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Allocating Benefits from the ASEAN Power Grid

아세안 전력 그리드 이익 배분에 관한 연구

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Abstract

The ASEAN Power Grid (APG) is a program aiming for an integrated Southeast Asian power grid system. The fact that the APG is profitable to member countries has been well-established by several studies. In this paper we focus on the allocation and stability of the program, by applying concepts developed in the cooperative game theory and the graph theory. The Myerson value shows that Laos and Thailand are key countries, among the Greatest Mekong Subregion (GMS), where Cambodia, Laos, Myanmar, Thailand, and Vietnam are located. We check the stability of the program through the core and the pairwise stability. While the core of grand coalition is empty, the current network is pairwise stable.

Keywords : ASEAN Power Grid, Cooperative Game, Myerson value, Core, Pairwise stability

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1 Introduction

The ASEAN Power Grid (APG) is a program established in 1997 by the ASEAN Heads of States and Governments under the ASEAN vision 2020. According to ADB (2013), there are four stages of regional power interconnection: bilateral trade with long-term Power Purchases Agreements, grid-to-grid power trading between any pairs of member countries, development of transmission lines dedicated to free power trading, and finally, fully competitive regional market with multiple sellers and buyers from each country. The APG program begins with the first stage and aims for the final stage, a totally integrated Southeast Asian power grid system.

A main objective of the program is to promote efficient and sustainable operation of power systems. To do it, the APG tries to optimize the use of energy resources in the region. The cooperation and good relationship among the member countries are included in the objectives as well.

In 1999, the Head of ASEAN Power Utilities and Authorities (HAPUA) was assigned to implement the APG based on ASEAN Interconnection Master Plan Study (AIMS). There are 16 projects, one of them was added by AIMS-II. Transmission lines under the projects connect 10 ASEAN countries, which is Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam. Some lines have been operated and the rest are under construction or planned for the future.

Some literature indicates that the APG has profitability and potential to achieve the objectives mentioned above. Li and Chang (2014) show the

APG+ program, which includes Yunnan province of China and India, is a commercially and financially viable plan. They also propose the optimal plan for maximizing benefits in the region. Watcharejyothin and Shrestha (2009) analyze the effects of power trade between Laos and Thailand. They found both countries get benefit from the power trade, as Laos is a net energy exporter and Thailand is a net energy importer. Numerous of country reports also expect positive effects from the APG.

Even though literature illustrates the existence of benefit from the program, it hardly tells us how to allocate benefit and whether the program is sustainable or not. We try to answer these two important questions by applying the concepts developed in the cooperative game theory and the graph theory.

To answer the first part, we reviewed a case of international gas trade from Russia to Europe. Hubert and Ikonnikova (2011) and Nagayama and Horita (2014) study the cost sharing problem in the gas trade and show bargaining powers among the participating countries by using the Shapley value. Similarly, we will show the marginal contribution of each country by using the Myerson value. It can give an implication on how to allocate benefit or which country plays relatively more important role in this region.

The second question is about the stability of the program. Since sustainable operation and cooperation among the member countries are included in the objectives of the program, it is meaningful analysis whether the current program is stable. We test the stability by two concepts. One is the core and the other is the pairwise stability. The core is developed in the cooperative game theory and test the stability of cooperation, while the pairwise stability is developed in the graph theory and more focus on the stability of network structure.

In the following of the paper, section 2 introduces the theoretic model including a cost function and a value function which are key elements to apply the cooperative game theory. We will also introduce the definition of the Myerson value, the Core, and the pairwise stability. Section 3 describes data information which we use in analysis. Section 4 presents and analyzes results from the model and the data. Finally, section 5 concludes discussion.

