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Review of dynamic pricing programs in the U.S. and Europe: Status quo and policy recommendations

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ABSTRACT

With the development of demand response (DR) technologies and increasing electricity demand, dynamic pricing has been a popular topic in many countries. This paper evaluates various dynamic pricing programs in the U.S. and Europe, and provides insights into various aspects including risks and rewards, enabling technologies, lower-income groups and customer types surrounding programs such as Time-of-Use (TOU), Critical Peak Pricing (CPP), Peak Time Rebates (PTR) and Real Time Pricing (RTP). We conclude this paper with three main findings: (1) policy coordination in promoting dynamic pricing programs between federal and state regulatory agencies is very critical; (2) customer engagement is very important and can be enhanced via more accessible educational programs and policy adjustments; and (3) more investment in related R&D is required to construct a commonly accepted methodology for measuring the effectiveness of dynamic pricing programs.

Contents

1. Introduction

Increasing electrification in the modern society boosts the demand of electricity, especially during peak hours [1]. Peak demand that targeted by most of dynamic pricing programs

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usually refers to the top 100–200 h/year, which are approximately 8–18% of annual peak loads, whereas the top 1% accounts for the greatest portion [2], for instance, top 1% peak load can determine 5–8% of the total installed capacity [3]. Based on this principle, dynamic pricing strategies are designed to reduce the peak load or shift part of the peak load to some other off-peak periods by providing price signals to electricity customers. From the perspective of system control, dynamic pricing can also link wholesale and retail electricity markets in the U.S. [4]. Reducing peak demand can bring down wholesale market prices in the near term while in the long run, it can defer or replace new generation capacity [5].

Effective pricing is a powerful tool to economically adjust the load curve [6–8]. Characteristics of dynamic pricing vary in the U.S., Europe and Asian countries. In many parts of the U.S., the deregulation of the electric industry has enabled a market-driven development. Responses to dynamic pricing incentives in the U.S. have tended to be conservative with less than 23% customers enrolled, and most of them are commercial and industrial (C&I) customers [1,8–10]. In comparison, EU countries are generally focusing on massive installations of hardware devices. Some countries (e.g. Italy) have experienced a progress from zero to almost 100% roll-outs of smart meters in 5–8 years since 2003 [11]. On the other hand, dynamic pricing in Europe is mainly focused on TOU tariffs.

Although dynamic pricing has also shown great potential in Asia, this paper only focuses on the U.S. and Europe because most Asian countries just started their pilot smart metering research in recent years with incomplete results available. As shown in Fig. 1, the top three Asian countries in terms of per million dollars GDP investments are China, Japan and Korea [12]. China initiated research in smart meter pilots in 2009 while Korea started from the end of 2010 and Japan started in 2012. All these countries have less than 3% smart meter penetration [13], except that the smart meter penetration across the residential customers would be around 10% by the end of 2013 in Korea. Related studies in Asia, especially in China, are currently concentrated on their industrial sectors, residential sectors are seldom attended to. Further evaluations of dynamic pricing programs in Asian countries can be followed after the completion of their pilot programs.

It can be seen that most of the work done on dynamic pricing in many developed and developing countries have been focused on pilot projects. The majority of the conducted studies was completed based on the various policy structures of their own utility system characteristics where resources, focuses and results of each pilot study are technically related yet structurally different from one region to another. The lack of a comprehensive review of dynamic pricing programs across countries was recognized in a number of academic papers [4,10,19], which created difficulties for

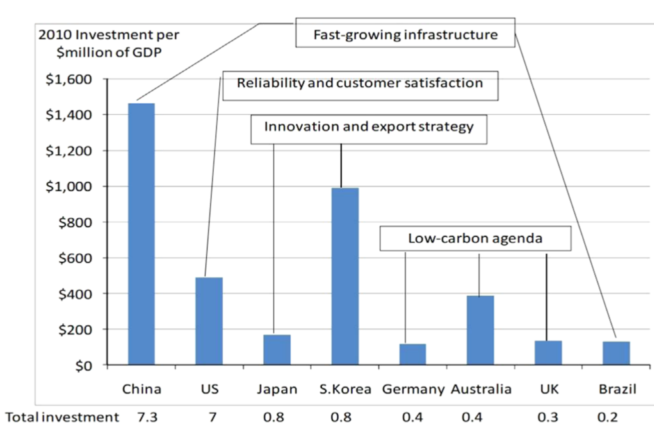

Fig. 1. Leading countries' focuses for investment in smart grid [12].

readers from other nations and states to study the experience and potential of implementing dynamic pricing in a global context.

As a result, this paper evaluates various dynamic pricing programs in the U.S. and Europe where such programs have a longer history and are more mature compared with the other countries. We try to provide insights into various aspects of dynamic pricing including risks and rewards, enabling technologies, lower-income groups and customer types surrounding programs such as TOU, CPP, PTR and RTP. This paper provides a valuable comparative analysis of dynamic pricing programs in terms of their differences and similarities horizontally between the U.S. and Europe. Such a paper can shed light on future dynamic pricing project implementation and offer instructions for improving the existing programs.

