Impact of TOU Rates on Distribution Load Shapes in a Smart Grid with PHEV Penetration

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***Abstract*--A smart grid introduces new opportunities and challenges to electric power grids especially at the distribution level. Advanced metering infrastructure (AMI) and information portals enable customers to have access to real-time electricity pricing information, thus facilitating customer participation in demand response. The objective of this paper is to analyze the impact of time-of-use (TOU) electricity rates on customer behaviors in a residential community. Research findings indicate that the TOU rate can be properly designed to reduce the peak demand even when PHEVs are present. This result is insensitive to seasons, PHEV penetration levels and PHEV charging strategies. It is expected that this paper can give policy makers, electric utilities and other relevant stakeholders an insight into the impacts of various TOU pricing schemes on distribution load shapes in a smart grid with PHEV penetration.**

***Index Terms*--Time-of-use rate, demand response, customer behavior, PHEV, and smart grid.**

I. Introduction

TODAY, a flat electricity rate is the most popular electricity tariff for residential customers. Several electric utilities offer time-of-use (TOU) rate to their customers. Such a variable electricity rate offers attractive off-peak prices, but relatively high peak prices. For a variable electricity rate to be useful, advanced metering infrastructure (AMI), together with its associated information portal and smart end-use appliances, are required. AMI delivers ability to display real-time electricity prices and usage information. The availability of such information will allow customers to react and respond to the variation in electricity prices. This is generally known as demand response [1].

The penetration of plug-in hybrid electric vehicle (PHEV) also creates new challenges to the distribution network. A study by National Renewable Energy Laboratory [2] showed that large PHEV penetration would place increased pressure on peaking units with an uncontrolled charging strategy. Researches from Oak Ridge National Laboratory [3] indicated that most regions would need to build additional generation capacity to meet the added demand when charging PHEVs in the evening.

This paper focuses on the development of the demand response model for residential customers with PHEV penetration that reflects customer behaviors in response to variable electricity prices. Research findings are the impact of different TOU pricing schemes on distribution feeder load shapes. It is expected that the proposed model can be used as a basis for analyzing the impact of various electricity pricing schemes on aggregated load shapes at the distribution level – with the presence of demand response and PHEVs. Such an analysis will be useful for electric utility companies and regulatory bodies for their future generation, transmission and distribution planning and TOU rate designs.

II. Household Load and PHEV Charging Profiles

A. Household load profiles

This paper uses hourly residential load curves of an average household in the U.S., which are available from the RELOAD database [4, 5]. To study the impact of variable electricity rates on a distribution feeder load shape, it is assumed that there are 780 homes connected to a distribution feeder of interest. This represents a number of households in a distribution feeder in the Virginia Tech Electric Service area.

Fig. 1 and Fig. 2 show residential load curves for a typical weekday in a summer and a winter month, respectively.

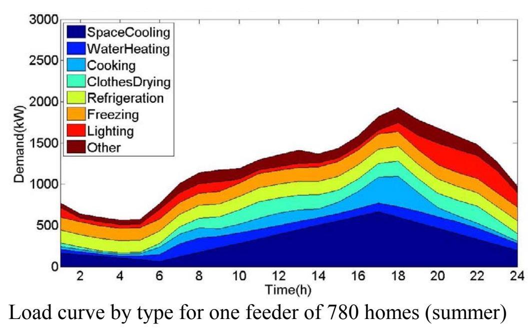

Fig. 1. Load curve by type for one feeder of 780 homes (summer)

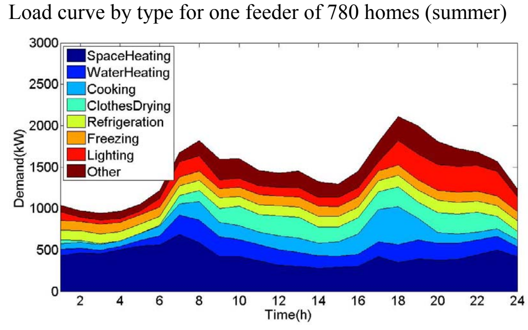

Fig. 2. Load curve by type for one feeder of 780 homes (winter)

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B. PHEV load profiles

1) Normal charge vs quick charge

This study considers two PHEV charging strategies: normal and quick charges. The normal charge is defined as the standard PHEV charge from the 110V/15A outlet as specified in Chevy Volt's specifications [6]. The quick charge is defined as the PHEV charging strategy when PHEVs are allowed to be charged at higher voltage and/or current to achieve a faster charging duration. The quick charge can be accomplished by charging from a 240V/30A outlet. The charging characteristics of a PHEV are presented in Fig. 3. As shown, it takes about 6.5 hours to charge a PHEV from a standard 110V/15A outlet, whereas it takes less than 2.5 hours from a 240V/30A outlet.