2 Model

2.1 Basic Setting

Let $N = \{1, \ldots, n\}$ denote a set of countries and $L = \{1, 2, \ldots, l\}$ be a set of resources for power generation. A power generation capacity matrix is denoted by $\Omega \in \mathbb{R}_+^{|L| \times |N|}$, where ith column vector, Ω_i, shows country i's existing power generation capacity. To adjust the load structure of countries, we distinguish peak demand and non-peak demand. Let $d = (d^P, d^N) \in \mathbb{R}_+^{|N| \times 2}$ denote peak and non-peak demands for each country. Similarly, the durations of peak and non-peak demands can be denoted by $h = (h^P, h^N) \in \mathbb{R}_+^{|N| \times 2}$. A summation of durations is equal to 8760 hours, a year in hour. Each resource has different operating cost. Let $c \in \mathbb{R}_+^{|L|}$ indicate operating cost for generating a unit MW by using each resource. We assume that $c_1 < c_2 < \cdots < c_l$.

A network $g = \{\{i, j\} : \{i, j\} \subset N\}$ is a collection of unordered pairs in N. We denote the elements of g simply as ij, instead of $\{i, j\}$. Let $G(N)$ be the set of all undirected networks on N. A path in a network g between i and j is a sequence of links $i_1 i_2, i_2 i_3, \ldots, i_{H-1} i_H$ such that $i_h i_{h+1} \in g$ for each $h \in \{1, \ldots, H-1\}$, with $i_1 = i$ and $i_H = j$. Countries i and j are connected in g if there exists a path in g between i and j. Given $S \subset N$, a subnetwork consists of countries in the subset S, denoted as $g|_S = \{ij \in g : \{i, j\} \subset S\}$. In the APG the link ij means transmission lines. Every transmission line is an undirected link, which implies two-way trade is available. Since transmission capacities vary by transmission line, let $k = (k_{ij})_{ij \in g}$ denote an existing transmission capacity for each link $ij \in g$. When a country transmits power to another country through transmission lines, a transmission cost arises. Let $e = (\varepsilon, \varepsilon, \ldots, \varepsilon) \in \mathbb{R}_+^{|L|}$ be a transmission cost between i and j, where ε is exogenously given depending on the distance between countries. A game we are interested is consisting of nine elements which are introduced. Therefore, our game is defined by $a = (N, L, \Omega, d, h, c, g, k, e)$.

Each country chooses two variables to minimize generation cost. One is country's actual production capacity to meet her power demand. Let $P \in \mathbb{R}_+^{|L| \times |N|}$ be an actual production capacity matrix, where each column vector P_i indicates a country i's actual production capacity. We assume self-sufficiency, that is every country can generate enough power to meet her power demand, $\sum_{l \in L} p_{li} \geq d_i^P$ for each $i \in N$.

The other variable each country chooses is an actual transmission capacity. Thanks to the APG, a country reduces the generation cost by importing power from other countries who can generate power using cheaper resources. A matrix $T \in \mathbb{R}^{|L| \times_{|N|} P_2}$ indicates an actual transmission capacity of ordered pairs in N. It's column vector, $T_{ij} \in \mathbb{R}_+^{|L|}$, denotes an actual transmission capacity from i to j. $T_{ij} = T_{ji} = 0$ if i and j are not connected in a network g and an element of the vector, $(t_{l,ij})$, shows an actual transmission capacity from i to j by using resource l. An aggregate transmission capacity that country i imports is denoted as $T_i^I = \sum_{j \in N \setminus \{i\}} T_{ji} \in \mathbb{R}^{|L|}$. Similarly, $T_i^E = \sum_{j \in N \setminus \{i\}} T_{ij} \in \mathbb{R}^{|L|}$ is an aggregate transmission capacity that country i exports.

2.2 Cost Function and Value Function

The cost function is a key element to apply the cooperative game theory. The cost of a coalition is defined by considering the minimal cost of producing the same outcome, either jointly or singly, to the members of the coalition. Before we define the cost function, we divide our game a, taking account of the load structure. We assume that the peak demands are overlapped through all countries. This is a natural assumption because the ASEAN member countries face with the similar circumstance. Therefore, we divide a year into $|N|+1$ periods under the game a.

