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A Hierarchical Peer-to-Peer Energy Trading in Community Microgrid Distribution Systems

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***Abstract*—The concept of community microgrid distribution system presents a new framework for operation and management of the future distribution systems with various operating constraints and a business model. It aims at extending the benefits of traditional microgrid by sharing the energy resources among multiple partners. Peer-to-peer (P2P) energy trading model seems to be one of the suitable models for energy trading in future community microgrid distribution system. This paper proposes a hierarchical peer-to-peer (HP2P) energy trading framework for future community microgrid distribution networks to provide efficient energy trading in the microgrid energy market. The proposed HP2P framework is applied to a sample community microgrid distribution system. It results in cost saving and hence its effectiveness is verified by simulation study.**

***Index Terms*—Community distribution system, energy sharing, hierarchical peer-to-peer energy trading, internal pricing**

I. Introduction

Microgrid has a major role in the existing power system and it is vital player in the transformation of the existing power grid to a sophisticated smart grid in the future [1]. A microgrid can be formed by connecting several nanogrids. A nanogrid can be defined as a low voltage power distribution system for a single house/group of small residential houses or small residential buildings, with an ability to connect/disconnect to/from other power entities via a gateway [2]. The financial incentives, reduction in electricity bills, and environmental benefits motivate the house owners to install renewable based distributed generation and energy storage at their residential buildings [3].

Several nanogrids serving in geographically closed locations can be combined to form a community microgrid. Fig. 1 shows the detail structure of community microgrid. Similarly, several geographically closed community microgrids can be connected to form a microgrid network which is normally known as a multi-microgrid system. The network of different community microgrid establishes a community microgrid distribution system [4]. The basic structure of future community microgrid distribution system is shown in Fig. 2.

From Fig. 1 and Fig. 2, three levels of hierarchy can be observed in the future community microgrid distribution system. The residential nanogrids are at the lowest level of the hierarchy. The community microgrids are in the middle level and the utility grid is at the top-level of hierarchy [4].

A community microgrid distribution system integrates the multiple owners distributed energy resources and critical loads,

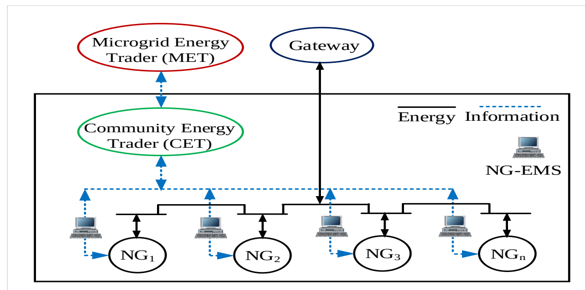

Fig. 1. Structure of community microgrid consisting of several nanogrids

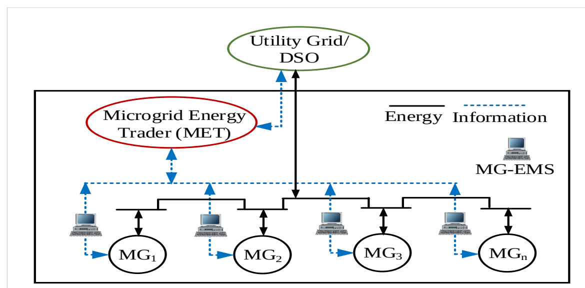

Fig. 2. Structure of community microgrid distribution system

and presents a new basis for future distribution grid with various operating constraints and a business model. It aims at extending the benefits of the traditional microgrid by sharing the energy resources among multiple partners. In addition, the on-site use of energy generated from local distributed energy resources is more attractive than feeding the utility grid. Thus, a proper energy exchange model is necessary to manage the exchange of local energy among multiple entities.

Peer-to-peer (P2P) energy trading model seems to be one of the suitable models for energy trading in the future community microgrid distribution system. P2P energy trading is the flexible trading between the peers, where the excess energy from many small-scale distributed energy resources (DERs) is traded locally [5].

