A Canonical Coalitional Game Theoretic Approach for Energy Management for Nanogrids

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***Abstract*—This paper explores the benefits of forming a coalition of a number of nanogrids in a smart community when they assist by supplying their energy surplus to a shared facility controller (SFC). In this context, a canonical coalition game (CCG) is studied, in which a number of nanogrids, such as households, form a grand coalition in order to supply a contracted amount of energy to the SFC with a view to gain some revenue. A suitable utility function is proposed that captures the benefit to the coalition of trading the energy with the SFC, as well as the penalty that may occur if the coalition fails to provide the SFC with the contracted energy amount. The properties of the coalition are studied and a fair utility allocation technique, i.e., a proportional payoff division scheme, is exploited for distributing the benefits between the participating nanogrids based on the supply they contribute.**

***Index Terms*—Nanogrid, game theory, canonical game, energy management, smart grid, shared facility.**

I. Introduction

There has been a growing interest in increasing the use of renewable energy sources for electricity generation in smart grid. The objective is to alleviate the dependence on fossil fuels due to their detrimental environmental impact and higher costs. As a consequence, matching demand with intermittent renewable supply, i.e., demand-response management (DRM), has become a critical part of emerging smart grid designs [1]–[5]. Essentially, the smart grid offers the reporting and control mechanisms for matching such variable supply to demand at both the large and small scales of the grid system.

The challenge of DRM can be addressed by combining communications with power distribution so that consumers with distributed energy sources (DERs) can communicate their demands (or, surpluses), and the electricity controllers, e.g., shared facility controllers (SFCs) [6], can communicate their supply availability (or, requirements) [7]. Since significant penetration of DERs in individual houses and buildings is becoming a reality, energy management via microgrids and *nanogrids* is expected to play a significant role in future smart grid systems [7], [8].

A nanogrid is a small power system with DERs, which is typically designed such that renewable sources supply the average load demand, whereby storage and non-renewable generation are used to ensure that the loads enjoy a continuous supply of power in presence of the intermittent renewable generation [9]. The total load in a nanogrid is typically quite small, e.g., a small rural community may have a total load of less than 20 kWh [10]. As a fairly new field with smart grid research, the existing studies of nanogrids have mainly focussed on whether power generation and energy storage are the key components of nanogrids [10]. For instance, generation is considered as the key component of a nanogrid in [11] and [12], whereas energy storage is acknowledged as an optional element in [1] and [13]. However, one potential aspect that has not received much attention in the existing nanogrid literature is how nanogrids can assist SFCs in managing their electricity in a local community setting considering their lower capacity. It is important to note that unless the nanogrids, like other energy entities in smart grid, can act as a beneficial component to the SFC, e.g., either as a complete or partial source of energy source or storage, the overall economic rewards of using DERs by the nanogrid would be unattractive [14]. Besides, despite a number of recent works (e.g., see [15] and the references therein) that have extensively studied residential DRM, these DRM techniques might not be suitable for nanogrids due to their considerably smaller capacity of energy generation and storage. In brief, there is a need for solutions that can exploit the characteristics of nanogrids in designing energy management schemes for smart grid systems.

This paper proposes an energy management scheme for nanogrids for supplying energy to an SFC in a smart community. Considering the fact that nanogrids are entities with relatively low energy capacity compared to the electricity

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requirements of an SFC[1], the aggregated energy from the nanogrids is considered, and a canonical coalitional game (CCG) [16] is formulated to realize such aggregation. We stress that cooperative game theory has been studied before in the context of smart grid energy management. For instance, our work is motivated by the work done by Saad et al. in [17], where the authors proposed a *coalition formation game* to coordinate the power transfer among micro-grids and between micro-grids and a macro-grid. The authors in [17] proposed an algorithm to allow the micro-grid to coordinate the power transfer among themselves and with a macro-grid as according to changes in the environment.