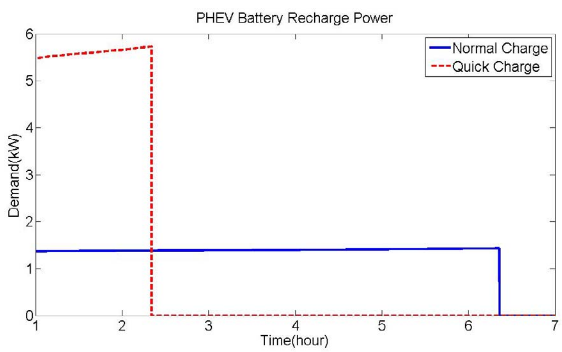

Fig. 3. Charging characteristics of normal and quick charge

2) High and low PHEV penetration scenarios

This study looks into the impact of two PHEV penetration levels. For the low penetration level, it is assumed that there is one PHEV for every five houses. For the high penetration level, it is assumed that there are two PHEVs for every five houses. Since there are 780 houses in the distribution circuit of interest, these scenarios will result in the total of 156 and 312 PHEVs, respectively, using similar assumption stated in [7].

3) PHEV charging profiles

To create a PHEV charging profile for this residential community, it is assumed that the PHEVs charging time follows a normal probability distribution function with the mean at 6 pm and one hour variance.

For the low PHEV penetration scenario, Fig. 4 illustrates the aggregated PHEV charging loads (156 PHEVs) using both normal and quick charge strategies.

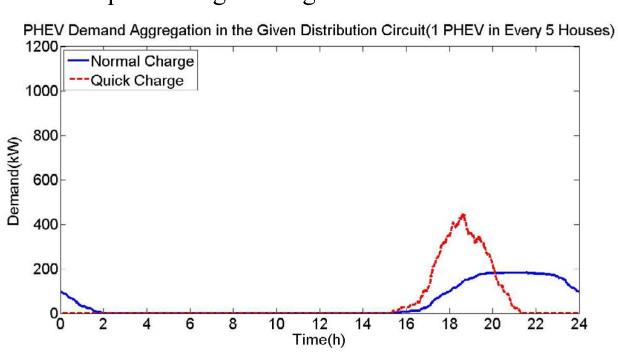

Fig. 4 Aggregated charging profiles of 156 PHEVs using normal and quick charge strategies

As shown, the peak PHEV demand using a normal charging strategy is about 200kW. The charging time spans between 3pm and 3am. The peak PHEV demand using a quick charging strategy is about 500 kW. The charging time for the quick charge strategy is much shorter, and stretches from 3pm to 11pm.

For the high PHEV penetration scenario, Fig. 5 illustrates the aggregated PHEV charging loads (312 PHEVs) using both normal and quick charge strategies. The peak PHEV demand with a normal charge is about 400kW. The charging time occurs between 3pm and 3am. The peak PHEV demand with a quick charge is about 1000 kW. The charging time is about the same as in the low PHEV penetration scenario.

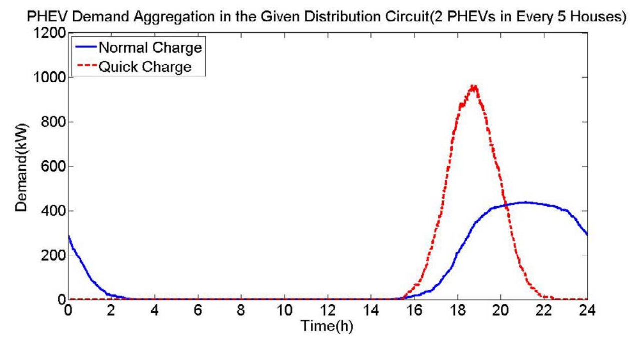

Fig. 5 Aggregated charging profiles of 312 PHEVs using normal and quick charge strategies

C. Household load profiles with PHEVs

Fig. 6 illustrates the summer household load profiles with PHEVs. The gray area represents the original household load profile without PHEVs. Please refer to Fig. 1. The solid and dash lines represent the total household load profiles with PHEVs in various scenarios.