A period τ is when $(|N|-\tau+1)$ countries are still in the peak demand. For example, the period 1 is when all countries are in the peak demand. In the next period, the country who has the shortest duration of peak demand turns to the non-peak demand and other $|N|-1$ countries are still in the peak demand. Let H^τ be a set of countries who are in the peak demand at the period τ.

$$H^\tau = \{i \in N \,|\, h_i = h_i^P \text{ at the period } \tau\}$$

for $\tau \in \{1, \ldots, |N|+1\}$. Also, we define a duration of each period τ, h^τ, as below.

$$h^\tau = \begin{cases} \min\{h_i^P \,|\, i \in H^1\} & \text{if } \tau = 1 \\ \min\{h_i^P \,|\, i \in H^\tau\} - \min\{h_i^P \,|\, i \in H^{\tau-1}\} & \text{if } \tau \in \{2, \ldots, |N|\} \\ \min\{h_i^N \,|\, i \in N\} & \text{if } \tau = |N|+1 \end{cases}$$

We divide the game a into $(|N|+1)$ small games with respect to the period τ. Then each small game is denoted as $a^\tau = (N, L, \Omega, d^\tau, h^\tau, c, g, k, e)$, where

$$d_i^\tau = \begin{cases} d_i^P & \text{if } i \in H^\tau \\ d_i^N & \text{otherwise} \end{cases}$$

for $\tau \in \{1,\dots,|N|+1\}$ and $i \in \{1,\dots,n\}$. Moreover, given $S \subset N$, we define a reduced small game as $a_S^\tau = (S, L, \Omega_S, (d_i^\tau)_{i\in S}, (h_i^\tau)_{i\in S}, c, g|_S, (k_{ij})_{ij\in g|_S}, e)$ for $\tau \in \{1,\dots,|S|+1\}$.

The cost function for network g, $c : G(N) \to \mathbb{R}$, minimizes the aggregate cost of members in the coalition with respect to the network. Countries can cooperate to reduce their total generating cost only if they are connected in the subnetwork $g|_S$. Besides, as we consider the load structure, the cost of a coalition $S \subset N$ is the summation of costs of the coalition S from $|S|+1$ small games. Formally the cost of coalition S, $c(g|_S)$, is defined as

$$c(g|_S) = \sum_{\tau=1}^{|S|+1} c^\tau(g|_S) \tag{2.1}$$

where

$$c^\tau(g|_S) = \min_{(P_i)_{i\in S},(T_{ij})_{\{i,j\}\subset S}} \sum_{i\in S} h^\tau \left[P_i' \cdot c + T_i^{I'} \cdot (c+e)\right] \tag{2.2}$$

for $\tau \in \{1,2,\dots,|S|+1\}$, satisfying following four conditions.

(1) Feasibility condition

$$P_i + T_i^E \leq \Omega_i \tag{2.3}$$

for all $i \in S$.

(2) Efficiency condition

$$\sum_{l\in L} (p_{li} + t_{li}^I) = d_i^\tau \tag{2.4}$$

for $\tau \in \{1,2,\ldots,|S|+1\}$ and for all $i \in S$.

(3) Transmission condition A

$$\sum_{l \in L} t^{\tau}_{l,ij} \leq \min\{k_{i1}, k_{12}, \ldots, k_{(h-1)h}, k_{hj}\} \tag{2.5}$$

where $i1, 12, \ldots, (h-1)h, hj$ is a path between i and j.

(4) Transmission condition B

$$\sum_{\{h,k\} \subset S^{\tau}_{ij}} t^{\tau}_{hk} \cdot \mathbf{1} \leq k_{ij} \tag{2.6}$$

where $S^{\tau}_{ij} = \{\{h,k\} \subset S |$ a path between them includes a link $ij\}$ for $S \subset N$ at the period τ and $\mathbf{1} = (1,\ldots,1) \in \mathbb{R}^{|L|}$.