The remainder of this paper is organized as follows. In Section 2, we conduct a detail literature survey and analyze selected programs in the U.S. and Europe individually. We conclude the discussion in Section 3 with the major findings and policy suggestions.

2. Review of dynamic pricing programs in the U.S. and some European Countries

2.1. Status quo in the U.S.

In the U.S., the most popular forms of dynamic pricing are TOU, CPP, PTR, and RTP. We here follow the definition of the three major tariff mechanisms by [9] at the beginning of Section 2 and below:

- TOU: These daily energy or energy and demand rates are differentiated by peak and off-peak (and possibly shoulder) periods.
- CPP: CPP is an overlay on either TOU or flat pricing. CPP uses real-time prices at times of extreme system peak. CPP is restricted to a small number of hours per year, is much higher than a normal peak price, and its timing is unknown ahead of being called.
- RTP: RTP links hourly prices to hourly changes in the day-of (real-time) or day-ahead cost of power.

In comparison with the above three, PTR is less common and refers to the payment that consumers can receive for reducing demand during peak periods on event days. According to [14], TOU is the most effective tariff for customers to reduce power usage when the total consumption is low. Prices are usually set higher when power usage is high, and lower prices are applied for the rest of the period. Seasonal prices are also applicable for TOU tariffs. CPP, on the other hand, is called upon by significantly increasing tariffs when the reliability of the power system is threatened (e.g., during a very hot day). In order to reduce risks, utility companies are usually allowed to adjust CPP tariffs and notify customers one day ahead of time. PTR tariffs are inverse from CPP, where customers will be reimbursed for the amount of reduced power consumption during the critical peak period (compared with the predicted amount) [14]. For RTP, enabling technologies (e.g., smart meters) are usually involved to support the accuracy of measurements. The reason RTP highly relies on enabling technologies is that it has to be closely connected with wholesale market prices, as well as with consumer feedbacks (two-way communication required).

Among the different forms of demand response, it has been generally agreed upon that the most sophisticated form is RTP, and the simplest design is TOU since time periods and prices are usually fixed at least one year in advance [15]. Meanwhile, there is an increasing volume of research studying CPP, in which prices for top 60 to 100 h are known ahead of time [2]. As RTP is not widely deployed, this paper will primarily concentrate on TOU, CPP and PTR.

In this following section, we will review case studies in several states, including California, Connecticut, Michigan, and Washington D.C. The earliest pilot study in California was from 2003 to 2005. The longest test by far was done by Baltimore Gas and Electric (BGE) from 2006 to 2008. Most of the case studies contain multiple research objectives and focuses including:

- **Risks and rewards**: risks and returns of different dynamic pricing programs
- **Enabling technologies**: effectiveness of using smart meters
- **Types of dynamic pricing programs**: discussion of TOU, CPP and PTR
- **Lower-income groups**: response of lower-income groups
- **Customer types**: C&I and residential customers
- **Temperature**: influence of cold, mild and warm weather conditions on price responsiveness

2.1.1. Statistical methods and focuses

The commonly used variables for statistical analysis with dynamic pricing programs include temperature, levels of price elasticity, consumer types, consumer income, and effectiveness of devices. Panel data analysis is often used to understand the effectiveness of each indicator under different price mechanisms [16,19]. More specifically, constant elasticity of substitution is recognized to be the most appropriate analytical method [16,19]. The constant elasticity of substitution refers to two substitutable joint equations of: (1) the model of peak to off-peak ratio (other factors can also be considered) and (2) the function of daily electricity consumption (expressed in logs) for constructing a systematic yet reliable prediction of electricity consumption under the changing conditions and time periods [16]. Given the nature of panel data, researchers can label binary representatives to the characteristics of participating groups such as high/low income group, hot/cold temperature, etc. Responsiveness of each price mechanism is therefore reflected from each parameter. The convenience of using constant elasticity of substitution is that the electricity consumption can be modeled given various consumer behavior changes. Furthermore, equations can be tested by using the ordinary least square (OLS) linear regression method which aims to provide unbiased analytical results [16].

In [16], major factors including the impacts from cold, average and hot weather, and electricity prices are tested for residents and C&I customers respectively. The study focusing on Connecticut investigates TOU, CPP and RTP prices for both residential and C&I customers based on low and mild temperatures [17]. According to [7], tests in Michigan contain variables of standard rates, CPP rates, peak-time rates, and price-information only rates (using the traditional rate but providing customers the information of alternative prices). In comparison, the research on Washington D.C. engaged regular (non-electric heat) and all-electric (electric heat) customers at the residential level, considering three types of pricing strategies, i.e., hourly pricing (real-time pricing), critical pricing and critical pricing with rebates, during summer and winter periods [18].