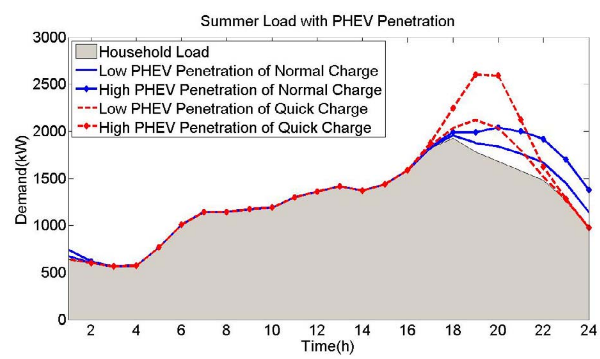

Fig. 6 The household load profiles with PHEVs in a summer month

The solid lines (blue) represent the total household load profile with low and high PHEV penetration levels while PHEVs use the normal charging strategy. The dashed lines (red) represent the total household load profile with low and high PHEV penetration levels with PHEV quick charge.

Fig. 7 illustrates the winter household load profiles with PHEVs. The gray area represents the original household load profile without PHEVs. Please refer to Fig. 2. The solid and dashed lines represent the total household load with PHEVs in various scenarios, as previously discussed.

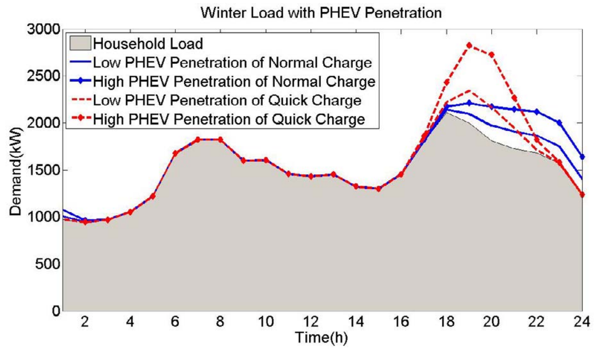

Fig. 7 The household load profiles with PHEVs in a winter month

The peak demand for all scenarios considered – two seasons, two PHEV penetration levels, and two PHEV charging strategies – are summarized in Table I.

TABLE I
SUMMARY OF PEAK DEMAND (KW) FOR ALL SCENARIOS

	Scenarios	Peak (kW)
Summer	- Original without PHEVs	1,926.8
	- with low PHEV penetration, normal charge	1,955.7
	- with high PHEV penetration, normal charge	2,040.5
	- with low PHEV penetration, quick charge	2,121.2
	- with high PHEV penetration, quick charge	2,600.6
Winter	- Original without PHEVs	2,111.4
	- with low PHEV penetration, normal charge	2,140.2
	- with high PHEV penetration, normal charge	2,209.7
	- with low PHEV penetration, quick charge	2,342.4
	- with high PHEV penetration, quick charge	2,821.7

III. PRICE STRUCTURE AND DEMAND RESPONSE STRATEGIES

A. Price Structures

When the system is under stress, customers can help a utility by means of voluntary demand management programs if they are offered the right incentives. Over the years, many utilities have explored the value of TOU rates in lieu of flat rates [8]. Compared to the flat rates, TOU rates provide more incentives for customers to shift load to the less expensive hours.

To investigate the customer's behavior in response to the price change, we use electricity tariffs from two electric utilities in the Washington DC area: Baltimore Gas & Electricity (BG&E) and Dominion Virginia Power (DOM) [9-10]. Fig. 8 illustrates the TOU rates of both BG&E and DOM in August (the summer peak month). Table II gives more detailed information on specific TOU periods and rates, together with the corresponding flat rates in the summer. The prices shown here only represent the energy and delivery charges and do not include other service charges and taxes.