In [6], P2P energy trading among smart households is proposed to determine the optimal microgrid energy and price for P2P trading. A customer-to-customer business was introduced based on the architecture model for P2P energy trading in [7]. The results show that P2P energy trading is able to balance local generation and demand.It has the potential to support a large amount of renewable penetration in the power grid. An efficient and privacy-preserving P2P energy exchange scheme in a smart grid environment is presented in [8] with the novel optimization approach to increase efficient energy transfer without information leakage. In [9], a new algorithm for automating electricity trading by prosumers in the P2P electricity market has been proposed. A framework for performance evaluation using several indices is proposed in [10] to assess the economic performance of P2P energy sharing models.

The main contribution in this paper is to implement the P2P energy trading model for hierarchical community microgrid network to promote regional energy trading. A hierarchical P2P energy trading model becomes suitable for managing large-scale energy trading in the future community microgrid distribution system as there exists a hierarchical nature.

The remainder of the paper is organized as follows: The concept of hierarchical P2P energy trading with the details of energy pricing for the internal energy trading is discussed in section II followed by simulation results in section III, and finally, some concluding remarks are drawn in section IV.

II. Hierarchical P2P energy trading model

As a three-level hierarchy exists in the proposed framework of the future distribution systems, P2P energy trading can be implemented in the three levels below:

1) P2P among the nanogrids within the community microgrid.
2) P2P among the community microgrids in a multi-microgrid system.
3) P2P among the various multi-microgrid system

After implementation of P2P energy trading in each level of the future distribution system, there will be a P2P market across all levels. The main aim of this hierarchical P2P trading model is to keep energy and power balance in each level from the lower level to the higher level. The hierarchical P2P energy trading model helps to reduce the loss in energy delivery. It also reduces the dependency of the community microgrid on the main grid to balance the discrepancy between supply and demand in the microgrid by sharing energy with other microgrids in the community. The availability of the local energy resources in the first level is the basis for the P2P energy trading in the whole hierarchical future distribution system.

There are a few factors which determine the suitability of the P2P energy sharing model in the nanogrid community. First is the configuration of the smart prosumers nanogrid in the community. Second is the organizational structure of the smart nanogrid community to facilitate the energy sharing. The most important factor is the pricing mechanism for internal energy trading in the community. The superiority of the P2P energy sharing model in the nanogrid community can be justified over the direct trading with the upstream grid (peer-to-grid) only if the P2P energy sharing model is economically beneficial. The internal pricing mechanism determines the overall economic benefit from the P2P energy sharing model.

A. Organizational Structure for P2P Energy trading

As shown in Fig.1, each nanogrid in a community microgrid has a local energy management system called nanogrid energy management system (NG-EMS). An entity called community energy trader (CET) is proposed to facilitate the energy sharing/trading activities in the community microgrid. The CET can be either an operator of the community microgrid or an independent third-party organization that focuses on the energy business. The CET is responsible for maintaining power balance and payment balance in the community microgrid in which energy sharing takes place. In the same manner, an entity called microgrid energy trader (MET) is responsible for facilitating energy sharing among several community microgrids in the community microgrid distribution system as shown in Fig. 2. The MET works in coordination with both the upstream utility grid and the CET whereas the CET communicates with the MET and the nanogrids in the community microgrid.

B. Energy Pricing for Internal Energy Trading

All nanogrids comprise of different types of loads and DERs. The demand profile of a nanogrid before participating in the energy sharing activity can be defined as:

$$D_i = [D_i^1, D_i^2, D_i^3, ..., D_i^T] \qquad i \in [1, 2, 3, ..., n] \tag{1}$$

where i/n is the index/total number of nanogrids in the energy sharing community, and T is the total number of intervals considered.

The generation from DERs in each nanogrid during the same period can be defined as:

$$G_i = [G_i^1, G_i^2, G_i^3, ..., G_i^T] \qquad i \in [1, 2, 3, ..., n] \tag{2}$$

The amount of power consumed within the nanogrid i at time interval t is given by

$$S_i^t = min(D_i^t, G_i^t) \tag{3}$$

The amount of power to import ($P_{im,i}^t$) and amount of power to export ($P_{ex,i}^t$) for nanogrid i at time interval t are given by

$$P_{im,i}^t = D_i^t - S_i^t \tag{4}$$

$$P_{ex,i}^t = G_i^t - S_i^t \tag{5}$$

As there is no influential entity that affects the internal prices in the energy sharing zone, the supply to demand ratio (SDR) is the foundation that determines the internal prices, which can be co-decided by all prosumers participating in the energy sharing activities [11].