A feasibility condition (2.3) says for each country, the total amount of production and export is bounded by the existing power capacity. An efficiency condition (2.4) means the total amount of production and import should exactly same with the demand at the period τ. The other two conditions are related to the transmission. The first transmission condition (2.5) implies that transmission capacity should be less than the minimal capacity of transmission lines on the path. The second transmission condition (2.6) implies when more than two countries use the same link $ij \in g$ at the same period τ, the summation of capacity transmitted by each pair of countries who use the link ij should be less than the existing transmission capacity of that link, k_{ij}.

The equation (2.2) is the definition of the cost of coalition at the period

τ. We assume when countries trade, importing countries pay the generating cost that appears in the exporting countries and the transmission cost from exporting countries to themselves. Thus, in this model no profit is allowed for the exporting countries. We denote the cost of grand coalition as $c(g)$.

From the cost function, we define a cost savings or a value function, $v(g)$, as below

$$v(g) = \sum_{i \in N} c(g|_{\{i\}}) - c(g)$$

Also a cost savings of coalition, $v(g|_S)$, is

$$v(g|_S) = \sum_{i \in S} c(g|_{\{i\}}) - c(g|_S)$$

for each $S \subset N$. Therefore the cost savings of coalition implies the benefit from cooperation of members in the coalition S. This paper will focus on the value function from now on.

2.3 Allocation Rule and Core

An allocation rule is a function $Y : G \times V \to \mathbb{R}^{|N|}$ such that $\sum_{i \in N} Y_i(g, v) = v(g)$ for all v and all g. The rule allocates the value generated by a network to the countries. A well-known allocation rule is the Shapley value suggested by Shapley (1953). Although the Shapley value has a powerful implication, it needs some modification in order to apply to the cooperative game with networks. Myerson (1977) successfully defined a Shapley value-like solution concept for networks.

The Myerson value is defined as

$$Y_i^{MV}(g,v) = \sum_{S \subset N \setminus \{i\}} \left(v(g|_{S\cup\{i\}}) - v(g|_S)\right) \left(\frac{|S|!\,(n-|S|-1)!}{n!} \right) \tag{2.7}$$

where $S \subset N$.

The Myerson value allocates the average marginal contribution to each country. To be specific, a country i gets the marginal contribution when she participates in the coalition $S \in N \setminus \{i\}$. We average the marginal contribution of country i for every possible coalition S, which induces the equation (2.7). Hence, the Myerson value implies country's contribution on the APG.

One way to test the stability of the APG is to see whether the countries agree with participating in the grand coalition and taking the allocated cost savings. An allocation $y \in \mathbb{R}^{|N|}$ is in the core if

$$\sum_{i \in N} y_i = v(g) \text{ and}$$
$$\sum_{i \in S} y_i \geq v(g|_S) \text{ for all } S \subset N.$$

The first equation implies that allocation should be efficient. The second inequality implies that countries have no incentive to go out of the grand coalition. If the inequality doesn't hold, some countries get larger benefit by exiting from the grand coalition and forming their own coalition. The allocation may not be in the core. Furthermore, the core may be empty. If the core is empty, no allocation can satisfy both conditions at the same time, that is countries have a motivation to form a subcoalition instead of the grand coalition. In that case, the grand coalition is not stable.

2.4 Pairwise Stability

Another way to test the stability of the APG is to check the pairwise stability. While the core concentrates on the coalitions, the pairwise stability focuses on the network structure. Since countries take bilateral agreements at the beginning, pairwise stability is enough to check the stability of network. Before define the pairwise stability, we need an utility function first. An utility function $u_i : G(N) \to \mathbb{R}$ represents the net benefit that country i receives if a network g is in place. Formally,

$$u_i = c(g|_{\{i\}}) - c_i(g) \tag{2.8}$$

where $c_i(g)$ is country i's generation cost in the grand coalition. Since we assume no profit is allowed for exporting countries, the benefit of a net exporting country is equal to zero.

