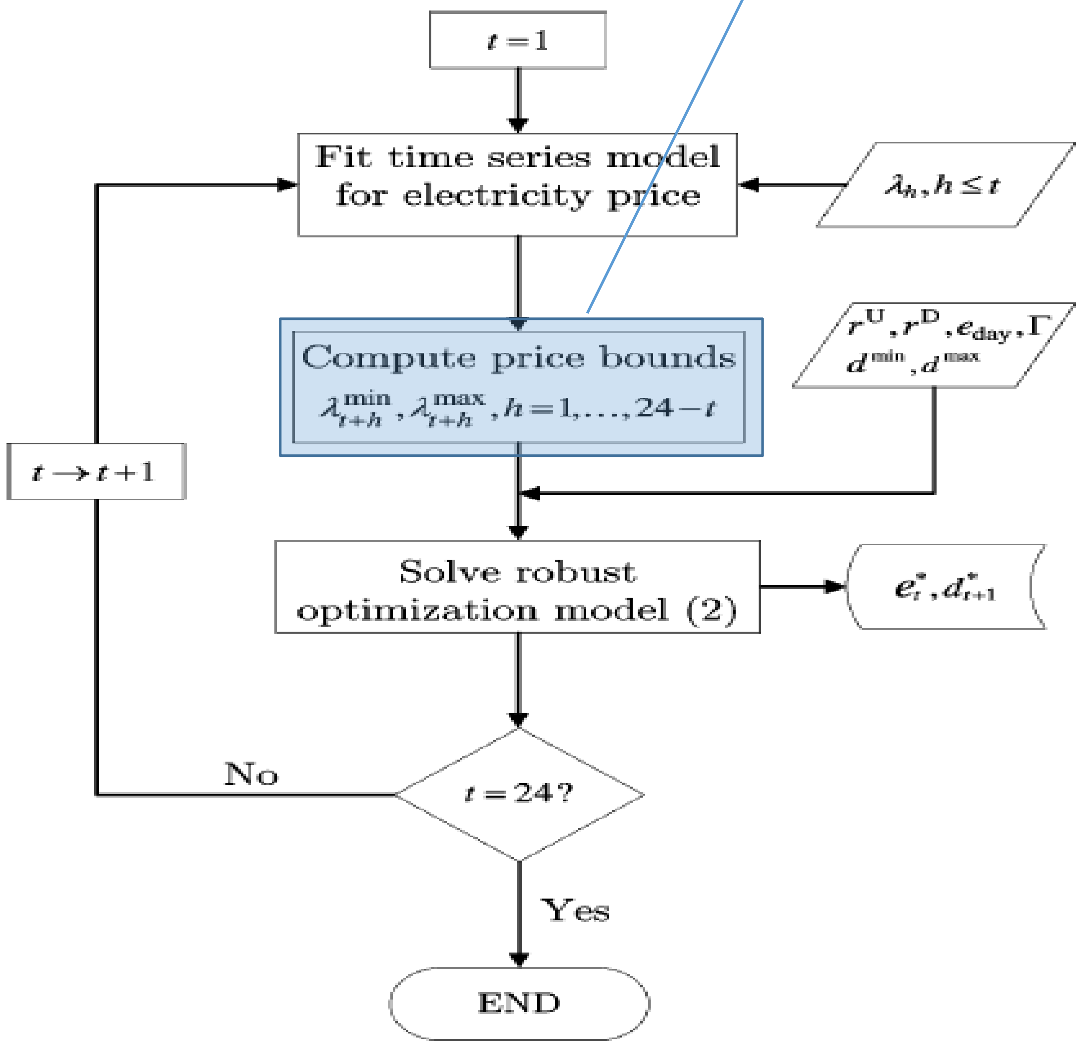
FLOW CHART

Formulate ARIMA based model to fit the time series by taking electricity prices for 1st to t-1 hours into account