2.1.2. Risks and rewards of various programs

Many researchers argue for the existence of both risks and rewards of dynamic pricing options. Although RTP contains the highest rewards for participating customers, its embedded risks are also high due to the associated highest price uncertainty in comparison with traditional pricing tools. TOU, on the other hand, has the lowest risks as it is conceptually simplistic with low rewards. CPP is an option with moderate risks as well as moderate rewards. Fig. 2 illustrates the curve of risks and rewards for three incentives. According to [2], consumer preferences, represented by the indifferences, would be maximized at the points of tangency shown in the figure.

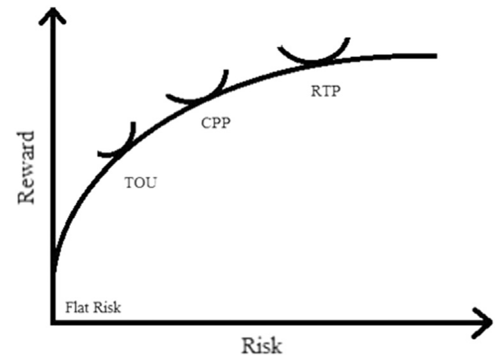

Fig. 2. Pricing choice frontier represented as indifference curves [9].

Furthermore, [18] compared the impact of CPP with and without rebates with hourly prices in Washington D.C., and summarized that all three types of incentives are stable and provide sizable demand reductions. As to this point, the descending order of load reduction from high to low is CPP, PTR, and the hourly prices. The reason of the lowest response for hourly pricing, according to [18], is because day-ahead hourly wholesale prices in the U.S. markets are mathematically correlated, which means hourly prices in a certain time period are similar so that the users' incentives to shift demand are reduced.

2.1.3. Enabling technologies

The official definition of smart meters in the U.S. is [9]:

“Meters that measure and record usage data at hourly intervals or more frequently, and provide usage data to both consumers and energy companies at least once daily. Data are used for billing and other purposes. Advanced meters include basic hourly interval meters, meters with one-way communication, and real time meters with built-in two-way communication capable of recording and transmitting instantaneous data.”

There are a lot of discussions on the effectiveness of smart meters and other types of enabling technologies. The principle of a smart meter is to provide an advanced measurement of power usage when different rates are applied to various time periods. Some research proposes that lack of smart meters for residential customers creates a technical barrier to the deployment of dynamic pricing programs.

The study on California tested CPP and TOU, found that customers are price-responsive and prices are positively correlated with enabling technologies [16]. The study in [19] made up the missing tests for RTP in California. Findings are similar but supplementary to [16] including: (1) customers are price-responsive; (2) CPP and PTR rates have similar responses, and (3) enabling technologies can improve consumer responses. The Connecticut Light and Power (CLP) experiment had similar findings that price responsiveness is positive and enabling technologies can improve responses, whereas CPP customers without rebates are more price-responsive than PTR (peak time rebate) customers, and TOU customers have the least price responsiveness [19]. Their study shows that CPP rates are of substantially higher price-responsiveness than PTR rates, which is supported by a later test done by Pepco Holdings in Washington D.C. [18].

However, field studies in [19] as well as [16] point out the comparison of with and without smart meters does not show significant differences as to customer choices. Also regarding price responsiveness, customers in Michigan showed the same responsiveness to the equivalent designed PTR and CPP without rebates during the testing period. For a given elasticity of substitution,[1] the consumers' response tends to increase with a higher peak to off-peak ratio, but at a decreasing rate. The peak to off-peak price ratio explains a large portion of the variations in demand response, whilst the remaining can be explained by other factors like weather, consumer attitudes, etc. Meanwhile, it is illustrated the magnitude of customer response varies with the price incentive, with and without enabling technologies [19]. Their study shows a positive correlation between incentives and responses when enabling technologies are not applied.

Furthermore, it should be of note that a study [16] points out that manual responses and automatic adjustments are not directly comparable because each sample may consist of different customer types according to the nature of their consumption. It is reasonable that higher income groups and higher power consumption groups are more likely to rely on technology to manage their energy consumptions, whereas low-income and low-consumption groups may find it unnecessary to install additional devices for such purposes. According to the study, the manual response group is representative of the overall statewide population in California, but the automatic adjustment group only consists of high-consumption residential homes with central air-conditioning in some particular climate zones in San Diego.

2.1.4. Influence on low-income groups

Another topic that receives great public attention is the influence of dynamic pricing on low-income groups. According to the study on Michigan [19], substitution elasticities for low-income groups are not significantly different from other target groups. Impacts from other factors, such as enabling technologies, as well as CPP or PTR treatments are also not distinguishable among all income groups. Study of Connecticut [19] shows that although there is no available data about income diversity, it is confident to state that elasticities of substitution for low-income customers are actually the same as those for the average customers with known income data if we ignore the fact that only 552 out of 1251 customers responded to the survey.

It is believed that there is a minimum influence of dynamic pricing programs on lower-income population [2]. They referred to a broader application of price responsiveness in other fields such as sports game ticket sales and showed consumers can save money through altering their behavior between higher-price peak-demand periods and other times. It is argued that most customers prefer this way of pricing, which can actually benefit lower-income population. They further pointed out that HydroOne TOU survey shows 72% of customers wanted to remain on dynamic pricing rates while only 4% found the changes in their daily activities to be inconvenient.

