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Modeling consumer opinions towards dynamic pricing: An agent-based approach

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Modeling consumer opinions towards dynamic pricing: An agent-based approach

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Abstract—Using an agent-based modeling approach we show how personal attributes, like conformity or indifference, impact opinions of individual electricity consumers regarding innovative dynamic tariff programs. We also examine the influence of advertising, discomfort of usage and the expectations of financial savings on opinion dynamics. Our main finding is that currently the adoption, understood as a positive opinion or attitude toward the innovation, of dynamic electricity tariffs is virtually impossible due to the high level of indifference in today's societies. However, if in the future the indifference level is reduced, e.g., through educational programs that would make the customers more engaged in the topic, factors like tariff pricing schemes and intensity of advertising will become the focal point.

Index Terms—Dynamic pricing, Demand response, Opinion formation, Agent-based model

I. INTRODUCTION

RECENTLY the ambitious goals set by the EU (e.g. in the Climate Policy 3x20 and in the Directive 27/2012/EC) have a great impact not only on power generation but also on consumption. As the power system of the future has to be more sustainable, built on a greater energy efficiency and a high share of renewable energy, the changes will certainly impact the households. In order to increase energy efficiency, the consumers will need to decrease their electricity consumption and may need to make new investment in more efficient home appliances.

One of the crucial challenges of the coming years is to optimize the use of existing capacity while meeting ever-increasing demand for electricity and reducing CO₂ emissions. It seems that this could be achieved at a relatively low cost by introducing Demand Side Management (DSM) and Demand Response (DR) instruments [1]–[4]. The DSM/DR tools are designed to influence consumption patterns and energy efficiency of end-users and therefore to reduce energy production and load variability. The literature considers DSM/DR instruments ranging from education (encouraging efficient usage of energy), through time-based pricing (time-of-use rates, critical peak pricing, real-time pricing) to incentive-based DR (direct load control, emergency demand response programs, capacity market programs) [1]–[3].

Among the DSM/DR tools, dynamic tariffs are one of the most common and interesting. They have been invented to flatten the demand curve and to shift the load from on-peak hours to off-peak hours. The shift of load implies a change in consumers' habits and daily routines. Sometimes it may be

connected with the reduction of the overall energy consumption. It reduces the imbalance between peak demand and peak supply and helps to manage the power supply costs. With a variable electricity tariff, the price of electricity depends on the balance between supply and demand in the market. With such a tariff the consumer may experience several changes in price levels during the day due to the fluctuations of supply and demand [2]–[5].

In the recent years, a number of pilot programs, focused on the reduction of peak demand and energy conservation at the consumption level, have been run in the U.S. and in Europe [2], [6], [7]. Many experiments were conducted in an attempt to understand consumers' responsiveness to variations in retail electricity prices [5], [8]–[10].

It has been shown that in the case of flat tariffs the electricity demand is price inelastic. On the other hand, implementation of time-of-use rates (TOU) or critical-peak pricing (CPP) programs increases price elasticity over time, due to consumers' gradual adaptation of daily routines to the new tariffs. TOU rates induce a drop in peak demand that ranges from 3% to 6%, while CPP tariffs induce a drop in peak demand from 13% to 20%. However, the elasticity level depends on climate conditions, seasons of the year, income levels and appliance ownership [2], [5].

When accompanied by enabling technologies, like e.g. smart-meters, smart plugs, in-home displays, etc., the introduction of TOU rates leads to a drop in peak demand up to 15% and of CPP rates to a drop in peak demand up to 44% [7]. Moreover, according to [1] and [9], a reduction of energy consumption increases from 5% to 10% with enabling technologies. Enabling technologies greatly improve the overall impact of demand response and significantly increase the savings in both avoided capacity and avoided electricity for the utility. The main problem with this solution is that the cost of the enabling technologies is currently higher than potential savings [6].