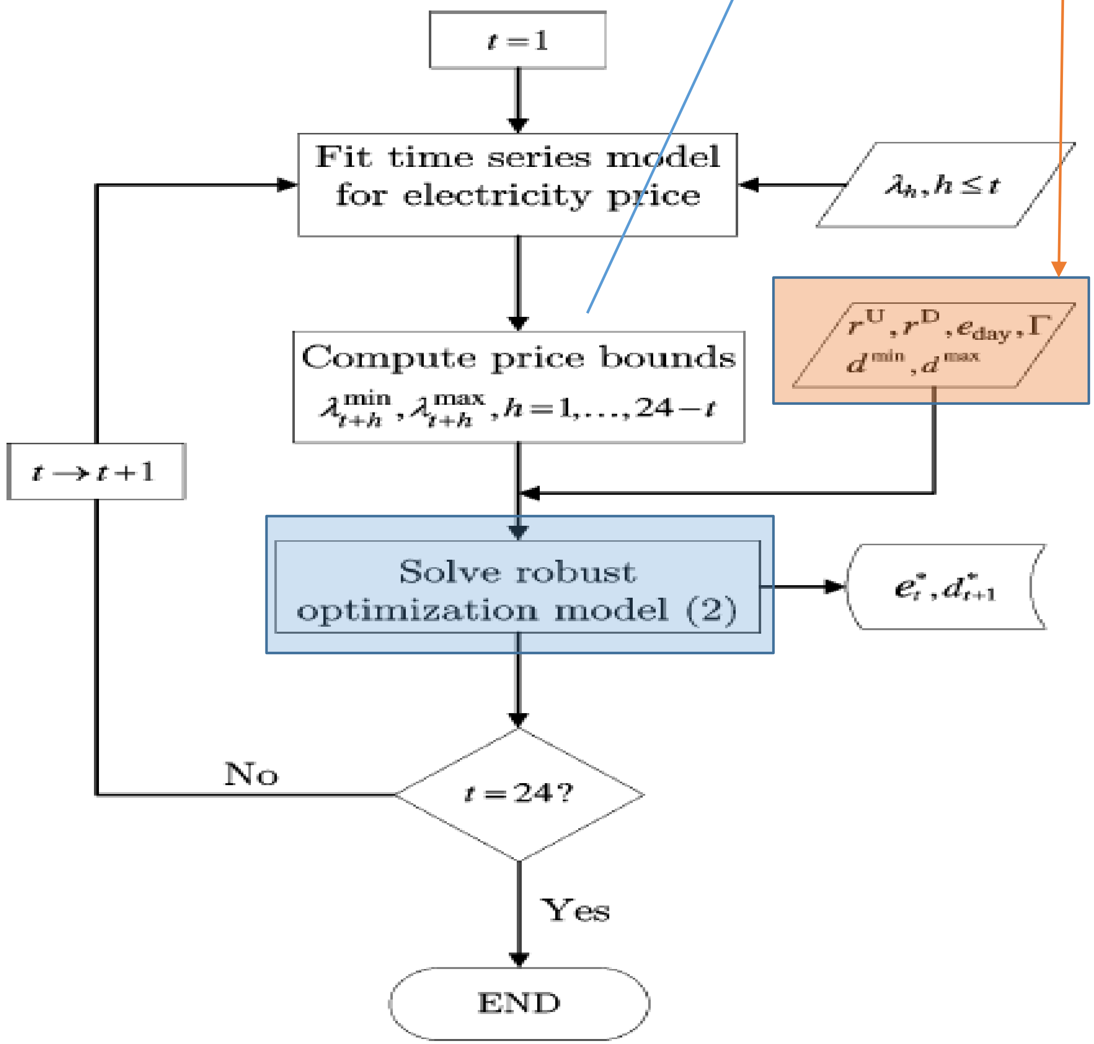
FLOW CHART

Estimate the electricity price bounds for the remaining hours of 24 hour span.