Similarly, Fig. 9 illustrates the TOU rates of both BG&E and DOM in January (the winter peak month). Table III gives more detailed information of specific TOU periods, rates, together with the corresponding flat rates in the winter.

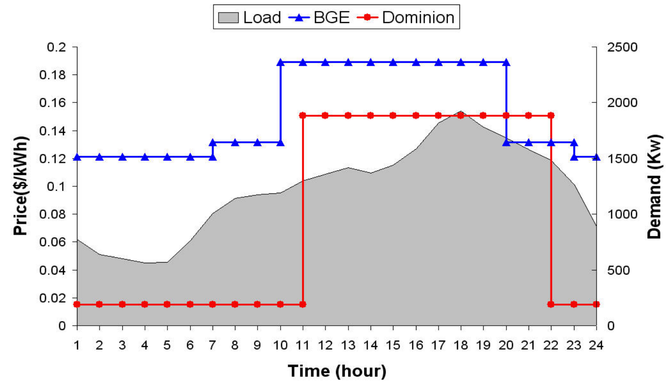

Fig. 8. The summer TOU rates from the chosen utilities

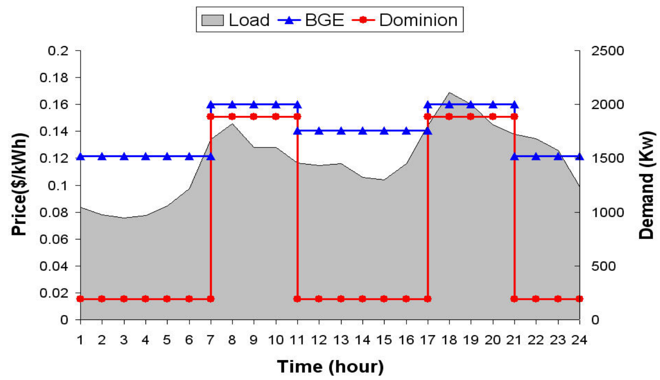

Fig. 9. The winter TOU rates from the chosen utilities

TABLE II
TOU AND FLAT RATES FROM THE CHOSEN UTILITIES (SUMMER)- 2009 DATA

Company	Pattern	Period	TOU Rate ($/kWh)	Flat Rate ($/kWh)
BGE	On-peak	10am-8pm	0.18897	0.15062
	Shoulder	7am-10am 8pm-11pm	0.13140	
	Off-peak	11pm-7am	0.12116	
Dominion	On-peak	11am-10pm	0.15085	0.06507
	Off-peak	10pm-11am	0.01514	

TABLE III
TOU AND FLAT RATES FROM THE CHOSEN UTILITIES (WINTER)- 2009 Data

Company	Pattern	Period	TOU Rate ($/kWh)	Flat Rate ($/kWh)
BGE	On-peak	7am-11am 5pm-9pm	0.15989	0.13987
	Shoulder	11am-5pm	0.14038	
	Off-peak	9pm-7am	0.12154	
Dominion	On-peak	7am-11am 5pm-9pm	0.15085	0.06507
	Off-peak	11am-5pm 9pm-7pm	0.01514	

B. Demand Response (DR) Strategies

Various approaches have been implemented to estimate and predict the customer behavior in dynamic electricity markets. Lawrence Berkeley National Laboratory has developed a series of DR strategies for residential demand saving [11]. Based on their survey results, a series of DR strategies are developed to achieve peak shaving and peak shifting according to different load types. Load-shedding schemes can be implemented to ensure service continuity to critical loads and control the levels of peak demand.

This paper classifies nine residential customers' load types discussed in section II into three groups: critical, interruptible and deferrable loads. PHEVs can fit into the 'deferrable load' type. The load shedding and shifting strategies for all load types used in this paper are shown in Table IV:

TABLE IV
DR STRATEGIES BY LOAD TYPE

Priority	Type	DR Strategy
Critical loads	Refrigerator	These loads will not be shifted or shed.
	Freezer	
	Cooking	
	Lighting (50%)	
Deferrable loads	Water Heating	Shut down the equipment when the price is higher than a pre-determined value, the load will be shifted to the less-expensive hours
	Clothes Drying	
	Others	
	PHEV	
Interruptible loads	Space Cooling/ Space Heating	From 9am-5pm: turn off From 5pm-9am: adjust by 10F and resume after peak hours
	Optional Lighting (50%)	Turn off 50% of the lighting loads when the price is higher than a per-determined value.