However, the current study differs from the work in [17] in a number of ways. Firstly, in contrast to [17], we propose a coalition game in its *canonical form*, which is significantly different than a coalition formation game [16], to study the energy trading behavior of nanogrids. Secondly, in [17], the main contribution is the design of an algorithm to enable the participating micro-grids to decide on their participation in energy trading. However, in this work we study the properties of the proposed game to show how the possibility of gaining higher net payments (or, to pay less penalty) can encourage the nano-grids to form a large coalition. We also show that the grand coalition of the proposed game is stable. To this end, the main contribution of the proposed work can be summarized as follows:

1) We study a CCG for nanogrids with low energy capacity to leverage their energy trading with an SFC in a smart community.
2) A suitable utility function is proposed that can capture the benefits to the coalition of trading energy with the SFC as well the penalty that may be incurred to the coalition due to the failure of supplying contracted energy to the SFC.
3) We study the properties of the coalition and show that the proposed CCG[2] is stable. Therefore, no nanogrid has any incentive to leave the grand coalition if the energy trading environment remains unchanged.
4) Through numerical analysis, we show the beneficial properties of the proposed energy management scheme.

II. System Model and Problem Formulation

Consider a smart community, which consists of an SFC, a grid and N nanogrids, e.g., households, where $N = |\mathcal{N}|$. Each nanogrid $n \in \mathcal{N}$ is equipped with a small renewable energy source and energy storage [1], such that the generated energy from renewables is sufficient for the nanogrid to run its own activities under favorable weather conditions, and if there is any deficiency, it can buy electricity from the main grid. Motivated by the fact that nanogrids are capable of interconnection with each other [7], it is also assumed that the nanogrids can also sell electricity to the SFC if they have any surplus after meeting their regular demands. On the other hand, an SFC is an energy entity that controls the electricity consumption of facilities such as lifts, water pumps, corridor and parking lights, which are used by the residents of a community on a daily basis [6]. The SFC does not have any storage capacity and it solely depends on the main power station and nanogrids for its required electricity. All the energy entities in the system are connected to one another with power and communication lines [6]. A graphical representation of the system model is shown in Fig. 1.

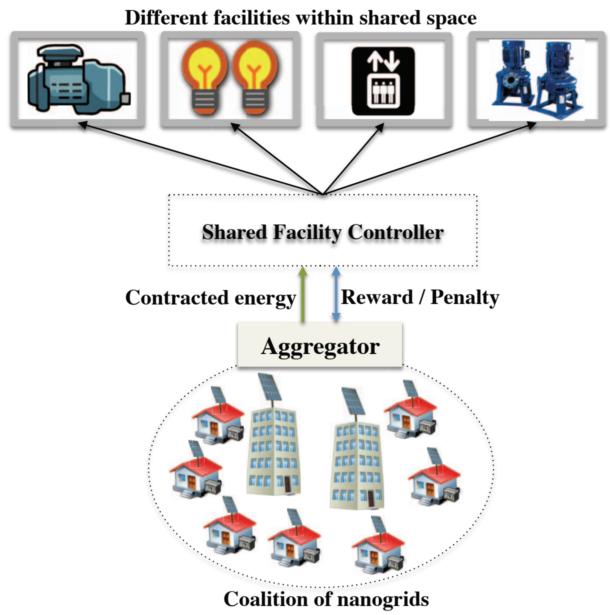

Fig. 1: Energy management through a coalition of nanogrids (e.g., households).

We assume that at any time t of the day each nanogrid $n \in \mathcal{N}_t$, where $\mathcal{N}_t \subseteq \mathcal{N}$, has some surplus of electricity e_n, after meeting its usual demand, that it wants to sell. Since, the buying price by the grid is considerably smaller than the buying price of an SFC [6], it is reasonable to assume that the nanogrids will be interested in selling their surplus energy to the SFC. Furthermore, it is assumed that the SFC has an energy requirement of E_s for the considered time slot, from which it wants to buy $E_h \leq E_s$ amount of electricity from the nanogrids. Since, the amount of electricity produced by a nanogrid is quite small [7], and the energy consumption pattern of equipment and machines such as lifts and water pumps are relatively very high, it is reasonable to assume that $e_n << E_h,\ \forall n \in \mathcal{N}_t$. In this context, we assume that the SFC would be inclined to buy the aggregated amount of electricity rather than buying electricity from each $n \in \mathcal{N}_t$. This assumption is motivated by the following fact [18]: the power transfer between a nanogrid and an SFC will be accompanied by a cost

[1]Which could be significantly larger than a nanogrid's surplus depending on the usage of facilities, e.g., lifts, water pumps, corridor and parking lights.