FLOW CHART

Solve model using price bounds and



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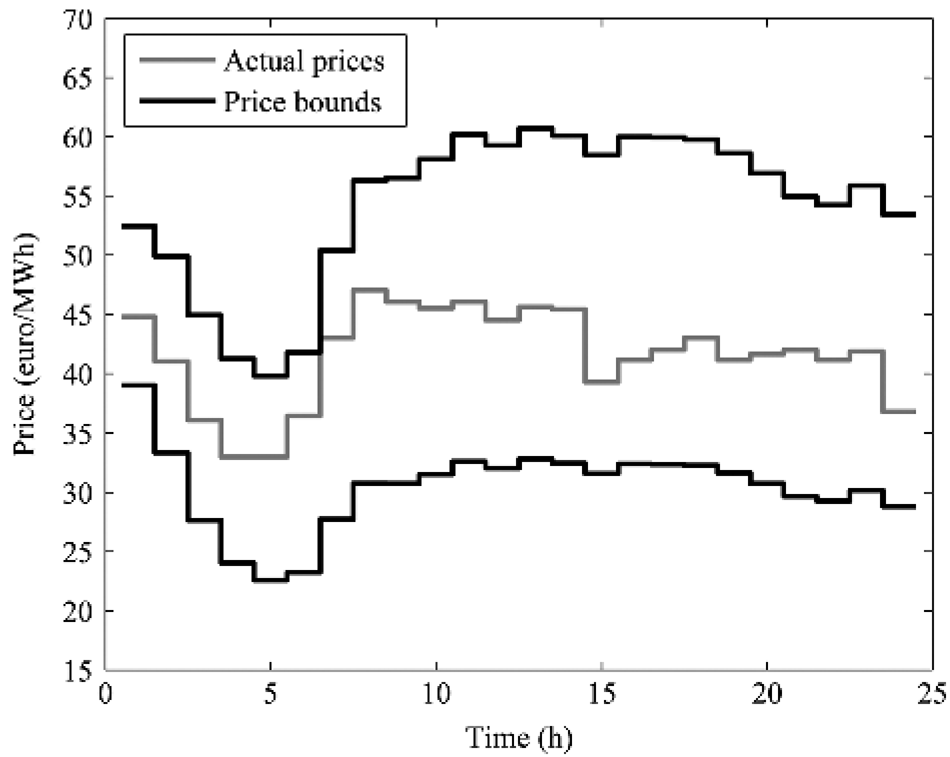
DATA USED

TABLE I
CONSUMER DATA

Maximum hourly demand	3	MW
Minimum hourly demand	0	MW
Minimum daily consumption	15	MWh
Ramping up limit	1	MW/h
Ramping down limit	1	MW/h
Consumer utility	41.5	€/MWh



Actual prices were obtained from Spanish area of electricity market of Iberian peninsula and price bounds were computed using ARIMA model.

ALTERNATIVES

- Two types of scenarios were considered:
  - With smart grid – which ensures that the consumers have information about the hourly prices
  - Without smart grid – in which the consumers do not have information about hourly prices. Thus the problem is reduced to computing the objective function of robust model for t=1.
- Comparative analysis for these two cases has been published.