Critical loads will not be shed or shifted regardless of the electricity price. The deferrable loads will be shut down when the electricity price is higher than its corresponding flat rate. After peak hours the deferrable loads will resume, adding up to the original loads. For the interruptible loads, the optional lighting loads will be shut down when TOU rate goes higher than its flat rate. If the price is high during the daytime (9am to 5pm), the space cooling/heating loads will be drastically reduced during generally unoccupied hours. During the rest of the time, the thermostat will be adjusted 10 degree up or down. When the price drops back below the flat rate, the thermostat will be set back to its normal setting. It is also assumed that, once the electricity rate resumes to its normal level, the electricity consumption of the space cooling/heating loads will be increased by 10% (as a test case) during the start up, if they have been shut down for a period of time. This is to compensate for the increase in energy required to bring the temperature back to the desired level. It is to be noted that, for space cooling loads, decreasing the thermostat setting by 1 degree F will result in 1% demand saving [12].

IV. IMPACT OF TOU RATES ON THE LOAD SHAPES

Based on the hourly load curves with PHEV charge profiles and the DR strategies described earlier, a simulation model is developed in MATLAB/Simulink to study the impacts of different price structures on distribution feeder load shapes.

Due to the fact that electricity is an inelastic good [13] and not many customers respond to price changes, this study considers a conservative scenario by calculating a percentage of customers who are willing to shift their loads according to the increase in electricity prices as compared to the base rate.

In other words, the level of customer participation in demand response is calculated using the assumption that: if the TOU price is increased by 100% from its corresponding flat rate, 20% of customers are willing to shift or shed their non-critical loads. For simplicity, we assume that the participation function is linear. This assumption gives a general idea to represent the customer behavior, and the model also provides flexibility to reflect other levels of participation.

A. Load shapes w/ demand response in the summer month

Fig. 10 - Fig 13 illustrate the original household and PHEV load profiles (gray and dark gray areas respectively) and the updated load shapes after demand response (solid lines) under BG&E's and DOM's TOU rates in the summer month.

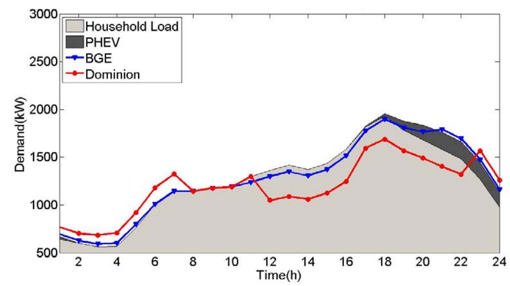

Fig. 10. Summer load profiles with low PHEV penetration – normal charge.

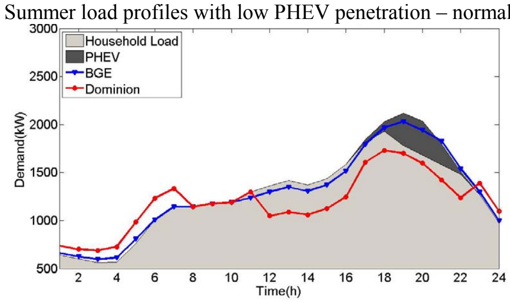

Fig. 11. Summer load profiles with low PHEV penetration – quick charge.

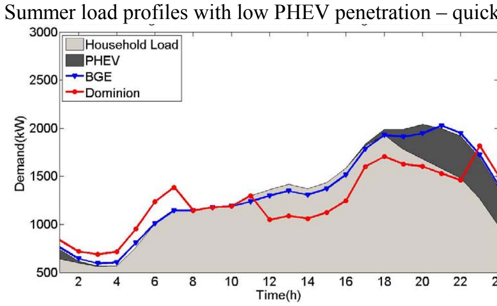

Fig. 12. Summer load profiles with high PHEV penetration – normal charge.

