Citizens Collaboration to Minimize Power Costs in Smart Grids
A Game Theoretic Approach

Tarek AlSkaif[1], Manel Guerrero Zapata[1] and Boris Bellalta[2]
[1]*Dept. of Computer Architecture (DAC), Universitat Politecnica de Catalunya (UPC), 08034 Barcelona, Spain*
[2]*Dept. of Information and Communication Technologies, Universitat Pompeu Fabra (UPF), 08018 Barcelona, Spain*

Keywords: Smart Cities, Smart Grids, Renewable Energy, Game Theory.

Abstract: Generating the power necessary to run our future cities is one of the major concerns for scientists and policy makers alike. The increasing global energy demands with simultaneously decreasing fossil energy sources will drastically affect future energy prices. Strategies are already being implemented to develop solutions for the generation and efficient usage of energy at different levels. Involving citizens in the efficient planning and usage of power is a key. In this paper, we propose a game theory based power sharing mechanism between end-users in smart grids. We consider that citizens can produce some amount of electric power obtained from on-site renewable sources rather than just purchasing their whole demands from the grid. Simulation results show that consumers can achieve considerable cost savings if they adopt the proposed scheme. It is also noticed that the more the consumers cooperate, the higher the percentage of cost savings is.

1 INTRODUCTION

Smart grids are intelligently integrated operational and technological systems for optimizing power generation, distribution, and consumption across a city. They are the most dominant components of smart cities. Unlike existing grids, where electricity flows one-way from generators to consumers, smart grids will ensure a two-way flow of electricity and information between power plants and appliances, and all points in between.

Demand-side management (DMS) (Gellings and Chamberlin, 1987) refers to an efficient power consumption planning at electric utilities and consumers. In smart cities, power demands of consumers have to be determined so that the allocation of power supply and distribution can be performed optimally. For additional power supply the power generator may charge a higher price than the price in a periodic contract due to the instantaneous need, which is random and difficult to predict (Jirutitijaroen and Singh, 2008). Moreover, generators and city governments will take into account the limitations on energy sources in the city, which will also affect electricity prices drastically. Generally, consumers have conflicting interests. They need to increase their power consumption in some occasions, but at the same time they want to reduce their monetary expenses and collaborate in the sustainability of their cities.

To achieve these conflicting goals, cooperation between consumers themselves is a key. Power consumers (e.g., home, buildings, industry, among others) can cooperate and share their electricity sources in an intelligent and harmonized manner. For example, suppose there are two neighboring consumers who may have different power consumption schedules. The first consumer may need additional power in the morning, or in certain days while the other is at work, or does not need it. If both consumers share their power sources, they may allow each other to borrow some predetermined amount of their unused power. This way cities will allow inhabitants to share responsibilities while offering maximum control at the lowest level.

Game theory (Nisan et al., 2007) has been used recently in a remarkable amount of research in this area since it provides efficient analytical tools to model interactions among entities with conflicting interests in a distributed manner. Many games have been applied to address different challenges in smart grids which will be summarized in Section 2. In this paper, we propose a power sharing framework and use game theory to model the interaction between rational consumers in smart grids. Consumers may bor-

AlSkaif T., Guerrero Zapata M. and Bellalta B..
Citizens Collaboration to Minimize Power Costs in Smart Grids - A Game Theoretic Approach.
DOI: 10.5220/0005490103000305
In *Proceedings of the 4th International Conference on Smart Cities and Green ICT Systems* (SMARTGREENS-2015), pages 300-305
ISBN: 978-989-758-105-2

row/lend each other some amount of power instead of usually purchasing it from the provider at a higher cost. The consumers cooperate and at the end of each predetermined stage, they calculate their payoff (e.g., power costs) and decide to keep cooperating or not. We prove and illustrate through simulation that cooperation is always preferable (i.e., rational consumers always achieve cost savings by sharing their power). To the best of our knowledge, this is the first work that investigates the usability of game theory formulations to design a local power sharing scheme between consumers in smart grids.

The rest of the paper is organized as follows. Section 2 surveys the related work. The system model is illustrated in Section 3. The proposed game model is described and analyzed in Section 4. Numerical results are discussed in Section 5. Finally, we conclude the paper and give pointers for possible future directions in Section 6.