[2]Hereinafter, we use CCG and coalition game alternately to refer to the proposed CCG.

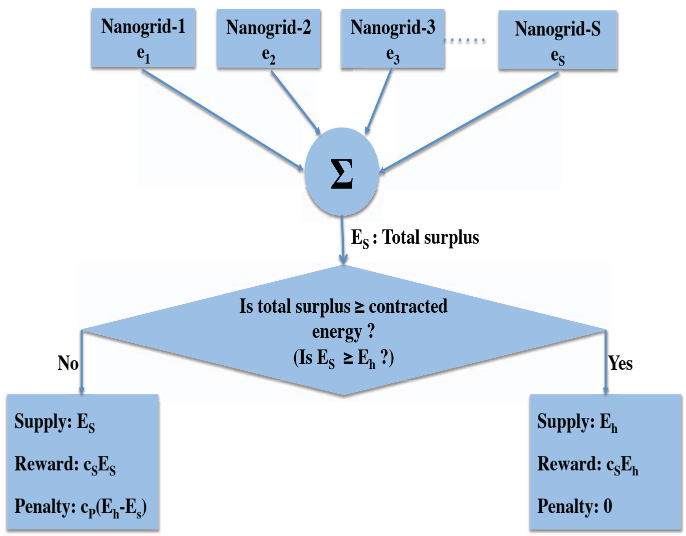

Fig. 2: Description of the energy management rules of the proposed coalition.

that corresponds to the loss of power over the distribution line. Hence, if a small amount of electricity from a single nanogrid is transmitted through the distribution line, the effective energy that the SFC might receive could be insignificant compared to the associated cost.

Accordingly, let us assume that the SFC has a contract with the aggregator of nanogrids that it would supply E_h amount of energy[3] to the SFC in exchange for a price c_s per unit at the considered time slot. The aggregator can be assumed to be an entity that is responsible for the coalition $\mathcal{S} \subseteq \mathcal{N}_t$ of nanogrids, and for distributing the rewards from trading between them. The aggregated amount of electricity from the coalition $\mathcal{S}$ can be written as

$$E_{\text{S}} = \sum_{n \in \mathcal{S}} e_n. \tag{1}$$

However, if the aggregator fails to supply the agreed amount, i.e., $E_{\text{S}} < E_h$, it is penalized by a price c_p per unit of energy for the deficient amount $E_h - E_{\text{S}}$. And, if $E_S > E_h$, then the coalition can only sell the contracted amount to the SFC, i.e., $E_S = E_h$. Thus, we propose that the amount of reward that the nanogrids in coalition $\mathcal{S}$ receive from trading energy with the SFC from such a coalition can be quantified by

$$\Pi(E_h, \mathcal{S}) = c_s E_{\text{S}} - c_p \left(E_h - E_{\text{S}}\right), \tag{2}$$

where c_p could be any value depending on the contract between the aggregator and the SFC. For instance, one possible choice of penalty price could be $c_p = c_{g,s}$, which manifests the situation when the SFC would penalize the coalition with the grid's selling price $c_{g,s}$ per unit of energy. A schematic representation of this energy management rule of the coalition is shown in Fig. 2.

However, a nanogrid may also want not to be a part of a coalition and act noncooperatively to trade its surplus. In this regard, the noncooperative payoff[4] of a nanogrid $n \in \mathcal{N}_t/\mathcal{S}$, if there any, is assumed to be

$$\Pi(\{n\}) = c_{g,b} e_n, \tag{3}$$

where $c_{g,b}$ is the buying price of the grid. Equation (3) is chosen based on the assumption that the SFC will not buy any electricity from any individual nanogrid because of its contract with the aggregator, and hence any noncooperative nanogrid needs to sell its electricity to the main grid. It is important to note that the grid's selling price is significantly high [6]. Therefore, as an alternative, the SFC is always interested in buying as much as possible from the nanogrids. As a consequence, it would set the price c_s considerably higher than the grid's buying price $c_{g,b}$, i.e., $c_s >> c_{g,b}$ in order to encourage the nanogrids to sell their surplus to the SFC instead of selling to the grid [6].