If TPD^t and TPS^t are the total power demand and total power supply at time slot t within the energy sharing zone respectively, then the SDR of the zone at time slot t is defined as:

$$SDR^t = \frac{TPS^t}{TPD^t} \tag{6}$$

Considering the fluctuations of DERs generation and prosumers demand, the SDR is also not constant at different time slots.

The internal pricing for P2P energy trading in the hierarchical community microgrid distribution system can be described by the following three stages:

- *Stage 1:*

At the first stage, the NG-EMS in each nanogrid in the community microgrid determines whether there is an excess or a shortage of power in the corresponding nanogrid for each time frame by calculating the net power (NP) as follows:

$$NP_i^t = D_i^t - G_i^t, \qquad t \in [1, 2, 3, ..., T] \tag{7}$$

Since there is a communication channel between each NG-EMS and CET, CET receives information about the net power of each nanogrid. The CET calculates the total power available (TPA) for selling and the total power needed to buy (TPB) in each hour as follows:

$$TPA^t = -\sum_{i=1}^{n} NP_i^t, \qquad NP_i^t < 0 \tag{8}$$

$$TPB^t = \sum_{i=1}^{n} NP_i^t, \qquad NP_i^t \geq 0 \tag{9}$$

Then, the CET calculates the difference in power (DP) between the available and demanded power in each hour as:

$$DP^t = TPB^t - TPA^t \tag{10}$$

After calculating the DP, each CET sends this information to the MET which manages the energy trading in community microgrid level.

- *Stage 2:*

When MET receives information about DP, it calculates TPA and TPB for the corresponding multi-microgrid system as follows:

$$TPA^t = -\sum_{j=1}^{m} DP_j^t, \qquad DP_j^t < 0 \tag{11}$$

$$TPB^t = \sum_{j=1}^{m} DP_j^t, \qquad DP_j^t \geq 0 \tag{12}$$

where j/m is the index/total number of community microgrid in the energy sharing community or multi-microgrid system.

The SDR of the multi-microgrid system at time slot t is defined as:

$$SDR^t = \frac{TPA^t}{TPB^t} \tag{13}$$

The MET purchases and sells power from/to utility grid at the unit price of ρ^{buy} and ρ^{sell} respectively. The community microgrids in a multi-microgrid community purchase and sell power from/to the MET at the unit price of π_{buy} and π_{sell} respectively.

The internal price set (IPS) can be defined as:

$$\pi = (\pi_{buy}^1, \pi_{buy}^2, ..., \pi_{buy}^T; \pi_{sell}^1, \pi_{sell}^2, ..., \pi_{sell}^T) \tag{14}$$

For the economic benefit of P2P trading in terms of the overall cost reduction of the community microgrid over the direct trading with the grid, the following condition should be always satisfied.

$$\rho^{sell} \leq \pi_{sell} \leq \pi_{buy} \leq \rho^{buy} \tag{15}$$

where π_{sell} and π_{buy} represent the selling, and buying prices for energy trading between the microgrids in the multi-microgrid system.

Since, MET is in charge of energy trading among the microgrids, it calculates the prices for energy trading in the multi-microgrid system using equations (16) and (17). The following factors are considered while calculating the prices for internal energy trading: i. all-time economic balance in the microgrid community; ii. the inversely-proportional relationship between SDR and selling price of the commodity [12]; and iii. grid energy price as boundary constraints.

$$\pi_{sell}^t = \begin{cases} \frac{\rho^{sell}.\rho^{buy}}{(\rho^{buy}-\rho^{sell}).SDR^t+\rho^{sell}} & 0 \leq SDR^t \leq 1 \\ \rho^{sell} & SDR^t > 1 \end{cases} \tag{16}$$

$$\pi_{buy}^t = \begin{cases} \pi_{sell}^t.SDR^t + \rho^{buy}.(1 - SDR^t) & 0 \leq SDR^t \leq 1 \\ \rho^{sell} & SDR^t > 1 \end{cases} \tag{17}$$

- *Stage 3:*

After the MET calculates the price for energy trading among the microgrids in a multi-microgrid community, it sends an IPS to each CET in the corresponding multi-microgrid community and CET use this IPS as the baseline for calculating the energy price for internal energy trading in the corresponding community microgrid. Each CET has information about TPA and TBP in the corresponding community microgrid from stage 1 as given by equations (5) and (6) respectively. The CET of the community calculates SDR as follows:

$$SDR_m^t = \frac{TPA_m^t}{TPB_m^t} \tag{18}$$

For the economic benefit of P2P trading within the community, the following condition should be satisfied.

$$\pi_{sell} \leq \sigma_{sell} \leq \sigma_{buy} \leq \pi_{buy} \tag{19}$$

where σ_{sell} and σ_{buy} represent the selling, and buying price for energy trading between the nanogrids in the community.