2.1.5. Temperature effects

The relationship between temperature changes and price responsiveness based on manual responses and automatic adjustments is investigated in [2]. A 15-month experimental tariff between 2003 and 2004 gave participants in California a discounted two-level TOU rate, which increases the peak-period prices (2 p.m. to 7 p.m.) by about three times. Their findings show that the average demand reduction in critical periods in the manual response group is −0.23 kW per home (−13%) in hot weather (95–104.9 °F), −0.03 kW per home (−4%) in mild weather (60–94.9 °F), and -0.07 kW per home (−9%) during cold weather (50–59.9 °F). For utility-controlled customer groups, hot weather performance is also stronger than that of cold weather. Between 90 °F and 94.9 °F, the response approached −0.56 kW per home (−25%) for hot weather.

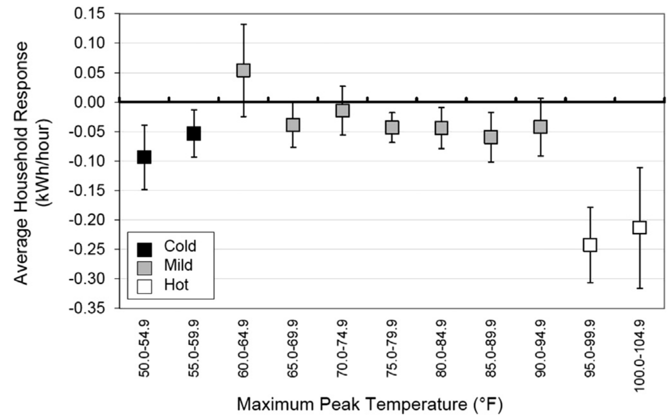

Fig. 3. Average customer response as a function of temperature (in kWh/hour; [4]).

The survey in [4] also concentrates on price responsiveness to temperatures. It is argued that the influence of seasons would cause a great impact to the shape of load curves [11]. Power load curves in winters are less significant than those in summers; more than one peak load could be seen in experimental periods with lower temperatures. Statistical evidence shows that mild weather provides slightly lower price responsiveness compared with that of warmer climate. It partly matches the results from [4]. However, as shown in Fig. 3 below, a more detailed description drawn from [4] shows that mild and cold temperatures have less influence on price responsiveness, whereas hot weather can significantly change the consumer behaviors.

In another test, [4] also separately analyzed summer and winter impacts on different price mechanisms. For both regular customers (non-electric heat) and all electric heat customers, load reduction for summer periods is significant, while winter periods have less precise estimation. Research also suggested that all electric heat users have greater potential of load reduction (maximum 12.6%), compared with regular users' 8.9%. CPP in both summer and winter shows larger reduction than hourly prices [19].

2.2. Status quo in Europe

In comparison with the in-depth analyses of dynamic pricing mechanisms in the U.S., Europe has a strong focus on large-scale roll-outs of smart meter devices. The definition of smart meters in Europe seems to be broader than that in the U.S. In some European countries, the key purpose of installing smart meters is to replace manual meter reading in order to reduce costs [7]. The function of providing real-time data has been minimal in most European countries. As stated by [8] and also illustrated by [9], the EU standard defines the term 'smart meter' by two components: it has to be more advanced than a conventional meter (mandatory) and to communicate billing information between utility companies and end users (optional). The European definition of smart grid determines the function and availability of smart meters. Therefore, smart meter technologies in Europe are expected to be less expensive and easier to be massively applied in comparison with the case in the U.S.

Studies clarified that most of the EU countries are using smart meters as substitutions of manual meter reading, not commonly

[1] The elasticity of substitution was defined as "a measure of the ease with which the varying factor can be substituted for others"[20]. The elasticity of substitution in the context of demand response refers to the relative changes in electricity consumption between peak and off-peak periods caused by a relative price change.

for sending price signals [18,21]. Distribution System Operators (DSOs) in most European countries did not show much enthusiasm to shorten data reading periods by using advanced metering infrastructure (AMI). At the moment, electricity consumption data are still collected on a monthly basis in most countries, and even with AMI technologies in place dynamic pricing mechanisms are still limited to end customers. Accordingly, [18] argued that policymakers in Europe have long been focusing on massive applications and engaging utility suppliers and end customers in tariff alternatives is often ignored.

As a typical case in Europe, smart meters in Sweden are simply seen as a replacement of labor, with current electric data still being recorded on a monthly basis. From the perspective of Swedish Coordination Council for Smart Grid, [24] stated an important reason for replacing traditional meters with smart meters was due to the high labor cost. He also pointed out that 99% of the traditional meters in Sweden were replaced by smart meters in 2009 and the next step is to enable hourly data delivering with limited focus on dynamic pricing.