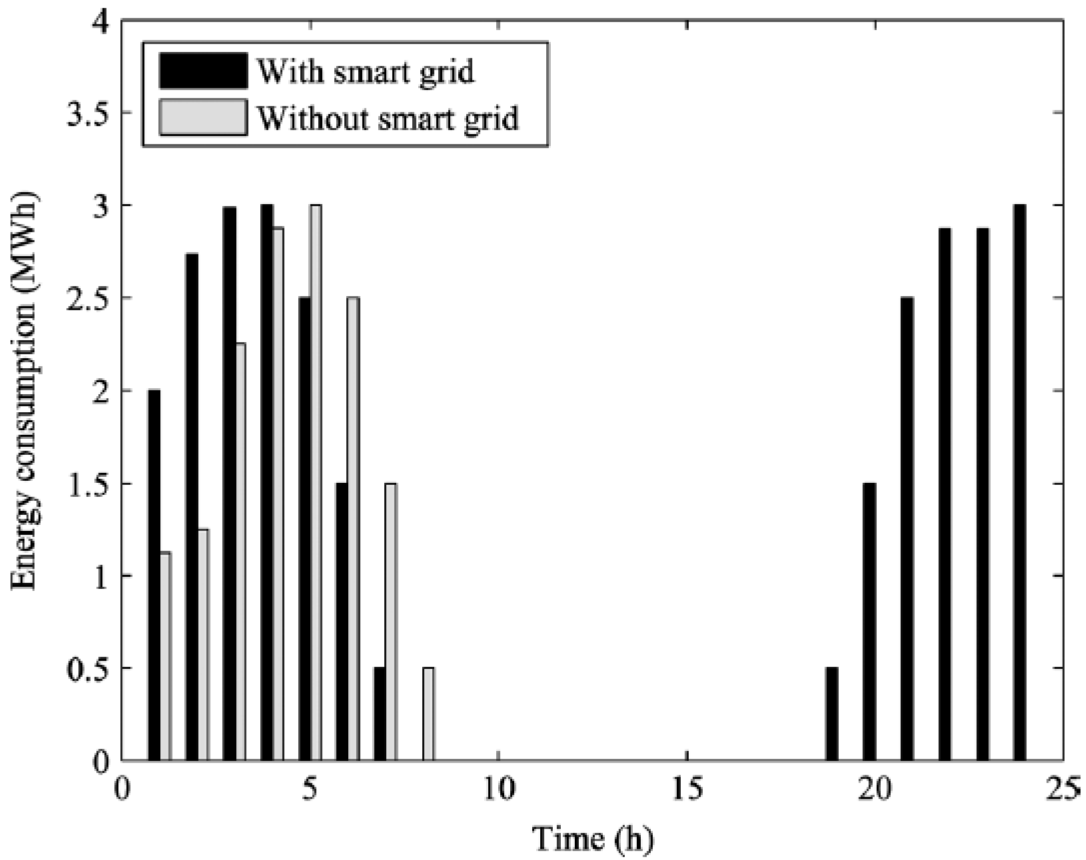
COMPUTING CONTROL VARIABLE

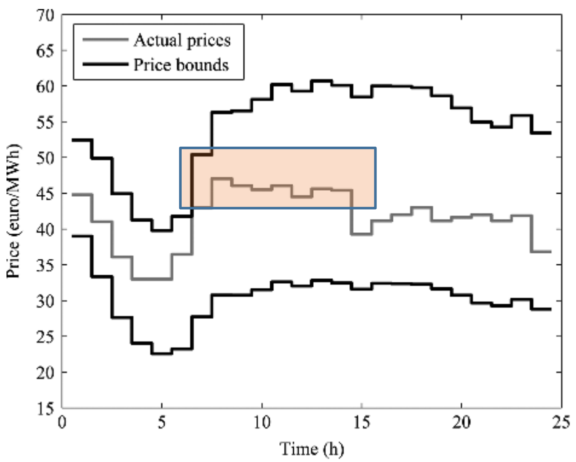
- Optimal values of **τ** have been computed by the authors.
- Table shows consumer utility with respect to different values of control variable.
- From the table it can be seen that in case of ‘with smart grid’ scenario maximum utility is achieved for 45% of maximum value.
- In the second case, maximum utility is achieved when control variable is between 75% -100% of its maximum value.

Γ %	With smart grid	Without smart grid
0	-2.49	-2.49
5	-2.13	-2.22
10	-1.87	-1.88
15	-9.7	1.05
20	0.22	1.23
25	1.24	2.56
30	2.06	21.21
35	6.95	24.95
40	72.24	25.12
45	77.07	25.16
50	66.81	18.94
55	51.03	37.61
60	56.68	37.61
65	64.88	48.09
70	69.73	57.92
75	69.73	66.52
80	69.73	66.52
85	69.73	66.52
90	69.73	66.52
95	69.73	66.52
100	69.73	66.52

ENERGY CONSUMPTION PROFILE

[FOR OPTIMAL VALUES OF CONTROL PARAMETER]





The result signifies that with the information about hourly prices, the consumer can change its load profile according to price bounds.

Is something missing?

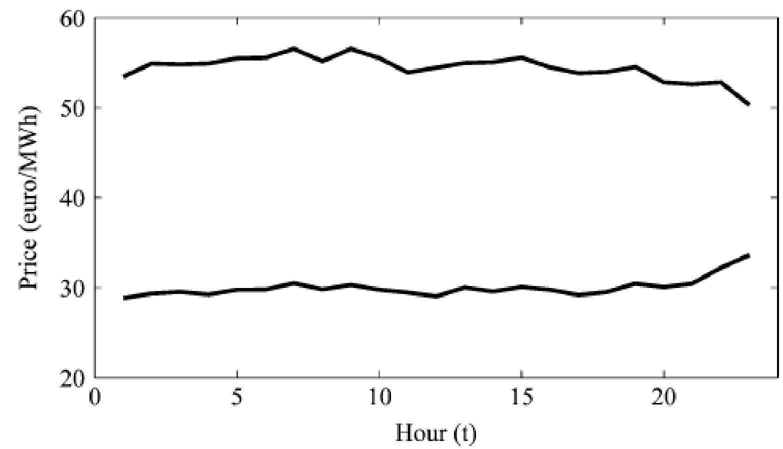
UTILITY RELATED RESULTS

Day	Utility (€)		Increment	Optimal Γ (%)	
	SG	No SG	(%)	SG	No SG
Mon	77.07	66.52	15.86	45	70
Tue	169.12	131.91	28.21	35	80
Wed	128.34	118.04	8.72	45	80
Thu	119.99	112.84	6.34	40	80
Fri	79.99	78.20	2.28	75	85
Mean	114.90	101.50	13.20	-	-

Results show that using smart grid to get hourly electricity prices and feeding them into the proposed model allows the consumer to maximize its utility by **13.2%.**

EFFECT OF CONSIDERING EVOLUTION OF PRICE BOUNDS

- It shows that utility is not maximized in all cases. Reasons for the same are:
  - Evolution is nearly constant, hence not much affect of prices.
  - Inaccuracies in modelling.
  - Most energy consumption is scheduled in earlier hours while significant changes occur in later hours.