Although promising results have been achieved in many pilot programs, another problem has been defined. Namely, only a small amount of participants of the pilot programs decided to sign up for the new tariffs. For instance, in Illinois in the AIU Power Smart Pricing Program only 18% of customers, where the pilot program was run, were aware of it. Moreover, only 10% of them understood the program and only 5% were interested in the program. In the end, under 1%

of customers enrolled in the program [7]. Lack of interest and fear of change were named as the main reasons for such low program participation rates [1], [9]. Moreover, according to a survey conducted in 2010 in the U.K. only 8% of respondents think that energy needs ‘attention and improvement’ [11]. The report of [9] provides even more dramatic numbers: 60-75% of consumers are not willing to shift their consumption to off-peak hours.

The important question that arises in this context is whether the households will switch to the new – more energy-efficient but less comfortable – dynamic tariffs and how fast or slow will this process take place. It is well recognized that an individual’s decision about an innovation is not an instantaneous act but rather a complex process that occurs over time [12]. Therefore at least two separate mechanisms, which affect the process, should be distinguished: change of opinions/attitudes and decision making. In this paper, we focus on the first issue and the second is discussed in [13]. Using an agent-based modeling approach, we show how personal attributes, like conformity or indifference, impact the opinions of individual electricity consumers. We also examine the influence of mass-media education programs and the expectations of financial savings on the opinion making process.

The paper is structured as follows. In Section II we introduce our agent-based model and present the Monte Carlo simulation scheme. In Section III we present the results of our extensive simulation study. Finally, in Section IV we conclude.

II. MODEL DESCRIPTION

In this paper, we focus on the process of opinion formation of electricity consumers regarding a new dynamic tariff. As in the classical diffusion of innovations theory [12], [14], in our model the new product adoption is driven by two forces:

- *Internal influence* that comes from the interactions between consumers (e.g., word of mouth). In our case the nature of these interactions is motivated by the psychological observation of the social impact and has been introduced originally in [15] to describe opinion dynamics.
- *External influence* (or external field), which in our case describes not only the marketing efforts (advertising, promotions) but also product features (potential savings, comfort/discomfort of usage of a particular tariff, etc.).

We consider a set of $i = 1, \dots, N$ agents, called spinsons (=‘spin’ + ‘person’; to reflect their dichotomous nature) on a square grid (i.e., a chessboard). Each spinson represents a household and is characterized by its attitude S_i toward an innovative dynamic electricity tariff. If $S_i = -1$ the household prefers a traditional uniform tariff, if $S_i = +1$ it prefers the new dynamic tariff. At a given time t , the opinion of a particular spinson depends on three factors – conformity, product features and indifference.

1) *Conformity*: This kind of social influence represents a specific response to interactions (e.g., word of mouth) between the spinson and its neighbors. The neighborhood can be interpreted in terms of either physical or social connection.

As in [15] the nature of these interactions is motivated by the psychological observations of the social impact dating back to [16]. According to these observations, if a group of spinson’s neighbors unanimously shares an opinion, the spinson will also accept it. The importance of the social influence on the consumers’ intention to engage in environmental behavior (e.g. reduction of energy consumption) has been researched and proved by [8], [10], [17], [18] and many others.

2) *Product features*: In this paper product features are modeled by a global field, as in [19]. The strength of the field depends on features of the dynamic electricity tariff: potential savings, (dis)comfort of usage, intensity of advertising, etc., however, without going into details on the influence of a particular feature. From this point of view, this dependence reflects the rationality of agents. Although uncertainty and risk related to the innovation usually reduce rationality, it is hard to assume that people are completely irrational in opinions regarding electricity tariffs. Having to wait until late evening hours to turn on the washing machine may be a strong enough factor to prevent us from switching to a dynamic tariff. Even after switching, the actual discomfort related to this activity may lead us to revert to the original tariff after some time of using the dynamic tariff. The strength of the external field h is between 0 and 1.