The largest and most statistically robust trial conducted in Europe was by the Ireland Commission for Energy Regulation from 2008 to 2011 [25]. In order to test TOU mechanisms, customers were divided into four major groups: residents, small and medium enterprises (SMEs), prepayment customers, and multi-site customers.[2] Responses are separately analyzed for each group of customers. For residential customers, average response rate was 30%. Tariff rates were divided into four weekday rates and one weekend rate. Accordingly, a significant finding is that the overall electricity usage was reduced by 2.5% and the peak usage was reduced by 8.8%. Customers with higher education achieved higher reductions, and low-income groups also received benefits from TOU. For SME customers, rates were designed in three categories: day time, night time and peak time. Results for SMEs showed that reduction of overall electricity usage was 0.3% and reduction for peak usage was 2.2%. In their test, 72% of the SME customers did not reduce peak loads and 61% did not reduce their overall load at all. A major reason of this insignificance is that business operations cannot find an alternative time slot to shift the loads.

Another case study is Netherlands, which focuses on impacts of residential TOU rates with specific emphasis on time durations. A 15-month study on domestic energy monitors, referred to as Home Energy Management Systems is conducted [23]. Their results find that customer behaviors can be influenced for a short period. However, significance of longer-term utilization depends on customer groups. It is shown that with the installation of Home Energy Management Systems, there was an initial saving of 7.8% in electricity consumption for the participants in the first four months. However, with an increasing testing period, savings on electricity consumption cannot be sustained since a significant number of participants tend to revert to the traditional patterns of electricity consumption. On the other hand, a certain group of people (characteristics unidentified in the article) can keep good practice of energy conservation after understanding the data from energy monitors. Therefore, [26] suggested energy monitoring systems should not be massively applied to the public at this stage and further designs should consider the fact that users' responses to a certain type of intervention could be different. Furthermore, they argued that a lot of participants added new electric devices such as air conditioners and dish washers into their houses during the 15-month period, which could be a factor that significantly influenced their total electricity consumptions. They pointed out that once new energy-efficient devices replace old devices, participants tend to use these new devices more often and the overall power consumption shows a ‘rebound effect’, which means the shifted demand peaks in another period.

The potential and limitations of global residential dynamic pricing programs is also explored [14]. 100 pilot studies (450,000 families were involved in total) were used to examine the use of mainly TOU and CPP (with and without rebates). The results on RTP were not summarized in their report due to lack of sufficient data. From the global perspective, it is evident that TOU tariffs indeed have the lowest response in comparison with CPP. However, TOU is a daily response while CPP only shows its significance during peak loads. On the other hand, consumers positively react to dynamic pricing mechanisms in the long run (e.g., over 2–3 years) and they can also be effective for consumer groups of over 1000 households. During these pilot studies, enabling technologies have been confirmed for having positive influence on energy efficiency. Regarding the debates that challenge the contribution of smart meters, they argued that the key difference they found between the success and failure of a pilot project is whether the program designers are able to meet consumer needs through energy efficiency programs. Technology should be seen as an enabler of the value chain of meeting customers' needs. It is therefore important to design a suitable pricing strategy instead of utilizing templates on a foreign case.

2.3. Summary of findings

Table 1 shows a detailed review on various case studies in the U.S., Ireland and Netherlands. The reason Ireland and Netherlands are chosen is due to the fact that only these two countries have done detailed studies on using smart meters for dynamic pricing programs in Europe.

2.3.1. Focuses of the U.S. and Europe

There are two major reasons why Europe focuses on smart meter roll-outs and the U.S. concentrates on research on dynamic pricing. First, results of the crest factor analysis (also called Peak-to-Average Ratio (PAR)) demonstrates a lower PAR value for Europe than that of the U.S., which indicates peak load is a bigger concern in the U.S. Fig. 4 illustrates the difference of power consumption between Europe and the U.S. The major peak load in EU27 usually happens during the winter period, which has been explained in [28] by the high popularity of electric heat in many of the EU countries. In contrast, peak of the U.S. electricity load happens in summer and power consumption is usually the lowest in winter. The peak load in the U.S. was 9% higher than that in EU27 from 2009 to 2012. The results of average PARs between April 2009 and June 2012 are 1.382 for the U.S. and 1.265 for the EU27 countries.

The results of the crest factor analysis have also been supported by [28] that a major difference between Europe and the U.S. is that European countries have less seasonal power consumption. The influence of temperature on power demand is further elaborated and significant different patterns were shown in summer and winter load curves [11]. The mild summer temperature in European mainland does not require a large number of air conditioner installations. Also, [29] pointed out that DR in the U.S. has greater potential due to the higher electricity consumption as well as a large percentage (2/3 of total electric users) of air conditioning customers in summer. Since the major cause of peak load is power consumption from air conditioners, the potential of peak load reduction in regions without air conditioners is minimal in summer.

[2] In this discussion, we only look at residential and SME groups since they provide comparable information to the U.S., while prepayment customers and multi-site customers are unique for Ireland.