Day	Utility (€) No price bound updating	Utility (€) Price bound updating	Increment (%)
Mon	77.07	72.63	-5.72
Tue	169.12	166.20	-1.73
Wed	128.34	135.10	5.27
Thu	119.99	122.02	1.69
Fri	79.99	79.99	0.00

NON-CONSTANT CONSUMER UTILITY

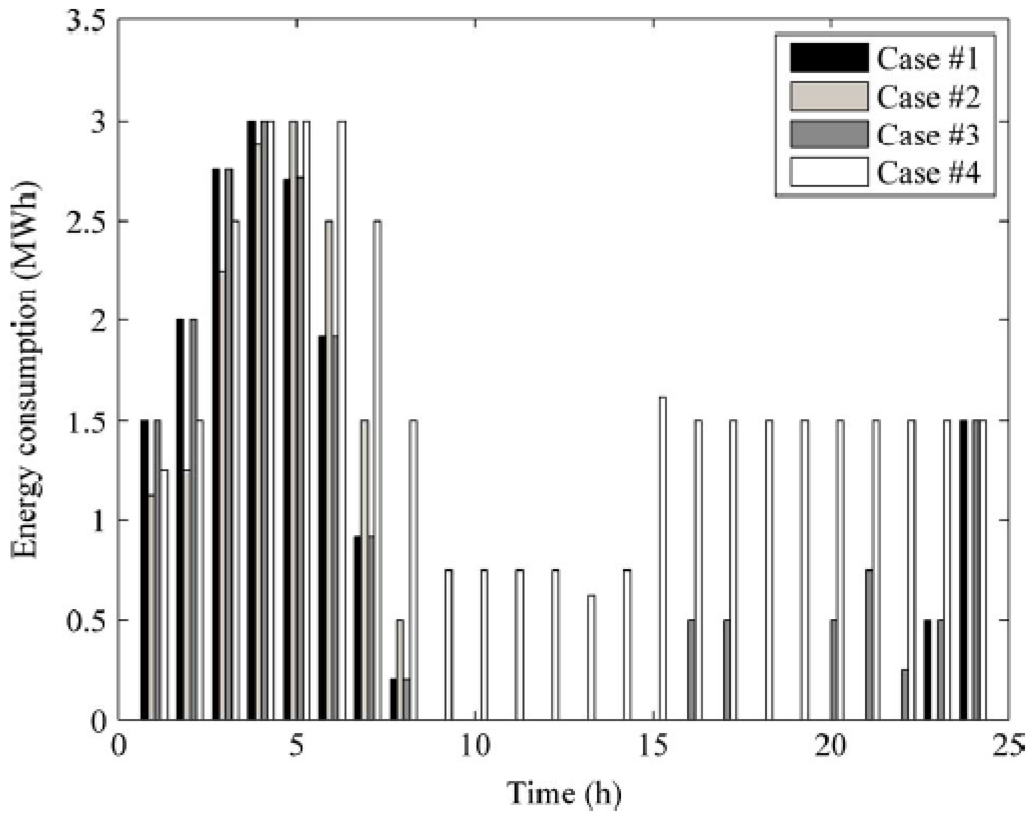
CASE #	UPDATE PRICE BOUND	SMART GRID	MODEL USED
1	NO	YES	ROBUST
2	NO	NO	ROBUST
3	YES	YES	ROBUST
4	NO	YES	INITIAL

TABLE VI
RESULTS WITH A NONCONSTANT UTILITY FUNCTION

Day	Utility (€)			
	Case #1	Case #2	Case #3	Case #4
Mon	73.33	66.52	72.89	58.69
Tue	133.32	127.62	131.45	130.99
Wed	123.40	121.26	123.96	101.52
Thu	99.97	94.28	104.53	88.66
Fri	76.90	73.13	76.13	56.27

The results show that case 1 and 3 maximize the consumer utility which is in accordance with expected behavior.