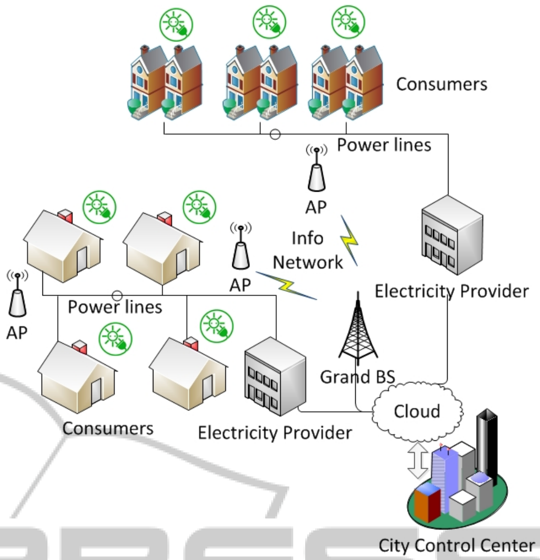

Figure 1: The proposed smart grid architecture.

2 RELATED WORK

Many surveys can be found in the recent literature that focus to a great extent on smart grids architectures, challenges, potential applications, and communications requirements like (Niyato et al., 2011; Fang et al., 2012; Siano, 2014). A survey of game theory methods for smart grids is provided in (Saad et al., 2012).

There are several studies that apply game theory models in the smart grid context. A distributed load management scheme based on a congestion game is proposed in (Ibars et al., 2010). The goal is to control the power demand at peak hours, and avoid overloading both the generation and distribution capacity of the grid. To reduce electricity costs and peak loads, a Real-Time Pricing (RTP)-based power scheduling scheme for residential power usage is proposed in (Chen et al., 2011) using a Stackelberg game model. In (Agarwal and Cui, 2012), a non-cooperative load balancing game among power demanding consumers and a retailer is formulated with two pricing schemes: an average-cost and an increasing-block pricing schemes. A Stackelberg game between utility companies and end-users is presented in (Maharjan et al., 2013). The goal is to maximize the revenue of each utility company and the payoff of each user. In (Atzeni et al., 2013), demand-side users are interested in minimizing their power costs by owning some kind of distributed energy source and/or energy storage device. A non-cooperative game is introduced to optimize their production/storage strategy. Two models of dynamic pricing are presented in (Cui et al., 2013) to solve the profit maximization problem of non-cooperative utility companies in an oligopolistic market. In (Chen et al., 2014), a game theory based real-time load billing scheme is proposed to effectively convince the selfish consumers to shift their peak-time consumption and to fairly charge the consumers for their energy consumption. A game theory based matchmaking solution that harmonizes load demands with the instantaneously available power, as well as the amount of stored renewable energy in smart grids is proposed in (Spata et al., 2014). A coalition game is presented in (Luan et al., 2014) to allow consumers not only to maximize their payment savings (i.e., by scheduling their power consumption), but also to consider the social welfare in the network as well.

3 SYSTEM MODEL

In this work we consider a generic smart grid which consists of an electricity provider and a set of consumers in a neighborhood (e.g., home, buildings, among others) $\mathcal{N} = \{n_1, n_2, \ldots, n_N\}$, as illustrated in Fig. 1, where $N = |\mathcal{N}|$. The consumers buy energy from the provider and can use renewable energy sources as well. We assume that users' power demands may be variable both in quantity and time, and that users can approximately predetermine their demands for future time periods. Such variability could be exploited by consumers to minimize the need of buying additional power demands from the provider. This is achieved by allowing consumers to cooperate through a borrow/lend power sharing scheme.

The consumers have demand management capabilities. That is, each consumer is equipped with a smart energy meter, which controls and organizes the power consumption intelligently. Smart meters are responsible of communications between consumers. They exchange information about consumers' additional demands and their available power that could be shared with others.