3) *Indifference*: This factor introduces indetermination in the system through an autonomous behavior of the individuals [20]. In the case of indifference the spinson is immune to the influence of the neighbors and the field. Indifference can be also understood as insignificance of the topic in the society, lack of importance and concern. The level of indifference p is between 0 and 1.

The results of the OFGEM analysis [11] and of the market survey [7] indicate that the majority of panel participants could be classified as ‘disengaged’, meaning that they neither knew their tariffs nor were willing to change them. Electricity consumers generally cannot evaluate different tariff features and are not interested in the problem. Hence, we can assume that they are characterized by a high level of indifference.

The way in which we define the immunity of some agents to the social influence distinguishes our model among others. The so-called indifference - connected with an autonomy of individuals - can arise if two options (e.g., traditional and dynamic electricity tariffs) offer both advantages and disadvantages and these advantages and disadvantages are not clearly comparable [19]. That is why the strategy finally adopted by an individual is broadly unpredictable and unstable. Because such an uncertainty is very strong in the case of electricity tariffs [1], [7], [11], we have introduced indifference as a kind of randomness into the model. The inconsistency of consumers’ behavior is proved by many social experiments, which suggest that simple situational factors are more powerful than individual traits in shaping human behavior [21]. This fact is reflected in our model by the probability of indifference, which means that in each time step an agent can be indifferent or susceptible with some probability and its behavior changes in time.

A. Simulation setup

In the simulation, we run M experiments. A single experiment consists of T Monte Carlo steps (MCS), which can be interpreted in terms of time intervals (e.g., days). In each MC step, N elementary sub-steps are repeated, as shown in Figure 1. The number of the sub-steps is equal to the size of the population (N) to ensure that on average each spinson is chosen once in a single MCS. As the outcome of a single MC simulation experiment m we compute the ratio $c_m(T)$ of spinsons in favor of the new dynamic tariff after time T to the total number of spinsons N in the system

$$c_m(T) = \frac{\#\{i : S_i(T) = 1\}}{N} \quad (1)$$

where $m = 1, \dots, M$. Next, we compute the average of the ratios of convinced spinsons over M experiments

$$c(T) = \frac{1}{M} \sum_{m=1}^M c_m(T) \quad (2)$$

The results depend on the length of simulation (T) and the parameter values (p , f and h). The longer the time horizon, measured by T , the closer is the system to the stationary solution.

In the simulations, we use the following specifications:

- Initially all spinsons are down, i.e., $c(0) = 0$. This corresponds to a situation in which the innovative dynamic tariff is still not available or unknown, so no one can be a consumer of the new product.
- The population inhabits a square lattice 100×100 and consists of $N = 10000$ spinsons. It is worth to mention that other system sizes were also investigated and all results presented in this paper are consistent with those for other lattice sizes.
- We count the number of convinced spinsons after $T = 720$ Monte Carlo steps, which corresponds to a two year period. Longer and shorter time horizons were also investigated, but these results are not presented in this paper.
- The results are averaged over $M = 1000$ experiments.

III. RESULTS

A. Model performance

Let us first consider the general performance of the model, for both low and high values of indifference. In Figure 2 we present snapshots showing a sample time evolution of the system of 100×100 spinsons, initially all preferring the traditional tariff ($c(0) = 0$), having a low level of indifference ($p = 0.01$) and influenced by a relatively weak external field ($h = 0.11$). As a result of social influence (e.g., word-of-mouth), small clusters of convinced (dark green) appear. Some of these clusters disappear and other (if a critical size is reached) spread like a virus. Notice that after time $T = 210$ a small cluster of 73 spinsons appeared (indicated by a hollow arrow). After further 90 steps (i.e., for $T = 300$) it disappeared. Then at time $T = 455$ two clusters formed –

Fig. 1. A single Monte Carlo Step of a system that consists of N individuals for the model described in Section II.

one of 78 spinsons (indicated by a hollow arrow) and another of 147 spinsons (indicated by a filled arrow). The former one disappeared (90 steps later it is not visible anymore), while the latter one started to spread like a virus.