Theorem 1. *Consider $\mathcal{N}_t = \{1, 2, \ldots, N_t\}$ as the set of N_t nanogrids that take part in energy trading with the SFC and the grid at time t. The reward (i.e., net payment) will increase for the nanogrids as more of them agree to form a coalition $\mathcal{S} \subseteq \mathcal{N}$ for trading their surplus provided the difference between c_p and c_s is not significant.*

Proof. First, we note that the generation capacity of a nanogrid n is very limited [1]. Hence, the amount of surplus e_n after meeting its own demand will also be insignificant. As a consequence, according to (3), the reward from selling noncooperatively to the grid, given the fact that $c_{g,b} << c_s$, will be considerably low. On the contrary, from (2) as more nanogrids from $\mathcal{N}_t$ form a coalition to supply the contracted electricity E_h to the SFC, their expected penalties will reduce and at the same time their rewards from selling energy will increase. Hence, if c_p is not significantly greater than c_s in (2), it would always be beneficial for each nanogrid to cooperate in order to reap greater rewards from its energy trading with the SFC, and thus Theorem 1 is proved. □

According to Theorem 1, coalitional energy trading will always manifest itself in increased profit that can be shared among the participating nanogrids in the coalition. However, the net benefit may also be affected by the available surplus to each of the nanogrids, which we will discuss further in Section IV. Now, we introduce a coalitional game model in the next section to study the cooperative behavior of nanogrids.

III. Coalitional Game for Nanogrids

Coalitional games, also known as cooperative games [16], is a branch of game theory that studies whether a group of players, i.e., the nanogrids in this paper, can be better off if

[3]The amount can be derived through any statistical estimation technique, such as using a Markov chain, from the historical available transaction records.

[4]Which we consider as a benchmark for comparison in Section IV.

they decide to play jointly in an alliance. A CCG is defined by a pair $(\mathcal{N}, v)$ where $\mathcal{N}$ is the set of participating players and $v : 2^{\mathcal{N}} \to \mathbb{R}$ is a function that assigns every coalition $\mathcal{S} \subseteq \mathcal{N}$ a real number, which represents the rewards achieved by $\mathcal{S}$.

A. Proposed Game

Now, to develop a CCG between the nanogrids, we need to define a value function $v(\mathcal{S})$ for any coalition $\mathcal{S} \subseteq \mathcal{N}_t$. To do so, it is important to note that for a given contract E_h, the reward that a coalition of $\mathcal{S}$ can obtain is expressed as (2). Depending on the total number nanogrids N_S within the coalition $\mathcal{S} \subseteq \mathcal{N}_t$ that are participating in the coalition, the reward can vary significantly as demonstrated in (1) and (2). To this end, we can formally define the value function for the nanogrids coalitional game $(\mathcal{N}_t, v)$ as

$$v(\mathcal{S}) = \max_{N_S \in \mathcal{S}} \Pi\left(E_h, \mathcal{S}\right), \ \forall \mathcal{S} \subseteq \mathcal{N}_t. \tag{4}$$

Since (4) represents a revenue paid to the coalition $\mathcal{S}$, it can be divided in any arbitrary manner between the members of $\mathcal{S}$. Therefore, the proposed coalitional game $v(\mathcal{S})$ in (4) is a game with *transferrable utility* [16].

B. Stability of the Coalition

It is important to note that a stable coalition is not always guaranteed to exist in a coalitional game. Hence, we need to investigate whether the proposed game possesses a stable coalition. In this context, the most renowned solution concept is the core [16], which is a set of payoff allocations known as imputations[5]. Essentially, the existence of a core in a coalitional game guarantees the stability of the grand coalition. To this end, we now investigate whether the proposed CCG $(\mathcal{N}_t, v)$ has a *non-empty core*[6].