A power demand of a consumer i depends on a time period $t \in \mathcal{T}$, where $\mathcal{T}$ is the set of all time periods. At every time period t, each consumer has three power values: i) an amount of power received from the provider, ii) an amount of green power generated by on-site renewable energy sources, and iii) a power demand value. From these value a consumer can determine at every t if an additional power demand is required or if there is a redundant amount of power. After a series of time periods the consumer i will have a power vector P_i that indicates the additional demands, as well as the available power, at different time periods $\mathcal{T}$. This power vector is defined as $P_i = [P_i^1, P_i^2, \ldots, P_i^T]$, where $P_i \in \mathbb{R}$. A negative value of P_i indicates a required additional demand, while a positive one represents the available power that could be shared with other consumers. Each time period can represent different timing horizons such as an hour of a day, a day in a month, a month in a year, among others. We can easily calculate P_i as follows:

$$P_i = (P_{\text{ren,i}} + P_{\text{cont,i}}) - P_{\text{dem,i}} \quad (1)$$

where $P_{\text{ren,i}}$ represents the power received from renewable sources, $P_{\text{cont,i}}$ represents the contracted power received from the electricity company, and $P_{\text{dem,i}}$ is the power demands of a user i. Let $P_i^{(+)}$ denote a vector contains the positive values of the power vector P_i (i.e., offers), and $P_i^{(-)}$ denote a vector contains the negative values of P_i (i.e., additional demands). We have:

$$P_i = P_i^{(-)} + P_i^{(+)} \quad (2)$$

This power vector will determine the benefit and costs of each consumer in the system, as we will see in Section 4. By sharing power, it is possible that a consumer can increase his/her power consumption at a certain time period without the need of buying an additional amount of power from the provider. However, consumers who borrow some amount of power from their neighbors should also lend them an amount of power at different schedules (i.e., when the other consumer has some additional demands).

4 GAME FORMULATION AND ANALYSIS

We formulate the interaction between consumers using a non-cooperative game similar to the repeated Forwarder's Dilemma game that has been used to address several problems in the wireless communication field (Felegyhazi and Hubaux, 2006). In this game users cooperate in order to obtain mutual advantage. The game can be defined as follows:

- **Players.** The set of players in this game are end-users (i.e., power consumers) in a smart grid, $\mathcal{N} = \{n_1, \ldots, n_N\}$.
- **Strategies:** The set of strategies, $\mathcal{S}$, for each player i:
  - **Cooperate (C).** A consumer shares an amount of power with another consumer in the grid. A consumer who cooperates keeps cooperating as long as his/her opponent cooperates.
  - **Defect (D).** The consumer decides to stop sharing power and leaves the game if the cost of additional demands after sharing power (C'') are not reduced, or if the other player defects.
- **Payoff or Utility.** The satisfaction of a player i in a game is determined through the payoff function. The benefits obtained (i.e., the indirect cost savings achieved by borrowing an amount of power), as well as the payments (i.e., remaining power demands that have to be purchased from the provider ($P_i'^t$), and the reduced amount of available power that has been lent to an opponent ($P_i''^t$)) are the major factors that determine the payoff function of this game at a time period t. We define the payoff function of a consumer i as follows:

$$\pi_i = -C_1 P_i'^t - C_2 P_i''^t \quad (3)$$

$$P_i'^t + P_i''^t = P_i^{(-),t} \quad (4)$$

where C_1 is the cost of buying each additional kWh from the provider (i.e., outside the contract), and C_2 ($C_2 < C_1$) is the cost of each kWh in the fixed contract. It is worth mentioning that in case of cooperation, the cost of additional demands is reduced (i.e. an implicit benefit is achieved).

In this game, we assume that consumers are rational users who want to maximize their own welfare by minimizing their power monetary costs. A player's strategy specifies the action he/she will take at each stage for each possible strategy played by the other player. We assume that the interaction among players is reciprocal (i.e., consumers may be offering/demanding for a certain amount of power at different time periods, and need to borrow/lend some

Table 1: The payoff matrix.

		Player 2	
		Cooperate (C)	Defect (D)
Player 1	Cooperate (C)	a_1, a_2	c_1, b_2
	Defect (D)	b_1, c_2	d_1, d_2

amount of power from each other). Thus, we can isolate any pair of consumers and study the interaction between them as a two-player game.

Definition 1. *Nash equilibrium is a strategy profile, from which no single player can individually improve his welfare by deviating.*