This is an interesting phenomenon that cannot be obtained within classical theories of the diffusion of innovation [14] and may correspond to the important feature of real-world systems known as the *valley-of-death* [22]. On the other hand, a cluster of 147 spinsons that formed after $T = 455$ MCS was able to grow and spread in the society. It seems that if some critical size of the cluster is crossed, the innovation is able to spread in the society, which agrees with the *critical mass theory* [12] – a crucial concept in understanding the social nature of the diffusion process. Note that in our model, the reversal to the original product is possible. The vanishing clusters in Fig. 2 show that a group of convinced spinsons can loose its interest in the new dynamic tariff and after a short period of time can be again in favor of the traditional flat tariff.

Figure 3 presents the intricate relation between number of convinced agents and the indifference level p . From the left panel in Fig. 3 it can be noticed that for very small

Fig. 2. Simulation snapshots showing a sample time evolution of a system of 100×100 spinons for the initial concentration of spinons $c(0) = 0$, indifference $p = 0.01$ and the external field $h = 0.11$. As a result of social influence (e.g., word-of-mouth) small clusters of convinced (dark green) appear. Some of these clusters disappear (hollow arrows) and other – if a critical size is reached – spread like a virus (filled arrow).

Fig. 3. *Left panel:* Dependence between the ratio of convinced spinons (customers) after two years (which corresponds to 720 MCS) and the level of indifference p for several values of the external field h . *Right panel:* Dependence between the ratio of convinced after two years and the external field h for several values of indifference p .

values of p , which are associated with problems of a great social importance and interest, appropriate level of external field is needed to convince consumers to accept the new product. If the external field is too low, consumers behave conservatively and prefer to use previously known products. Strong incentives are needed to change their attitude. As the level of indifference increases, the ratio of convinced spinons jumps to almost 1. This indicates that a minimum level of autonomy is necessary to ensure that the new idea spreads in the population. To some extent this result is in agreement both with the concept of innovators and the critical mass theory. Innovators play a central role in the innovation diffusion theory, which says that some individuals decide to adopt an innovation independently of the decisions of other individuals in the social system [14]. The critical mass theory says that some threshold of individuals or actions has to be crossed before a social movement explodes into being [12].

As it can be seen in the right panel of Fig. 3 for a small value of indifference there is a critical value of the external field, above which an innovation can spread in the market, which also is in agreement with the critical mass theory. This means that for issues of high social relevance or interest a certain threshold has to be crossed in order to adopt a new idea. Moreover, once the threshold is passed, further increase

of the external field does not result in a significantly higher number of convinced, which can be seen in the right panel of Figure 3 for indifference levels $p = 0.01$ and 0.1 .

For high indifference levels ($p > 0.5$), the ratio c of convinced spinons is much less sensitive to the model parameters – indifference p (see the left panel in Fig. 3) and external field h (see the right panel in Fig. 3). In the limiting case of $p = 1$, the opinions are purely random because neither the internal factors (like word-of-mouth) nor the external field influence individuals. Therefore in such a case, independently of the level of the external field, the ratio of convinced spinons c converges to 0.5. This result might seem paradoxical at first; it suggests that 50% of consumers prefer dynamical tariffs. However, one should remember that for $p = 1$ the opinions are very unstable. At a certain moment of time, a given spinon can have an opinion $\downarrow$, in the next changes it to $\uparrow$, then back to $\downarrow$ and back again – it flips up and down randomly. Hence, a spinon's opinion fluctuates a lot. This reflects more the general indifference to the topic than the attitude toward a new idea.

B. Diffusion of electricity tariffs

Let us now focus on the diffusion of dynamic electricity tariffs. As discussed before, the retail electricity market is characterized by:

- high values of indifference, i.e., $p > 0.5$, which expresses the fact that electricity tariffs are not a very popular discussion topic in the society and are hard to compare (i.e., are a source of confusion),
- a weak external field, i.e., h close to 0, which reflects the rather small potential savings, the significant discomfort of adopting a new dynamic tariff and the generally low level of advertising and lack of educational campaigns related to these products.