Then energy price for inter community P2P trading is calculated as follows:

$$\sigma_{m,sell}^t = \begin{cases} \frac{\pi_{sell}^t.\pi_{buy}^t}{(\pi_{buy}^t-\pi_{sell}^t).SDR_m^t+\pi_{sell}^t} & 0 \leq SDR_m^t \leq 1 \\ \pi_{sell}^t & SDR^t > 1 \end{cases} \tag{20}$$

$$\sigma_{m,buy}^t = \begin{cases} \pi_{m,sell}^t.SDR_m^t + \pi_{buy}^t.(1 - SDR_m^t) & 0 \leq SDR_m^t \leq 1 \\ \pi_{sell}^t & SDR_m^t > 1 \end{cases} \tag{21}$$

The overall cost of the individual nanogrid in different trading schemes is calculated as follows:

- For peer-to-grid trading

$$C_{p2g}^i = \sum_{t=1}^{T}(P_{im,i}^t * \Delta t * \rho^{buy}) - \sum_{t=1}^{T} P_{ex,i}^t * \Delta t * \rho^{sell}) \tag{22}$$

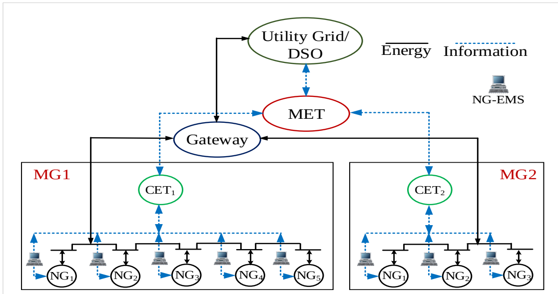

Fig. 3. Community microgrid distribution system for P2P energy trading

- For single-stage peer-to-peer trading

$$C^i_{p2p} = \sum_{t=1}^{T}(P^t_{im,i} * \Delta t * \pi^t_{buy}) - \sum_{t=1}^{T}(P^t_{ex,i} * \Delta t * \pi^t_{sell}) \tag{23}$$

- For hierarchical peer-to-peer trading

$$C^i_{hp2p} = \sum_{t=1}^{T}(P^t_{im,i} * \Delta t * \sigma^t_{m,buy}) - \sum_{t=1}^{T}(P^t_{ex,i} * \Delta t * \sigma^t_{m,sell}) \tag{24}$$

After calculating the internal prices at both levels of the P2P market on day ahead basis, the power and financial transactions are settled down in real time considering the uncertainty, which is out of the scope of this paper.

III. SIMULATION RESULTS

A community microgrid distribution system considered for studying the proposed scheme consists of two different community microgrids MG_1 and MG_2 as shown in Fig. 3. The MG_1 has five different nanogrids and MG_2 has three nanogrids.

Solar PV system is installed in each of the nanogrids as local generation, which makes the nanogrids as prosumer nanogrids. The generation and load profiles for nanogrids in MG_1 and MG_2 are as shown in Fig. 4, Fig. 5, Fig. 6 and Fig. 7.

Based on the actual electricity price of Singapore, the buying price of energy from the grid (ρ^{buy}) is taken as 20.3 cents/kWh and the selling price to the grid (ρ^{sell}) is taken as 8 cents/kWh.

The hourly energy price for P2P energy trading within the community microgrid MG_1 and MG_2 if a single-stage P2P trading scheme is applied is shown in Fig. 8 and Fig. 9 respectively.