Formally, a strategy profile is said to be a NE if for any player i, and for all of its strategies $s'_i \in \mathcal{S}$, we have that:

$$u_i(s_i, s_{-i}) \geq u_i(s'_i, s_{-i}) \quad (5)$$

The stage payoffs matrix is given in Table I, where $b_1 > a_1 > d_1 > c_1$ ($b_2 > a_2 > d_2 > c_2$) are the payoffs of player 1 (player 2) in the different strategy profiles. This game is known to be a symmetric nonzero-sum game in which the strategy profile (D,D) is a strictly dominated strategy, and a pure strategy Nash equilibrium (Felegyhazi and Hubaux, 2006). However, If both consumers plays D, they have to buy their entire additional power demands from the provider. If the game is repeated, consumers can mutually minimize their power costs by playing Cooperate (C) (i.e., by borrowing/lending some amount of power to each other). The costs could be minimized from $d_1(d_2)$ to $a_1(a_2)$ in this case. In other word, by cooperating, they can achieve an outcome that is better for both players than mutual defecting. A player i would play C as long as its opponent plays C. If one player changes and chooses D, then the other will play D forever. Switching to D could be interpreted as a punishment of the opponent. This may convince players to cooperate instead of exploiting short advantages. However, neither player would prefer defecting since they know the end of the game. Cooperating in every stage is also proved to be a Nash equilibrium in such a repeated game. We will ensure via simulation in Section 5 that players who have power to share can not achieve better payoff by defecting.

It is assumed that players calculate their payoff in each time period (e.g., weekdays). At the end of a predefined number of time periods (e.g., one week), each player measures the total payoff and compares it with the expected payoff received when buying the entire additional demands from the provider (i.e., when defecting). Then, a decision whether to continue cooperating or not is made. This power sharing game is illustrated in Fig. 2.

The reason of $d_1(d_2)$ being greater than $c_1(c_2)$ is because if one consumer cooperates and the other defects, the first has not only to buy the total additional demands from the provider, but also his/her available power will decrease. As we mentioned before, the cost of available power obtained from renewables and/or in a regular contract is assumed to be cheaper than the cost of additional demands ($C_2 < C_1$).

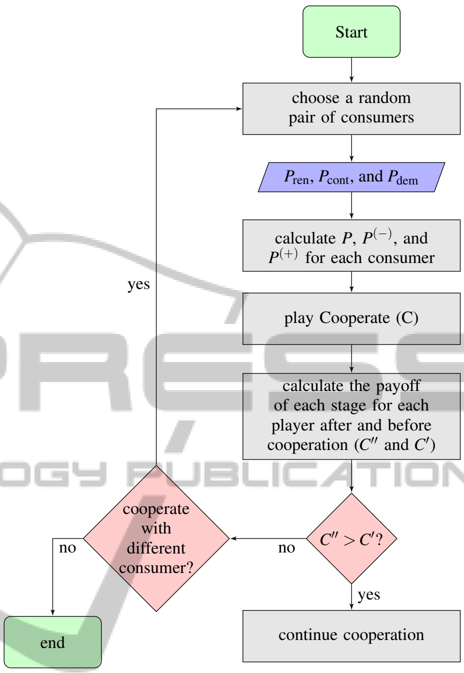

Figure 2: The flow chart of the proposed power sharing game.

5 NUMERICAL RESULTS

In our simulation, we consider a residential scenario consisting of N consumers. First we will take a random pair of consumers and study the interaction between them as a two-player game. Then, we will show via simulations that the payoff of a consumer could be increased by cooperating with more players. Each time period t is set as one day. The interaction is held onetime a day. Both players calculate their utility using the payoff function. After one week of interaction (i.e., playing C), each player measures the total utility, and compares it with the expected payoff received without cooperation. Then, the consumer decides to continue cooperation or not.

In our scheme we assume that citizens have on-site renewable energy sources and they choose the cheapest possible offer given by the electricity company. Let us consider that the consumers buy each kWh in the regular contract with a cost C_2= \$0.09/kWh, and the cost of each additional required kWh is C_1= \$0.20/kWh (these values are according to the payment of residential customers in the U.S (Energy Information Administration, 2014)). Demands in a regular contract can differ from one day to the other, as demands on weekends, for example, could be higher than in normal working days. Consumers can share redundant power (i.e., obtained from renewable energy sources and/or received from the utility company but not needed). However, if they do not use or share this power, they can not return it to the provider. We assume that values in power vectors are uniformly distributed inside the range $[x_1, x_2]$, where $x_1, x_2 \in \mathbb{R}$, negative values indicates the additional demands, and positive ones represents the offers (i.e., the available power).