Theorem 2. *The proposed coalitional game $(\mathcal{N}_t, v)$ always possesses a non-empty core.*

Proof. To prove the existence of a non-empty core, we need to consider two factors [19]: 1) a special class of coalitional game, which is a convex game, always possesses a non-empty core; and 2) a coalitional game $(\mathcal{N}_t, v)$ is convex if its value function v is supermodular. That is, for any $n \in \mathcal{N}_t$ and for every coalition $\mathcal{S}_1 \subset \mathcal{S}_2 \subset \mathcal{N}_t$ with $\mathcal{S}_1 \cap \{n\} = \mathcal{S}_2 \cap \{n\} = \emptyset$, we have

$$v(\mathcal{S}_1 \cup \{n\}) - v(\mathcal{S}_1) \leq v(\mathcal{S}_2 \cup \{n\}) - v(\mathcal{S}_2). \tag{5}$$

Hence, demonstrating that $v(\mathcal{S})$ is supermodular will consequently prove Theorem 2.

Now, irrespective of the values of c_p, c_s and E_h, it is important to note that as the number of nanogrids in a coalition $\mathcal{S}$ increases, the amount of aggregate energy that the nanogrids can provide to the SFC will also increase (according to (1)). As a result, from (2) and (4), the value of the coalition $v(\mathcal{S})$ will increase accordingly. To this end, let us assume that there exist two coalitions $\mathcal{S}_1$, $\mathcal{S}_2 \subset \mathcal{N}_t$ and a nanogrid n in the proposed game $(\mathcal{N}_t, v)$ such that $\mathcal{S}_1 \subset \mathcal{S}_2$ and $\mathcal{S}_1 \cap \{n\} = \mathcal{S}_2 \cap \{n\} = \emptyset$. Hence, clearly

$$(\mathcal{S}_1 \cup \{n\}) \subset (\mathcal{S}_2 \cup \{n\}). \tag{6}$$

In this context, it is obvious from the above discussion that for the proposed game $(\mathcal{N}_t, v)$, we have

$$v(\mathcal{S}_1) \leq v(\mathcal{S}_2), \tag{7}$$

and

$$v(\mathcal{S}_1 \cup \{n\}) \leq v(\mathcal{S}_2 \cup \{n\}). \tag{8}$$

Then, from (7) and (8), it is clear that $v(\mathcal{S}_1 \cup \{n\}) - v(\mathcal{S}_1) \leq v(\mathcal{S}_2 \cup \{n\}) - v(\mathcal{S}_2)$, and therefore $v(\mathcal{S})$ is supermodular. Thus, Theorem 2 is proved. □

Therefore, a subsequent conclusion that can be drawn from Theorem 1 is that the proposed game has a stable coalition.

C. Distribution of Coalition Payoff

Although it is demonstrated in Theorem 1 that a coalition may result in increased profits for the whole group of players and Theorem 2 guarantees the existence of a grand coalition in $(\mathcal{N}_t, v)$, these theorems do not clearly show how the cultivated rewards from the coalition should be shared among the participants. In this context, we note that various fairness criteria exist in the literature such as Shapley value, nucleolus, egalitarian, equal distribution and proportional fair payoff that could be used for the division of rewards of the coalition between the players [16]. Some of these techniques such as Shapley value and nucleolus require rigorous analysis to find the allocation within a given context. Here, considering the space limitations and for ease of understanding, we propose to adopt a simple payoff allocation technique, which is a *proportional payoff division* scheme. According to this scheme, the reward $v(\mathcal{S})$ will be distributed to coalition members *according to their contributions* to the aggregated energy that the coalition supplies to the SFC. Hence, the reward ϕ_n that each nanogrid $n \in \mathcal{S} \subseteq \mathcal{N}_t$ receives from the reward of coalition $v(\mathcal{S})$ is

$$\phi_n = v(\mathcal{S}) \frac{e_n - k_n}{E_S}, \tag{9}$$

where E_S is defined in (1), and

$$k_n = \min\left(\frac{\left[\sum_{n \in \mathcal{S}} e_n - E_h\right]^+}{N_S}, e_n\right), \tag{10}$$

where $[a]^+ = \max(0, a)$, is the burden of excess supply that needs to be borne by each of the participating nanogrids in the game if $\sum_n e_n > E_h$.

