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# Study on the promotion impact of demand response on distributed PV penetration by using non-cooperative game theoretical analysis

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## HIGHLIGHTS

- The promotion impact of demand response on distributed PV penetration is studied.
- A non-cooperate game theoretical model was developed and used.
- Nash equilibrium of smart home consumers in power market is obtained.
- The games among the consumers with different response capabilities are analyzed.
- The smarter homes are useful to integrated more distributed PV power.

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ABSTRACT

Promoting the penetration of distributed photovoltaic systems (PV) at the end-user side is an important and urgent task. This study aims to evaluate the promotion impact of the response capability of smart home consumers on the distributed PV penetration using non-cooperative game theoretical analysis. In the analysis, the Nash equilibrium can be found for consumers with different levels of demand response capability in an electricity market with real-time pricing (RTP) mechanism under different PV installed capacities and battery capacities. As a case study, 5 levels of consumers' response capability, 32 combinations of PV installed capacities and battery capacities were analyzed and inter-compared using the developed model. The results show that: (i) the consumers with higher response capability are able to accept larger PV capacity because the marginal revenue of new installed PV for smart consumers decreases much more slowly compared to that of a common consumer; (ii) the consumers with higher response capability need less batteries to promote PV economic acceptability; (iii) the consumers with higher response capability can meet the electricity demand in real-time with least expenditure, so they get more ultimate benefit from the games.

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## 1. Introduction

With the dramatic increase of fossil fuel consumption, the reduction of $CO_2$ emission and the promotion of renewable energy have become urgent tasks for societies. Most of renewable energy technologies such as Photovoltaic (PV) and wind power are distributed and installed at end-user side. To promote the application of PV, many kinds of subsidization policies have been proposed [1–3]. For example, in many countries, governments provide a lump-sum grant to consumers who install PV systems or subsidies on the electricity generated by PV. Moreover, utility companies are often obligated to purchase PV power at a price relatively higher than the regular tariff under government-supported feed-in tariffs (FIT). However, in the traditional power grid, PV power is difficult to integrate due to its intermittence and low voltage [4]. Thanks to the recent rapid development of communication and automation technologies using telemetry, remote and automated control have enabled smart grid and demand response, which is expected to help dispatch and utilize PV power in both macro-grids [5,6] and micro-grids [7,8].

Apart from policy and subsidies, highly varied electricity prices resulting from the restructuring of the electricity market can also create an incentive to incorporate more PV panels [9]. Practically,

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**Nomenclature**

*Indices*

| | |
|---|---|
| $t$ | hour series in a day (1–24) |
| $d$ | representative days (3 typical days) |
| $i,j$ | user group (1–5) |
| $c$ | controllable appliances |

*Parameters*

| | |
|---|---|
| $NCL(i,d,t)$ | non-controllable load (kW) |
| $STA(i,d,c)$ | earliest start time of one controllable appliance |
| $STO(i,d,c)$ | latest stop time of one controllable appliance |
| $RP(i,d,c)$ | rated power of one controllable appliance (kW h) |
| $IRR(d,t)$ | solar irradiation in terms of output power/rated power (%) |
| $DAYS(d)$ | amount of days represented by representative day in each year |
| $PV(i)$ | installed PV capacity (kW h) |
| $BA(i)$ | installed battery capacity (kW h) |
| $\alpha$, $\beta$ | coefficient of electricity price |
| $NRL(d,t)$ | non-residential load (kW h) |
| $CHAEFF$ | battery charge efficiency |
| $DISEFF$ | battery discharge efficiency |

*Variables*

| | |
|---|---|
| $be(i,d,t)$ | power bought from grid (kW h) |
| $se(i,d,t)$ | power sold to grid (kW h) |
| $ca(i,d,c,t)$ | power consumed by one controllable appliance (kW h) |
| $pr(d,t)$ | power price established by power retail (RMB per kW h) |
| $brin(i,d,t)$ | battery charge rate (%) |
| $brout(i,d,t)$ | battery discharge rate (%) |
| $\lambda$ | dual variables for constraints |

*Abbreviations*

| | |
|---|---|
| PV | photovoltaic |
| FIT | feed-in tariff |
| RTP | real-time pricing |
| TOU | time of use |
| GAMS | General Algebraic Modeling System |
| MCP | mixed complementarity problem |

energy demand is not constant, but varies from moment to moment depending on end-users patterns of usage. In order to meet the energy demand of consumers, the generation and transmission capacities of the grid need to be designed to satisfy the peak power demand rather than the average power demand, leading to an over-capacity system for much of the time. In the traditional power market, the electricity price is usually fixed. A fixed price cannot reflect the fluctuation of generation cost caused by peak load, unit commitment constraints, congested transmission lines etc., and thus consumers have no motivation to shift consumption during the peak load periods. This results in a redundancy of power generation capacity and transmission infrastructures in the off-peak times, and therefore, the whole system becomes inefficient and cost-ineffective. To solve this problem, economic dispatch based on a real-time pricing (RTP) system and demand-response technologies is proposed, which can motivate consumers to shift their loads from peak times. Various pricing strategies have been proposed to incentivize demand-response in smart grid, and the most efficient one is the RTP [10,11]. Demand response programs under real-time pricing markets have been widely adopted in practice, and the promotion impacts on market access to distributed energy have been determined in previous studies [12].

There have been several models focusing on optimal operations of applications in smart homes with distributed PV. The existing models can mainly be divided into two main types in terms of mathematical methodology. One type is the optimal model, including static optimization models solving optimal load commitment problems of electric appliances in smart homes with distributed PV installed [13–15], and dynamic optimization models solving optimal expansion planning problems for PV in smart homes [16,17]. However, the models dedicated to analyzing the promotion impacts of consumers' response capability on the PV penetration were still not proposed. Moreover, in the existing models, the electricity price is usually set as exogenous. The consumers are price-takers rather than players in the market, which means that the consumers' behaviors have no impacts on electricity price. Therefore, we employee the game theoretical model, for example the non-cooperative game models handling games among residential consumers equipped with distributed electricity generators [18–20], Stackelberg game models dealing with games between utility companies and smart end-users (such as residential smart homes) in demand response programs [21], and market equilibrium models focusing on the whole power market [22]. In these game theoretical models, consumers' strategies can affect the power price. Comparing to optimal models, game theoretical models have advantages in handling situations where market participants have different or even conflicting objectives, so they are more realistic.

The purpose of this study is to analyze the promotion impacts of the consumers' response capabilities on distributed PV penetration. In order to analyze the impacts of end users' participation and different levels of their response capability in an electricity power market, a non-cooperative game theoretical model was developed. In the model, consumers participate in the game in a real-time pricing market and every consumer pursues his/her own minimized expenditure on electricity consumption. Different with the existing studies, consumers' different response capability levels have been considered in the proposed model to analyze their impact on integrating distributed PV. The consumers' different response capability level is measured by the ability of responding to electricity price fluctuation. The development of smart home technologies is the foundation of the actualization of consumers' demand response. Such technologies include smart metering, remote controlling, and automated controlling, and so on [10,23]. The new built houses are always equipped with advanced smart electric device and can response to the price fluctuations quickly and flexibly. One the other hand, the old houses are always not smart enough and thus cannot allocate energy consumption according to the price fluctuation. Moreover, in the present study, we don't consider the issue of consumers' willingness for demand response. In other words, we assume that the willingness of the consumers is as big as their response capability in smart homes. The consumers of smart homes with different demand response capabilities were then analyzed and compared. The equilibrium results with different installed capacities of PV as well as batteries were obtained. Every consumer's optimal operation pattern and total expense can be clarified. The economical acceptability of PV

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