The results discussed above show that the external field, which describes important features of the tariff, plays a significant role only for relatively small values of indifference. When the indifference level is high, the ratio of convinced depends very weakly on the strength of the field. In the right panel of Figure 3, the curve representing the ratio c of convinced spinons is very flat for $p = 0.8$ and becomes only slightly steeper for lower indifference levels, like $p = 0.6$. This indicates that even large changes in the strength of the field will have very small effects on the diffusion process.

The results also indicate that the ratio of convinced can increase even if the external field is fixed. The left panel in Figure 3 shows that the reduction of indifference level from a very high (more than 0.5) to moderate (around 0.2) could result in a significant growth of the ratio of convinced customers. If we analyze a market with a weak external field, say $h = 0.05$, then the ratios for $p = 0.8, 0.5$ and 0.2 are $c = 0.506, 0.531$ and 0.790 , respectively. The change is not only quantitative but also qualitative. For the same field intensity and a smaller indifference level, the opinions will become more stable and will not fluctuate so often.

Finally, note that the independence between the product quality and the ratio of convinced cannot be achieved under a classical modeling approach. If all agents behave rationally and maximize their utilities, they should respond to the product features. Hence, one could expect that attractive products would gain popularity. In the proposed setup, the introduction of indifference enables modeling of consumer irrationality. This feature of our model is especially important in the context of the retail electricity market because it has been observed (see the discussion in Section I) that new tariffs remain unpopular regardless of their attractiveness.

IV. CONCLUSIONS

In this paper, we have presented the results of an extensive simulation study on the diffusion of dynamic tariffs in the retail electricity market. We would like to emphasize that the simple agent-based model (ABM) we have used, is based on established knowledge from social sciences. As in other diffusion of innovations studies [12], in our model the new product adoption is driven by the internal influence that comes from interactions between agents (e.g., word of mouth) and the external field, which describes not only marketing efforts (advertising, promotions, educational campaigns, etc.) but also product features (potential savings, comfort/discomfort of usage of dynamic electricity tariffs, etc.). What distinguishes our model among others, is the way, in which we define the immunity of some agents to the social influence. As noted by [20], the so-called indifference – connected with an autonomy of individuals – can arise if two options (e.g., traditional and dynamic electricity tariffs) offer both advantages and disadvantages and these advantages and disadvantages are not clearly comparable. In such a case the strategy finally adopted by an individual is broadly unpredictable. Because such an uncertainty is very strong in the case of electricity tariffs [1], [7], [9], [11], we have introduced indifference as a kind of randomness into the model. Moreover, social experiments show that people are inconsistent in their behavior and simple situational factors are more powerful than individual traits in shaping human behavior. This fact is reflected in our model by the probability of indifference – in each time step an agent can be indifferent or susceptible with some probability and its behavior changes in time.

The most important conclusion from this study is the following: *The adoption of dynamic electricity tariffs is virtually impossible due to the high level of indifference in today's societies.* For a high level of indifference, the fluctuation of an agent's opinion leads to his/her inability to make a decision and switch to a new dynamic tariff, no matter how strong is the influence of the external field. And high levels of indifference and disengagement of the consumers, who neither have knowledge about electricity tariffs nor are willing to change them, have been confirmed by many independent studies [9], [11].

Therefore, in light of the results of our model and of the pilot programs conducted in Europe and the U.S., we can derive an important policy recommendation: *If the indifference*

level of the retail consumers is not reduced, the efforts to smooth the electricity demand via dynamic tariffs will not bring the expected results. In order to overcome this problem, utility companies should cooperate with the policymakers, governments and ecological organizations. A public debate is needed. When customers engage more in the topic, the adoption of dynamic electricity tariffs will be much more likely. Finally, if in the future the indifference level is reduced, the external field (i.e., tariff pricing schemes, advertisements, etc.) will become the focal point.

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