Fig. 10. shows the hourly energy price for P2P energy trading within the multi-microgrid system (between the microgrids) if hierarchical P2P trading scheme is applied. The hourly energy price for P2P energy trading within the community microgrid MG_1 and MG_2 if a hierarchical P2P trading scheme is applied is shown in Fig. 11 and Fig. 12 respectively. The price graphs are spiky at some hours because of the change in the role of the community microgrids from seller to buyer or vice-versa.

Table I and II show the overall cost of each nanogrid in the community and the overall cost of community microgrid for time horizon of 24 hours in three different cases namely: direct

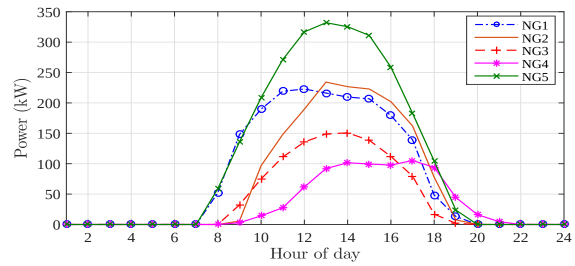

Fig. 4. PV generation profiles of nanogrids in MG_1

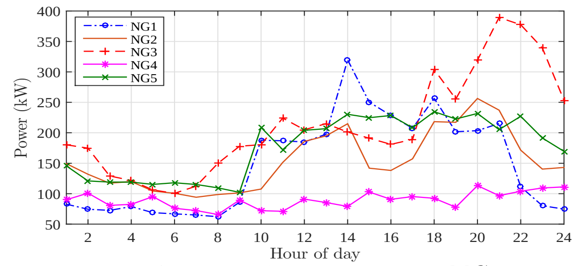

Fig. 5. Load profiles of nanogrids in MG_1

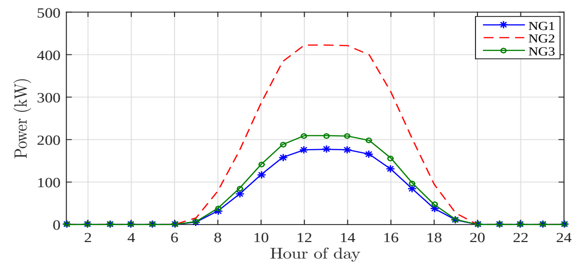

Fig. 6. PV generation profiles of nanogrids in MG_2

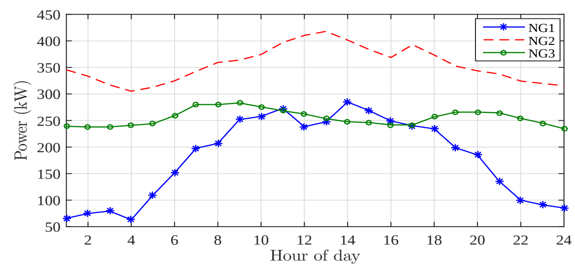

Fig. 7. Load profiles of nanogrids in MG_2

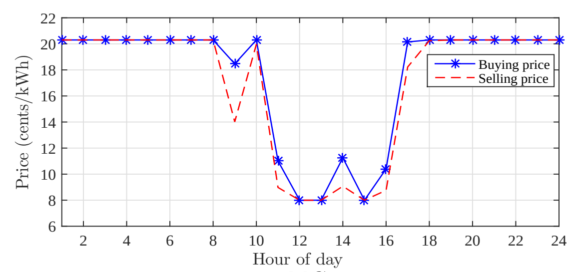

Fig. 8. Internal energy price in MG_1 with single-stage P2P trading

trading with utility grid (peer-to-grid), P2P energy trading within the community only (single-level P2P trading) and hierarchical P2P (two-level P2P trading)

The total cost of each nanogrid in both microgrids is highest without P2P energy trading scheme (in peer-to-grid trading). When a single-level P2P scheme is adopted (inter-microgrid P2P scheme), the overall cost is reduced for all nanogrids in MG_1 but remains same for MG_2 because in MG_2, none of the nanogrid has excess energy to sell in the P2P market and