Table 1
Case studies of dynamic pricing mechanisms in the U.S., Ireland and Netherlands.

	California Statewide Pricing Pilot [16]	**California BGE survey** [19]	**Connecticut CLP survey** [19]	**Michigan Personal Power Plan** [18]	**Washington D.C. PowerCent DC** [19]	**Ireland** [25]	**Netherlands**[22]
Time period	2003–2005	2006–2008	2003–2004	2008–2009	2008	2008–2011	2008–2009
Mechanism effects	CPP > TOU	CPP = PTR	CPP > PTR > TOU; residents > C&I	CPP = PTR; both substitution elasticities were higher than those in California cases	CPP > PTR > hourly prices; all three mechanisms are significant in load reduction	TOU: residents > C&I	TOU
Temperature	Hot weather has more significant influence than cold weather	N/A	Hot weather has more significant influence than mild weather (no information on cold weather)	N/A	Hot weather has more significant influence than cold weather	N/A	N/A
Enabling technologies	Hard to compare, depends on income groups	Helpful	Tested 4 of them, most are helpful	Not helpful	Helpful	Helpful	Depends on customer groups
Income groups	N/A	N/A	No difference	No difference	N/A	No difference	N/A

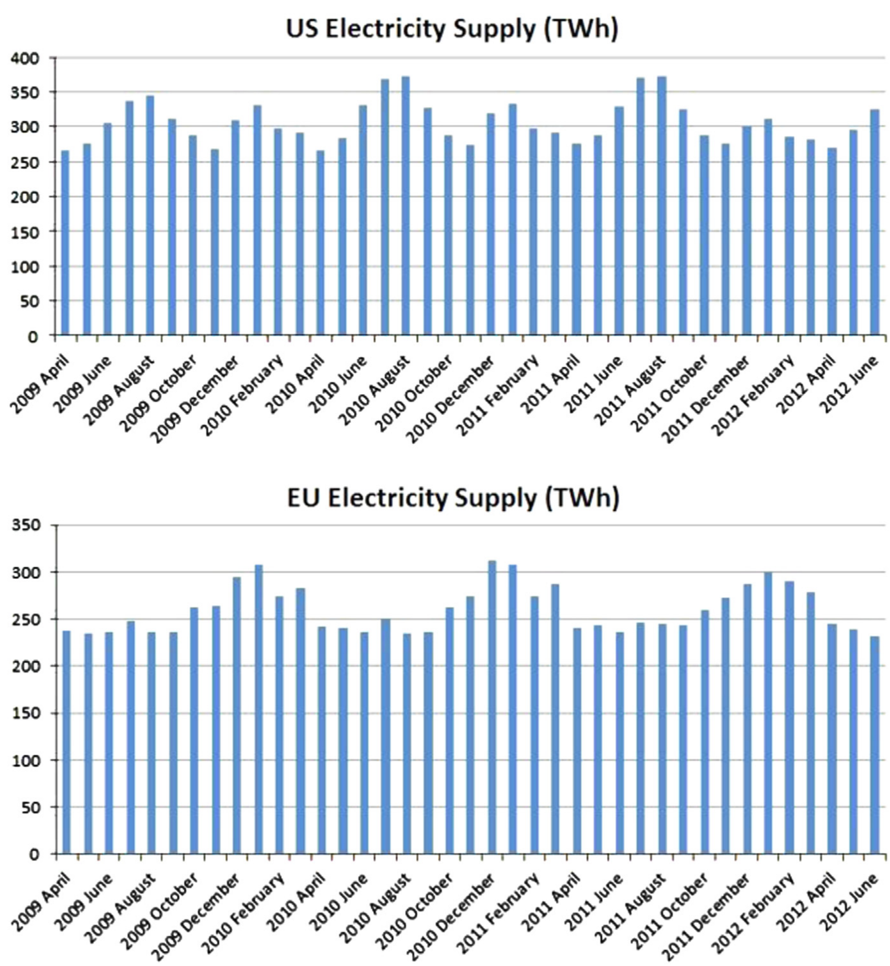

Fig. 4. U.S. and EU Electricity Supply [30].

Second, an important objective of European smart meter roll-outs is to reduce the labor cost of manually reading meters, which is a large amount of cost for many European countries [24]. As constantly increasing labor cost under an unfavorable economic environment is hardly accepted by the public, utilities in Europe are more motivated to reducing labor costs than promoting dynamic pricing mechanisms at the introductory period of smart meters, which means improvements of alternative price mechanisms may be implemented in the future.

As shown in Fig. 5, Italy has a 94% installation rate of smart meters, and Nordics have a 70% installation rate. All other countries are predicted to have smart meter installation at rates of more than 70% by 2015 due to the governmental incentives. According to [31], the fastest growing countries in smart meter

Fig. 5. The European smart meter market [31].

installations are expected to be U.K. and France, increasing from around 4% in 2011 to 50–60% in 2015.