NON-CONSTANT CONSUMER UTILITY



CONCLUDING REMARKS

- Paper presents a simple linear programming based algorithm capable of forecasting energy consumption levels of a particular consumer.
- The solution can be easily integrated with existing technology.
- Experimental results show that the consumers can benefit from the algorithm as it helps in reducing electricity cost while maximizing utility at the same time.

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CRITIQUE ON THE PAPER

- Good points:
  - Modelling price bounds of electricity in accordance with RTP scheme makes the paper realistic.
  - Information generated by the model can be used for energy management at the side of utility provider. [This is when the bidirectional communication would actually matter.]
- Weaknesses:
  - Difference between energy consumption in a particular hour and the consumer demand for next hour is not clear. Why do the authors need these separately?
  - Notion of consumer utility is very unclear.
  - It is not clear as to why these models are capable of producing realistic value of decision variables in the optimization problem.
- General Comment:
  - The models proposed in the paper have been presented directly. No hint about insight behind the variables and the computation details has been provided. [Common point in many peer critiques]

PEER CRITIQUES: POINTS FOR DISCUSSION

- If a consumer sends his current hour energy consumption to supplier then will supplier only supply that much of energy, not more than that? If user needs more energy, say in emergency? (Swadesh)
- On the gamma value. (Sunil)
- During the last hours of the day, if load is different than the known load, the pricing will be different than the forecasted prices, how are such cases incorporated for in the optimization algorithm? (Sandeep)
- What are the existing technological gaps to deploy the proposed methodology at utilities or distribution companies? (Gelli)

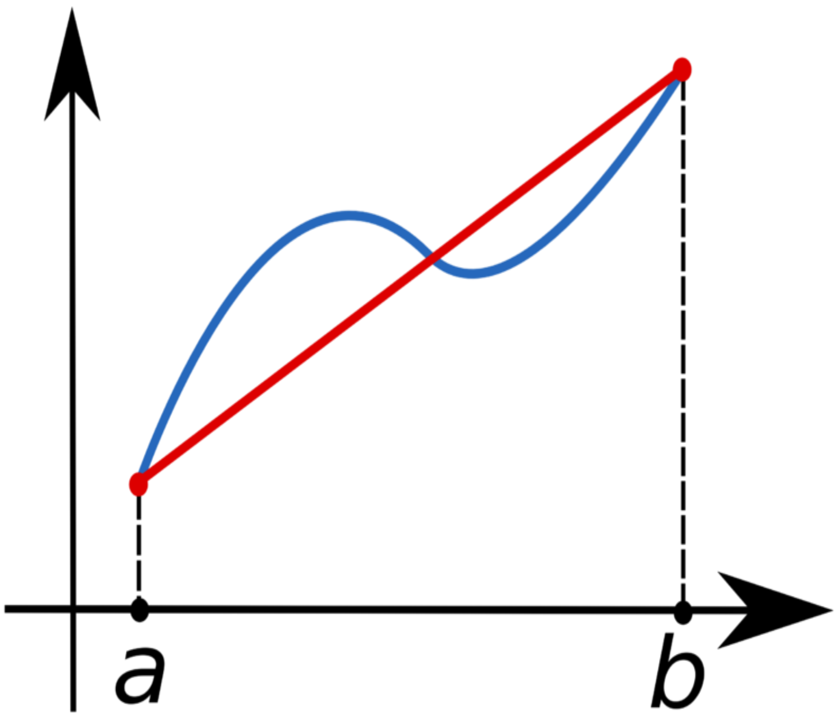
References

- Resource on demand response:
  - http://www.systemoperator.co.nz/presentations/demand-response-animation/
  - http://blogs.cas.suffolk.edu/salewis24/2012/02/06/demand-response/
  - http://en.wikipedia.org/wiki/Demand_response
- Understanding proposed models:
  - http://en.wikipedia.org/wiki/Trapezoidal_rule
  - D. Bertsimas and M. Sym, "Robust discrete optimization and network flows," *Math. Program., Ser. B*, vol. 98, no. 1–3, pp. 49–71, 2003.

GLOSSARY

Trapezoidal rule: It is a technique of approximating definite integral by approximating region under the graph as a trapezoid and calculating its area.

$$\int_a^b f(x)\,dx \approx (b-a)\frac{f(a)+f(b)}{2}.$$



GLOSSARY

- ARIMA [Auto Regressive Integrated Moving Average] Model: This model is fitted into the time series data for analytics based applications or forecasting applications.

- http://en.wikipedia.org/wiki/Autoregressive_integrated_moving_average