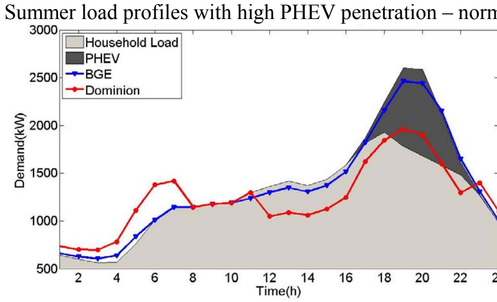

Fig. 13. Summer load profiles with high PHEV penetration – quick charge

In the low PHEV penetration scenarios (Fig. 10 and 11), it can be seen that, under both BG&E and DOM rate structures, the demand response can help lower the system peak in both normal and quick charging strategies. In the high PHEV penetration scenarios (Fig. 12 and 13), similar results can be observed. Table V summarizes the original summer peak loads (kW) without demand response (DR) and new summer peak loads (kW) with demand response implemented under two different TOU schemes.

TABLE V
SUMMARY OF NEW PEAK DEMAND (KW) FOR ALL SCENARIOS (SUMMER)

Scenarios (Summer month)	Peak (kW) No DR	Peak (kW) – w/ DR	
		BG&E's TOU rate	DOM's TOU rate
Loads w/ 156 PHEV, normal charge	1955.7	1,898.3	1,687.8
Loads w/ 312 PHEV, normal charge	2040.5	2,028.7	1,817.9
Loads w/ 156 PHEV, quick charge	2121.2	2,031.0	1,729.5
Loads w/ 312 PHEV, quick charge	2600.6	2,462.8	1,961.0

It is worthwhile to note that, under the DOM's TOU scheme, the on-peak price is $0.15085/kWh, whereas the flat rate is $0.06507/kWh. See Table II. This represents roughly 130% increase over the fate rate. Therefore, we can expect that about 26% of customers will response to this price – per our assumption stated earlier. On the other hand, under the BG&E's TOU scheme, the on-peak price is $0.18897/kWh, whereas the flat rate is $0.15062/kWh. This represents roughly 25% increase over its corresponding fate rate. Therefore, we can expect that about 5% of customers will response to this price using the similar assumption. As a result, we can expect that the load levels with demand response under the DOM's TOU pricing scheme will be lower than those under the BG&E's TOU pricing scheme.

B. Load shapes w/ demand response in the winter month

Fig. 14 - Fig 17 illustrate the original household and PHEV load profiles (gray areas) and the updated load shapes after demand response (solid lines) under BG&E's and DOM's TOU rates in the winter month.

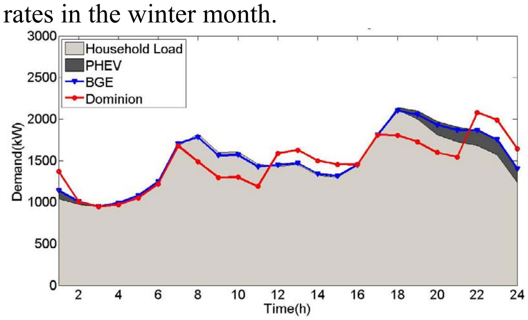

Fig. 14. Winter load profiles with low PHEV penetration – normal charge.

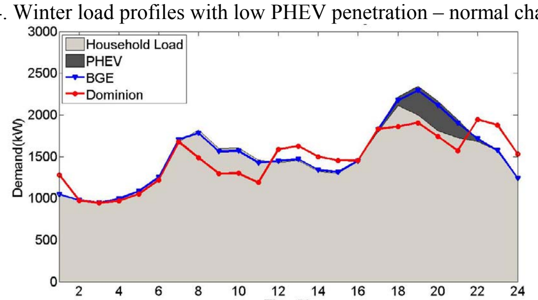

Fig. 15. Winter load profiles with low PHEV penetration – quick charge.

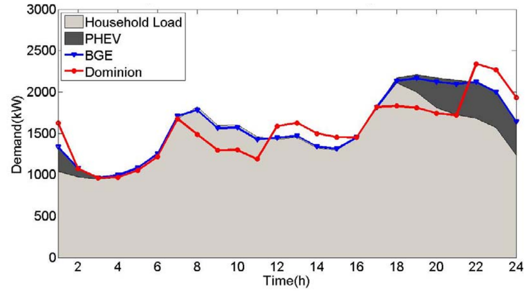

Fig. 16. Winter load profiles with high PHEV penetration – normal charge.