2.3.2. Tariff mechanisms

The overall focus of tariff mechanisms discussed is on the three price mechanisms: TOU, CPP and RTP. It is clear that TOU and CPP have received greater attention than that of RTP. Lack of research in RTP reveals RTP is still at the conceptual design stage without broad customer acceptance (especially among industrial customers); it also shows a global trend that TOU and CPP are more popular than RTP to customers. Another reason for limited RTP programs may be that, as pointed by [2], RTP has the highest rewards and the highest risks. Although dynamic pricing has been launched for 10 years, it is reasonable that consumers respond conservatively during the introductory period. From the global perspective, most of the European countries are still relying on TOU as the only program of smart meter roll-outs. In the U.S., despite of a low smart meter penetration rate of 23%, in-depth studies on TOU, CPP and PTR have been done.

Pilot studies in the U.S. have illustrated that TOU receives minimal interest from C&I costumers. Several surveys show that power consumption does not change at all after implementation of TOU prices [15]. However, [14] argued that TOU is the most effective tariff for customers whose overall consumption is low. Because the power consumption of the European countries is substantially lower than that in the U.S., Europe is currently mainly utilizing TOU tariffs to levelize the cost of smart meter installations.

It is argued that price incentives for C&I customers in general have lower responsiveness than those for residential customers, regardless of installation of enabling technologies [32]. Practically, [27] analyzed TOU pricing and its influences on C&I customers for a 12-month period. Their results show an insignificant impact of TOU on C&I customers. The effect of TOU on large utility bills and bill volatility could have been overstated. For example, the pilot project in Connecticut shows only a small number of firms were adversely affected by TOU pricing [27]. Actually the reduction in electric bills was due to a discount implicitly included in the prices, instead of behavioral response. Despite that TOU is the most commonly implemented pricing strategy; it induces very limited changes in load curves for industrial customers. This finding closely matches the results from Connecticut Light and Power [19].It is urgent and important for Europe to find alternative price mechanisms other than TOU. Although some regions provide available rebate programs via policy supports for CPP, we find out that the effects of these rebates are very limited. As shown in the studies on California and Michigan [19], customers' responses are very similar for CPP with and without rebates. The PowerCent DC and the Connecticut cases actually show a stronger effect of CPP without rebates, which indicates that CPP with rebates has a negative correlation with load reduction in those two cases. Although the consumption behaviors are different between the U.S. and Europe, the pilot projects in the U.S. can serve as references for European dynamic pricing program implementation.

2.3.3. Enabling technologies and income groups

The impact of enabling technologies has been tested by both the U.S. and European scholars. At this point, only the case study in Michigan shows that it is 'not helpful'. However, all other cases come to an agreement that having enabling technologies is necessary but not sufficient for reducing power consumption. According to [4], other factors, such as the consumption pattern of high-income groups and low-income groups, have to be taken into account. It is reasonable that higher-income groups have higher power consumption, thus customers in those groups are more likely to rely on smart devices for utility management. In comparison, potential reduction for lower-income groups is comparably less. The benefit for installing additional devices may be limited for them. The study in [26] supports [4] by claiming that different customers have various power consumption patterns. It is difficult to draw a uniform conclusion on whether enabling technologies are helpful or not. Lastly, when it comes to evaluating the acceptance and influence of enabling technologies on different income groups, almost all case studies agree that there is no difference between higher or lower-income groups. In Europe, researchers in Ireland and Netherlands have also studied the impact of income and enabling technologies on dynamic pricing. The study on Ireland [25] pointed out the need to integrate the analysis of income groups with enabling technologies. The conclusion of the study on Netherlands [15] critically claims that enabling technologies should be designed for each consumer type rather than using a "one-size-fit-all" solution.

The types of consumers partially explain why TOU tariffs merely work for residential consumers [27]. C&I electricity consumption is directly connected with their business activities, while residential consumers purchase electricity for self-consumption. For the residential consumers, temperature, enabling technologies and income groups are dominant factors. The three pilot studies in [16,18,19] have pointed out the significant influence of weather on power consumption. Price responsiveness to hot weather is stronger than that of mild and cold weather [4,19]. Comparing the three temperature studies, [4] conducted the most comprehensive research by categorizing five-degree temperature bins. Results were individually analyzed for effects of different enabling technologies as well as income levels. Their work separated electric appliances controlled by manual and utility-controlled devices. [18] investigated the impact of weather based on the level of electrification. The study of regular and all-electric customers can provide references for many European countries with high annual electricity rates associated with weather effects. [27] and [25] share the viewpoint that residential customers are more responsive to prices than C&I customers in both the U.S. and Europe. However, separate studies for C&I customers are still needed.