[5] Imputations are payoff allocations with the properties of group rationality and individual rationality [16].

[6] Whereas an empty core refers to the fact that there exists no reward allocation that can make the grand coalition stable.

TABLE I: Demonstration of reward in terms of net payment for each nanogrid of the grand coalition compared to the noncooperative case.

Nanogrid's index (n)	Payment from coalition (cents)	Non-cooperative payment (cents)	% Improvement
1	27.45	20.15	36.23
2	50.98	37.42	36.23
3	26.80	19.67	36.23
4	27.9	20.48	36.23
5	44.92	32.97	36.23
6	28.86	21.18	36.23
7	56.13	41.20	36.23
8	56.11	41.18	36.23
9	52.51	38.54	36.23
10	30.86	22.65	36.23
11	50.14	36.80	36.23
12	44.81	32.89	36.23
13	61.98	45.49	36.23
14	49.73	36.50	36.23
15	55.46	40.70	36.23
16	42.36	31.09	36.23
17	41.55	30.49	36.23
18	56.40	41.40	36.23
19	25.35	20.81	36.23
20	30.23	22.19	36.23

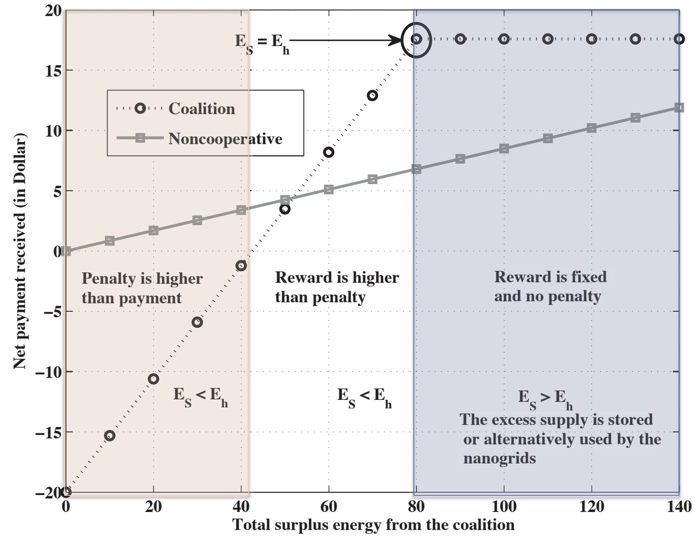

Fig. 3: Demonstration of the change of reward to a coalition (compared to the noncooperative case) as the total surplus from the coalition varies for a fixed contracted energy.

IV. Numerical Case Study

For numerical case studies, we consider that there are 20 nanogrids in a smart community, each of which has some energy surplus to sell to the SFC. For the time slot of interest, the typical energy generation capacity of each nanogrid is chosen to be 15 kWh, which is within the reasonable limit for any nanogrid system [10]. Based on the fact that the energy usage pattern of different nanogrids is random, the essential load of each nanogrid is chosen randomly and uniformly from 11 to 13 kWh. Thus, the available surplus energy of each nanogrid varies randomly in the range $[2, 4]$ kWh. It is assumed that the required energy by the SFC, which it contracted to receive from the nanogrids, is 50 kWh, and the purchase price of the grid and the SFC are assumed to be 8.75 and 20 cents per unit of energy respectively [6]. Note that the total required amount is chosen such that[7] $\sum_{n\in\mathcal{N}_t} e_n \leq E_h$. The penalty price is assumed to be 35 cents/kWh[8].

In Table I, we show the reward that each nanogrid receives from the coalition according to (9). As can be seen from the table, all nanogrids have the same improvement, which is 36.23%, when compared to the noncooperative case. The improvement is mainly due to the fact that when a nanogrid acts noncooperatively it needs to sell its surplus to the grid instead to the SFC at a considerably lower price. As a result, despite a higher penalty, the nanogrids in a coalition receive a noticeably higher payment compared to the noncooperative case. It is important to note that a nanogrid in both noncooperative and proposed cases receives rewards according to the amount of energy that it sells to the respective buyer, i.e., the payoff is proportional to a nanogrid's contribution. Therefore, for similar penalty and payment prices of the proposed scheme, the difference between payoffs that each player would experience from trading its surplus with the grid and the SFC would be the same for each player. Thus, similar improvement of 36.23% in terms of net payment is observed for the considered study in Table I.