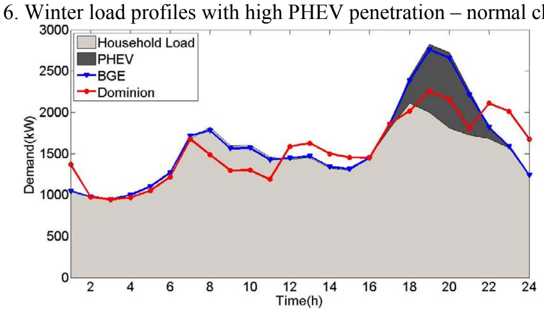

Fig. 17. Winter load profiles with high PHEV penetration – quick charge.

Table VI summarizes the original winter peak loads (kW) without demand response (DR) and new winter peak loads (kW) with demand response implemented under two different TOU schemes.

TABLE VI
SUMMARY OF NEW PEAK DEMAND (KW) FOR ALL SCENARIOS (WINTER)

Scenarios (Winter month)	Peak (kW) No DR	Peak (kW) – w/ DR	
		BG&E's TOU rate	DOM's TOU rate
Loads w/ 156 PHEV, normal charge	2140.2	2,102.0	2,079.2
Loads w/ 312 PHEV, normal charge	2209.7	2,163.7	2,340.0
Loads w/ 156 PHEV, quick charge	2342.4	2,292.4	1,945.1
Loads w/ 312 PHEV, quick charge	2821.7	2,757.3	2,257.7

For the winter low PHEV penetration scenarios (Fig. 14 and 15) under both BG&E and DOM rate structures, the demand response can help lower the system peak in normal and quick charging strategies. However, with high PHEV penetration and normal charge under the DOM's TOU pricing scheme (Fig. 16), there is a new peak, created by adopting demand response, at 9 pm. See Fig. 16 and 17).

This is because PHEV normal charge takes longer time and its peak is around 9 pm (see PHEV charging profile in Fig. 5). DOM's winter TOU pricing scheme defines 9 pm as off-peak time. Therefore, all deferrable loads will be shifted and started at 9 pm, which will create a new peak. The greater is the number of customers who respond, the higher the new peak will be. That is why DOM's winter new peak is higher than that of BGE.

Similar to the TOU rate in summer, under the DOM's TOU scheme, the on-peak price is $0.15085/kWh, whereas the flat rate is $0.06507/kWh. See Table III. This represents roughly 132% increase over the fate rate. Therefore, we can expect that about 26% of customers will response to this price – per our assumption stated earlier. On the other hand, under the BG&E's TOU scheme, the on-peak price is $0.15989/kWh, whereas the flat rate is $0.13897/kWh. This represents roughly 15% increase over its corresponding fate rate. The medium peak price is $0.14038/kWh, which is about 10% increase over its corresponding fate rate. Therefore, we can expect only about 2~3% of customer response under this pricing scheme using the similar assumption.

V. Conclusions

This paper studies the impact of customer responses to different pricing schemes on the distribution-level load shapes. Two seasons (summer and winter), two PHEV penetration levels (low and high) and two PHEV charging strategies (normal and quick charge) are taken into account. This study is performed in the context of a smart grid given that customers have full access to real-time electricity usage and pricing information, and every customer has an auto-DR system to conduct load control in respond to the price change.

Research findings pointed out the importance of TOU rate design, in terms of selecting the appropriate peak/off-peak price levels and peak/off-peak periods. Allowing deferrable loads and PHEVs to come online at 9:00 pm when the off-peak rates start (see Dominion VA Power rate, fig. 9), will create a new peak. This can be avoided by choosing to start the evening off-peak time after high evening demand, i.e. after 10 pm. To encourage more demand response, the on-peak price can be set higher as compared to the flat rate. However, if the peak TOU rate is too high, there can be more customer participation and again create new system peaks.

To this end, it should be noted that the developed model can also be adapted to analyze other real-time pricing schemes, including those that change every hour, as well as other demand response strategies. It is expected that the developed demand response model will benefit utilities and relevant regulatory bodies to analyze the suitability of various pricing schemes to be used in a smart grid environment.

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VII. Biographies

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