A network g is pairwise stable if

for all $ij \in g$, $u_i(g) \geq u_i(g - ij)$ and $u_j(g) \geq u_j(g - ij)$, and

for all $ij \notin g$, if $u_i(g + ij) > u_i(g)$ then $u_j(g + ij) < u_j(g)$.

The first statement implies that any two countries who are currently connected get more or equal benefit comparing the network without a link between them. If one of them gets more benefit in the absence of that link, she can delete the link without the agreement of the counterpart. The second statement says that if one country gets strictly larger benefit by adding a link with the other, then the other country gets strictly less benefit by that link. To add a link between two countries, both of them should consent to the new link. Therefore, a network is pairwise stable if no two countries both want to add a link and no country wants to delete a link.

3 Data Description

The APG has 16 identified projects through ASEAN countries. While our data is national-level, some links in the southern part are based on islands, instead of countries. Therefore, we focus on five countries located in the Greatest Mekong Subregion (GMS). Since the capacity of transmission lines is much higher in the GMS comparing to the southern part, we can analyze main effects of the APG by focusing on the GMS. Li and Chang (2015) is the main reference of data in this paper.

There are five countries in GMS, which are Cambodia, Laos, Myanmar, Thailand, and Vietnam. They have 6 transmission lines as Figure 3.1 shows. The number in the figure indicates a transmission capacity for each line.

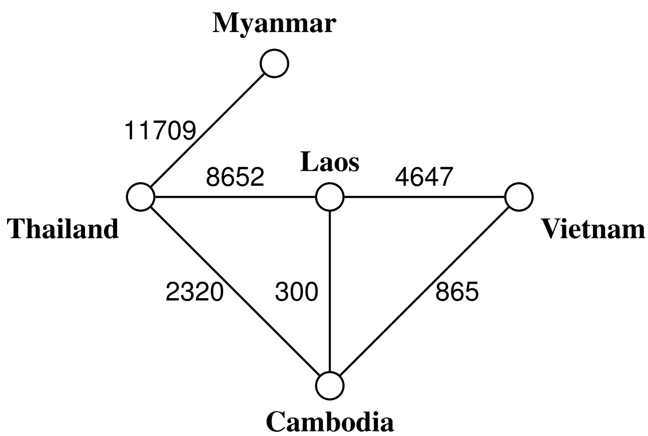

Figure 3.1 Transmission Network (Unit: MW)

Cambodia, Laos, and Thailand connect with three neighbor countries, Vietnam connects with two neighbors, and Myanmar connects with Thailand only. The line between Myanmar and Thailand has the largest transmission capacity, while the line connecting Cambodia and Laos has the smallest transmission capacity which is 300 MW.

The existing power generation capacity of countries is as below table.

	Cambodia	Laos	Myanmar	Thailand	Vietnam
Hydro	225	2,920	2,660	3,488	13,509
Small Hydro	1.9	8	40	128	75
Wind	0	0	0	1	8
Solar PV	0	0	0	10	0
Biomass	7	0	0	1300	0
Geothermal	0	0	0	1	0
Coal	13	0	120	6,599	4,930
Natural Gas	0	0	715	41,879	7,446
Diesel	321	50	0	523	1,041

Table 1 Existing power generation capacity (Base year 2012, Unit: MW)

Thailand has the largest power generation capacity, especially on natural gas. Vietnam has the largest power generation capacity related to hydro. In both Laos and Myanmar, the main resource to generate the power is hydro. Cambodia has the smallest power generation capacity and a proportion of diesel is relatively higher than other countries.