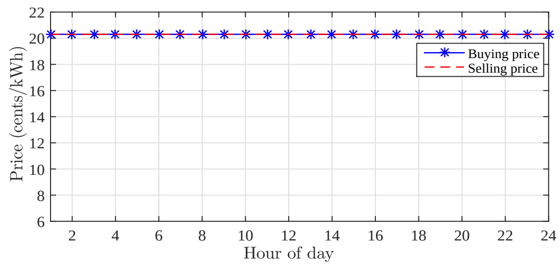

Fig. 9. Internal energy price in MG_2 with single-stage P2P trading

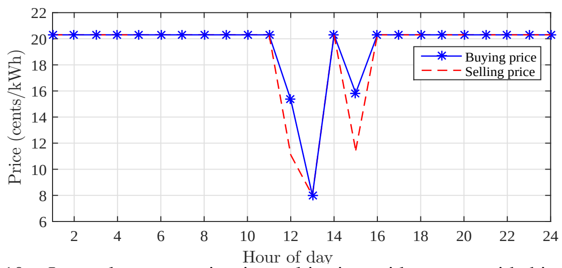

Fig. 10. Internal energy price in multi-microgrid system with hierarchical P2P trading

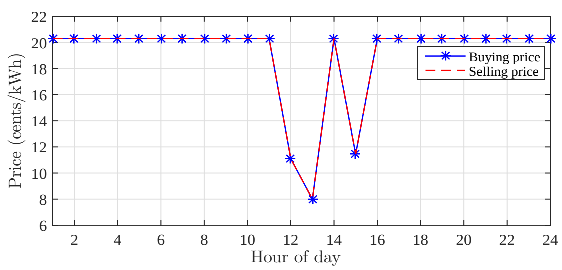

Fig. 11. Internal energy price in MG_1 with hierarchical P2P trading

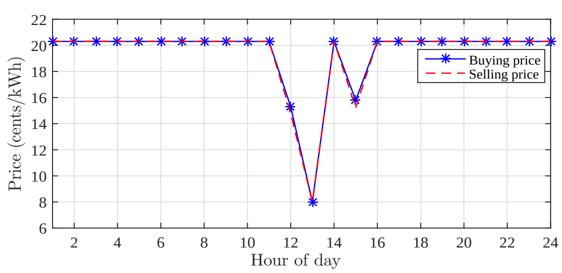

Fig. 12. Internal energy price in MG_2 with hierarchical P2P trading

must buy all the shortage energy from the upstream grid. The overall cost of nanogrids NG_2 and NG_5 in MG_1 is lowest in case of hierarchical P2P energy trading scheme but the cost of NG_1, NG_3, and NG_4 is higher than that of the single level P2P scheme but still less than that without the P2P scheme. This is because NG_1, NG_3, and NG_4 has nil or less excess power to sell in P2P market, so it cannot influence the internal trading price. But, overall cost of whole MG_1 is lowest in HP2P. In MG_2, the total cost for all the nanogrids is reduced when hierarchical P2P scheme is adopted because there is excess energy in MG_1 in a multi-microgrid community. So, MG_2 can buy energy from MG_1 at a price cheaper than the grid buying price. Hence, the cost is reduced. The HP2P scheme results in larger cost reduction than single stage P2P scheme for energy trading. The overall cost of each microgrid is same as given by the methods in [13].

TABLE I
OVERALL COST OF NANOGRIDS IN MG_1

Trading Scheme	Overall cost (SGD)					
	NG_1	NG_2	NG_3	NG_4	NG_5	MG_1
Peer-to-grid trading	367.69	455.43	827.91	286.69	416.91	2354.63
Single stage P2P trading	343.13	452.25	779.32	275.56	412.64	2262.90
Hierarchical P2P trading	350.81	442.59	808.03	278.69	378.70	2258.82

TABLE II
OVERALL COST OF NANOGRIDS IN MG_2

Trading Scheme	Overall cost (SGD)			
	NG_1	NG_2	NG_3	MG_2
Peer-to-grid trading	831.82	1635	1197.10	3663.92
Single stage P2P trading	831.82	1635	1197.10	3663.92
Hierarchical P2P trading	581.88	1073.70	908.91	2564.49

IV. Conclusion

In this paper, we proposed a HP2P energy trading framework for the future community microgrid distribution networks to provide efficient energy trading. The effectiveness of the proposed method was verified by applying it into small scale community distribution system. It is found that the HP2P scheme results in a larger cost reduction than a single-stage P2P scheme for energy trading and peer-to-grid trading scheme. In the future, this work can be extended by considering load control (demand response) and energy storage.

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