However, it is not guaranteed that the coalition will always be the best choice for energy trading. For instance, if the total surplus from the nanogrids is significantly low, forming a coalition could be detrimental for the participating nanogrids due to the presence of a high penalty. We consider this scenario in Fig. 3. In this figure, we assume the contracted energy to be 80 kWh and vary the total surplus from the coalition between 0 and 140 kWh. This variation in surplus could be a result of intermittency of weather or change in available generation at different times of a day, e.g., for solar. According to Fig. 3, when there is either no surplus or the surplus is significantly lower than the contracted energy, the penalty is very high and thus the reward for the coalition is negative. Thus, a coalition is detrimental in this situation and nanogrids are better off acting noncooperatively. Examples of such scenario can be the early morning or late afternoon time for nanogrids equipped with solar panels. Please note that during these periods of time, the generation of solar energy is very limited due to lower solar irradiance. Hence, it is reasonable to assume that the surplus available to each nanogird at such times could be also very small, which may motivate them to act noncooperatively due to the fact explained in Fig. 3.

However, as the total surplus becomes close to the contract, the reward of the coalition eventually increases and becomes more beneficial for nanogrids within the coalition. Then, once the total surplus becomes equal to or greater than the contracted energy, the reward of the coalition becomes constant and further increase is surplus does not change the reward at all. This is due to the fact that the coalition of nanogrids cannot

[7] Which ensures that, depending on the availability, the SFC may also penalize the nanogrids.

[8] The proposed technique is also valid for other pricing options as well.

sell more than the contracted energy, and hence the rewards from selling to the SFC do not change. The excess energy of each nanogrid, i.e., the burden from (10), can either be stored or used for other purposes[9]. Thus, the decision of a nanogrid to join a coalition can be affected by the total surplus of the coalition and the amount of energy that has been contracted between the aggregator and the SFC.

From Fig. 3 and above discussion, it is important to note that cooperation could be sometime detrimental to the nanogrids depending on the surplus available to them, particularly if the penalty price is considerably higher than the selling price as in the considered case[10]. One way to address this situation is to introduce coalition formation game to design the energy management problem in which the nanogirds may choose whether or not to form a coalition with other nanogrids in order to sell energy to the SFC. Nevertheless, this issue is beyond the scope of this paper.

V. Conclusion

This paper has proposed a coalitional game theoretic approach for energy management in a smart community with nanogrid systems. It has been shown that nanogrids can be considerably rewarded by supplying their surpluses, if there are any, to a shared facility controller if they work together in a coalition. To do so, a suitable system model has been designed to capture the energy trading between nanogrids and the SFC, and a coalitional game has been formulated that is applicable for the considered system model. The existence of a stable grand coalition, i.e., a non-empty core, has been proven, which guarantees that coalition formation is the best option for the nanogrids, in terms of achieved payment, if they want to trade their surplus energy. An allocation technique has been proposed to divide the reward of a coalition between the coalition members based on the contribution of each nanogrid to the total supply amount of the coalition. Numerical examples have explored the rewards accruing to a coalition compared to those for the noncooperative case.

One potential extension of the proposed work is to investigate how the coalition can be made beneficial to the nanogrid once the difference between the contracted energy and the available supply is significant. One possible approach could be to adopt a coalition formation game, in which the nanogrids can merge into or split from a coalition depending on the possible reward to the coalition from energy trading. Further, application of well known fair allocation schemes such as egalitarian fair, Shapley value and nucleolus need to be explored for the considered scenario.

[9]For instance, additional reward can be obtained by the users if they sell to the grid, which is not shown in Fig. 3.

[10]We intentionally keep the penalty price considerably higher than the selling price to explain this scenario.

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