3. Policy implications and conclusions

Based on the above discussions, we conclude the paper with the following findings:

1. Limited role of smart meters. While smart meters can significantly reduce the labor cost for meter reading in Europe, their role in communicating with the end consumers in dynamic pricing programs is limited. Studies have shown that installation of smart meters is not necessarily helpful for dynamic pricing. TOU and CPP can be implemented without smart meters as the prices embedded in those programs are predefined and only updated infrequently. In comparison, RTP pricing may require a large-scale installation of smart meters to constantly communicate the price and control signals between the consumers and utilities. But there is no yet significantly successful case study of such a RTP program.
2. Lack of customer engagement. DR in the U.S. has been developed for more than 10 years. However, according to [19], there are only approximately 23% of customers enrolled in DR projects where they are available. Agreed by [1], lack of customer support is a major barrier for promoting DR. Price disconnection and utility disincentive are the two major reasons that lead to low customer response.
   - First, only 25 states in the U.S. are part of a regional electricity market, while the utilities in the rest 25 states are still mostly vertically integrated. The retail prices for most customers are fixed while wholesale prices fluctuate widely in electricity markets. To address this price disconnection, [9] suggested a more efficient method, which is to place a small percentage of customers on wholesale electricity prices that are based on marginal production costs. This price linkage will incentivize consumers to adjust their electricity consumption in response to the variation of the wholesale electricity prices.
   - Second, utility companies lack incentives to promote DR projects without regulatory subsidies. In most cases, the implementation of DR leads to a reduction of utilities' revenues as the electricity consumption decreases. Regulatory actions and incentives are important to spur the effectiveness of DR programs.
   - Third, the 2009 American Recovery and Reinvestment Act's Smart Grid Investment Grant (SGIG) program has investigated the low representativeness of many current customer behavior programs[33]. The main barrier is that utilities and customers have different perspectives of approaching an appropriate DR tariff mechanism. Many customers initially considered environment as the primary reason for DR implementations; however, the key actual concern for customers was price [34].
3. Lack of consistent tools in evaluation, measurement and verification of demand reductions. As [9] stated, 'Current planning and forecasting tools are not sufficiently robust to model adequately the capability of DR to serve as an alternative to building new generation and transmission and to act as a resource to alleviate transmission congestion'. Lack of uniform standards and methodologies to analyze the cost-effectiveness of DR projects creates barriers to quantifying associated return on investment (ROI). Meanwhile, [33] also pointed out the difficulty of finding a convincing method to evaluate how many customers want to be involved in DR programs. Construction of a commonly recognized model can largely motivate the investment and implementation of DR projects. More research should be done to build a standardized accurate and reliable data collection system for DR resources to more precisely evaluate their contribution to reliability and their cost-effectiveness.
4. Discordant federal-state policy regulations. DR projects are primarily regulated at the state level in deregulated states, while commission jurisdiction plays a key role in regulated states. According to[34], regulatory policies on dynamic pricing and state statutes in several states could create policy barriers to exploring the potential of DR, such as rules on engaging customers in time-based rates, especially CPP. On the other hand, [9] mentioned that some wholesale and retail market designs are not favorable to participation in DR, e.g., the standard lengthy wholesale settlement periods utilized in ISO/RTO markets could delay payment to participating retail customers.

Based on the above issues, we propose the following policy recommendations:

1. There should be more investment in R&D on DR. The U.S. urgently needs a sophisticated yet commonly applied evaluation model for DR [9]. An immediate action would be to increase investment in relevant R&D to develop universally recognized methodologies that provide fair evaluation, measurement and verification.
2. Customer engagement should not totally rely on enabling technologies. Instead, promotion of DR projects should be enhanced through public education and price adjustments. More research should be done to analyze customer behaviors. Innovative pricing mechanisms such as linking retail prices with wholesale market prices can be implemented on certain pilot projects.
3. The coordination between federal and state level policies should be enhanced. Increased coherence between federal regulation, state policies, and third-party implementations can enhance policy effectiveness and reduce barriers to project implementations [34]. It is important for each regulatory level to consider the current policy context and the policy's implications on all involved entities and stakeholders. Policy integration could largely reduce associated risks of executing DR projects and increase the confidence of investors, as well as

promote collaboration between policy makers and third-party enterprises.

By discussing case studies in the U.S. and Europe, this paper reviews the major issues related to the implementation of DR programs in those regions. A variety of associated aspects including risks and awards, enabling technologies, dynamic pricing programs, temperatures, income groups, and customer types are investigated and compared between pilot studies in the U.S. and Europe. However, there are also some other key topics that need further investigation. For example, the implementation of RTP could be very complicated and could potentially change the behavior of customers based on the real-time market signals. Hence, we strongly encourage further research to investigate RTP when completed case studies and related data become more available.

Meanwhile, DR projects in many Asian countries have just started. For example, China has initiated a few municipal level case studies on industrial customers, whereas residential pilot studies are not yet applied to real end users. Instead, the State Grid China Corporation uses demonstration showrooms to illustrate similar residential consumer behavior patterns [35]. Several Korean and Japanese utility companies are also actively engaged in DR research [13]. Available conclusions are not yet available at this time. However, efforts in trying to develop feasible policy and technical frameworks to better adopt DR in their own systems have been on-going. Investigations in these Asian countries will largely contribute to the global picture of how DR is being implemented in different electricity markets.

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