In our simulation, power demands, as well as power offers, are generated through a uniform pseudo-random number generator. We suppose that consumers can share between 0 and 0.5 kWh of power obtained from renewable sources per day. It is also assumed that values in power vectors are between -2 and 2 kWh/day (i.e., $x_1 = -2$, $x_2 = 2$). In order to investigate the strength of the proposed scheme, we define three different simulation sets. In the first set, additional power demands are set to be higher than offers (i.e., demands are between -2 and -1 kWh/day, and offers are between 0.5 and 1 kWh/day). In the second one, power demands are set to be between -2 and -1, and offers are between 1 and 2. In the third set, demands are between -1.5 and -1, but offers are between 1.5 and 2. The proposed model is implemented in MATLAB. Each value represents an average of 100 runs. Fig. 3 and Table II compare the costs of additional power demands before (C') and after (C'') adopting the power sharing scheme in the case of the 2-players game. It is observed that power expenses are can be reduced if consumers mutually keep playing Cooperate (C).

Due to the randomness in power consumption of different end-users, the demands of a player may not be satisfied by cooperating with only one player. In addition, offers may not be totally borrowed -or even not borrowed at all. Since obtaining the required demand is limited by the offer availability of other players, when the number of cooperating players increases, the probability that the required demand is satisfied by one or more players is higher. In Fig. 4 and Fig. 5, we show how a consumer can reduce power costs if he/she cooperates with more players. It is also observed that cost savings are achieved in the three different simulation sets. Therefore, we believe that cooperation and power sharing will be preferable even for high power demanding users, which makes the proposed scheme eligible to be a solution for the proposed problem.

Table 2: The payoffs of players in one month for the three different simulation sets.

			Player 2	
			C	D
Simulation set 1	Player 1	C	-3.165, -3.090	-3.801, -2.804
		D	-2.896, -3.687	-3.532, -3.401
			C	D
Simulation set 2	Player 1	C	-1.801, -1.863	-2.539, -1.531
		D	-1.459, -2.622	-2.197, -2.289
			C	D
Simulation set 3	Player 1	C	-1.242, -1.287	-2.077, -0.911
		D	-0.860, -2.137	-1.694, -1.761

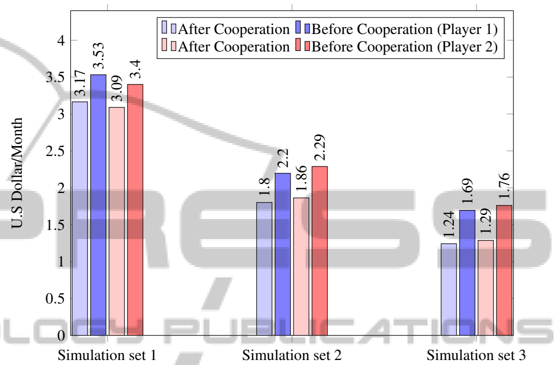

Figure 3: The average monthly payoff of each player in the power sharing game in case of playing (C,C) and (D,D).

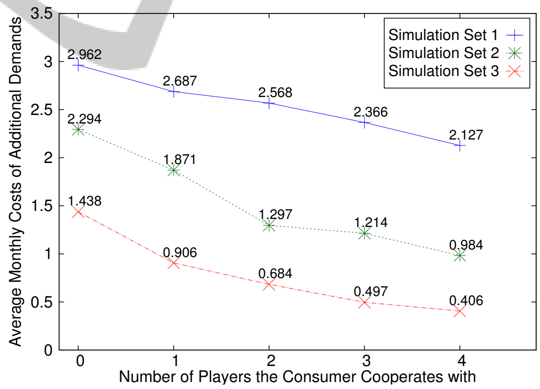

Figure 4: The average monthly payoff of a consumer as a function to the number of players he/she cooperates with.

6 CONCLUSION AND FUTURE WORK

Future directions in smart cities are to involve people and society in being part of the intelligence and success of the city, helping their environment, and reducing their costs as well. In this paper we have presented a game theory based power sharing scheme between end-users in smart grids. We have proved via simulations, and for different classes of consumers, that citizens can noticeably minimize their power costs if they

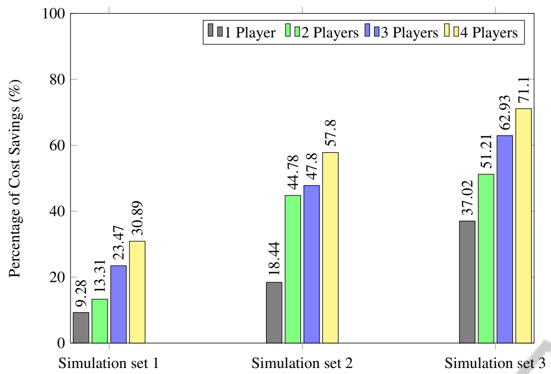

Figure 5: The percentage of average cost savings of a consumer when cooperating with one or more consumers.

share their power and cooperate. This scheme opens the door to some interesting extensions. In the future, we will propose a reputation/punishment scheme to address two different points: i) the effect of selfish and miss-behaving consumers, and ii) the reputation and incentives received from the city (e.g., for being green, for reducing the peak demands, or even for being positive in combating the climate change, among others). The distribution of power consumption during time periods, as well as power borrowing/lending policies will be given more attention.

ACKNOWLEDGEMENTS

This work was partially supported by projects TIN2013-47272-C2-2 and SGR-2014-881.

REFERENCES

Agarwal, T. and Cui, S. (2012). *Noncooperative games for autonomous consumer load balancing over smart grid*. Springer.

Atzeni, I., Ordóñez, L. G., Scutari, G., Palomar, D. P., and Fonollosa, J. R. (2013). Noncooperative and cooperative optimization of distributed energy generation and storage in the demand-side of the smart grid. *Signal Processing, IEEE Transactions on*, 61(10):2454–2472.

Chen, C., Kishore, S., and Snyder, L. V. (2011). An innovative rtp-based residential power scheduling scheme for smart grids. In *Acoustics, Speech and Signal Processing (ICASSP), 2011 IEEE International Conference on*, pages 5956–5959. IEEE.

Chen, H., Li, Y., Louie, R. H., and Vucetic, B. (2014). Autonomous demand side management based on energy consumption scheduling and instantaneous load billing: An aggregative game approach. *Smart Grid, IEEE Transactions on*, 5(4):1744–1754.

Cui, T., Wang, Y., Yue, S., Nazarian, S., and Pedram, M. (2013). A game-theoretic price determination algorithm for utility companies serving a community in smart grid. In *Innovative Smart Grid Technologies (ISGT), 2013 IEEE PES*, pages 1–6. IEEE.

Energy Information Administration, U. S. (2014). http://www.eia.gov/electricity/monthly/.

Fang, X., Misra, S., Xue, G., and Yang, D. (2012). Smart grid - the new and improved power grid: A survey. *Communications Surveys & Tutorials, IEEE*, 14(4):944–980.

Felegyhazi, M. and Hubaux, J.-P. (2006). Game theory in wireless networks: A tutorial. Technical report.

Gellings, C. W. and Chamberlin, J. H. (1987). Demand-side management: concepts and methods.

Ibars, C., Navarro, M., and Giupponi, L. (2010). Distributed demand management in smart grid with a congestion game. In *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, pages 495–500. IEEE.

Jirutitijaroen, P. and Singh, C. (2008). Reliability constrained multi-area adequacy planning using stochastic programming with sample-average approximations. *Power Systems, IEEE Transactions on*, 23(2):504–513.

Luan, X., Wu, J., Ren, S., and Xiang, H. (2014). Cooperative power consumption in the smart grid based on coalition formation game. In *Advanced Communication Technology (ICACT), 2014 16th International Conference on*, pages 640–644. IEEE.

Maharjan, S., Zhu, Q., Zhang, Y., Gjessing, S., and Basar, T. (2013). Dependable demand response management in the smart grid: A stackelberg game approach. *Smart Grid, IEEE Transactions on*, 4(1):120–132.

Nisan, N., Roughgarden, T., Tardos, E., and Vazirani, V. V. (2007). *Algorithmic game theory*. Cambridge University Press.

Niyato, D., Xiao, L., and Wang, P. (2011). Machine-to-machine communications for home energy management system in smart grid. *Communications Magazine, IEEE*, 49(4):53–59.

Saad, W., Han, Z., Poor, H. V., and Basar, T. (2012). Game-theoretic methods for the smart grid: An overview of microgrid systems, demand-side management, and smart grid communications. *Signal Processing Magazine, IEEE*, 29(5):86–105.

Siano, P. (2014). Demand response and smart gridsa survey. *Renewable and Sustainable Energy Reviews*, 30:461–478.

Spata, M. O., Rinaudo, S., and Gennaro, F. (2014). A novel matchmaking algorithm for smart grid applications. In *Engineering, Technology and Innovation (ICE), 2014 International ICE Conference on*, pages 1–6. IEEE.