The next table shows an operation cost of each resource to produce a unit MW of power. Due to the consideration of abundance in hydropower re-

Resource	Cost	Resource	Cost
Hydro*	6.24	Geothermal	25
Small Hydro	7.13	Coal**	31.86
Wind	15.1	Natural Gas	46.87
Solar PV	17.6	Diesel	229.75
Biomass	18		

Table 2 Operation cost (Unit: USD/MWh)

sources, Cambodia, Laos, and Myarmar are assumed to have 30% lower cost in hydropower generation. Likewise, Thailand and Vietnam are assumed to have 30% lower cost in coal-fired power generation. Hydro is the cheapest among all resources and Diesel is the most expensive one to generate the same amount of power.

The transmission cost depends on the distance of countries. We assume the distance of two countries as the distance of their capitals. If two countries are connected but does not have a link between them, the distance is a summation of distance between each pair of capitals which are on the path. The Table 3 indicates the transmission cost depending on the distance.

0-1600km	> 1600km	> 3200km
3	5	7.5

Table 3 Transmission cost (Unit: USD/MWh)

Each country in the GMS needs different amounts of power in both peak and non-peak demand. The power demand and duration of demand is described on the following table[1].

	CAM	LAO	MMR	THA	VNM
Peak Demand	563	655	1547	27496	23426
Peak Duration	4380	4745	2428	4015	2428
Non-peak Demand	225	60	162	8692	6862
Non-Peak Duration	4380	4015	6332	4745	6332

Table 4 Power Demand and Duration of the Demand (Unit: MW, hours)

Thailand and Vietnam need lots of power in both peak and non-peak

[1]For simplicity, we abbreviate Cambodia to CAM, Laos to LAO, Myanmar to MMR, Thailand to THA, and Vietnam to VNM. In some cases we shorten more so that C implies Cambodia, L is Laos, M is Myanmar, T is Thailand, and V is Vietnam.

demand comparing to the other three countries. All countries are self-sufficient, which means each country can meet her power demand by using her own generation capacity. If they trade the power, however, they can expect some cost savings.

4 Analysis

4.1 Total Cost Savings

We set four scenarios depending on the amount of transmission capacity. Firstly, Trade75 is when countries allow up to 75% of domestic power demand to be met by trade. Trade50 requires more strict regulation on the transmission. It is when countries allow up to 50% of domestic power demand to be met by trade. Likewise, if we limit the transmission capacity much more, Trade25 is when countries allow up to 25% of domestic power demand to be met by trade respectively. Trade0 is the benchmark scenario when each country meets domestic power demand by herself.

The total cost savings, or in other words, the cost savings of grand coalition for each scenario is stated on the Table 5. The information of cost savings for each coalition $S \subset N$ is in the appendix.

Scenario	Trade75	Trade50	Trade25	Trade0
$v(g)$	1333.6	1267.8	955.1	0

Table 5 Total cost savings (Unit: Million USD)

We find the cost savings of grand coalition in Trade75 is about 1,334 million US dollars. Comparing to the benchmark scenario, countries get a huge amount of cost savings. We also find that the maximum trade capacity of existing transmission lines doesn't exceed 60% of domestic power demand for all countries. Therefore every scenario that allows at least 60% of domestic power demand to be met by trade, then the total cost savings is the same. The total cost savings in Trade50 is less than Trade75. The difference between them is about 65 million US dollars. The more countries restrict trades, the less total cost savings arises. In Trade25, the total cost savings reduces to 955 million US dollars. Still, countries get benefit comparing to the benchmark scenario. The rest of the paper focuses on Trade75, 50, and 25.

4.2 Myerson Value

Since the Myerson value allocates the cost savings to each country with considering marginal contribution, it gives a good implication on the way of allocating cost savings. The Table 6 shows the Myerson value of every country for all three kinds of scenarios.

	Trade75	Trade50	Trade25
Cambodia	212.1 (15.9)	176.9 (14.0)	109.7 (11.5)
Laos	335.2 (25.1)	319.1 (25.2)	248.4 (26.0)
Myanmar	135.8 (10.1)	145.2 (11.5)	98.3 (10.3)
Thailand	501.3 (37.5)	484.4 (38.2)	394.4 (42.3)
Vietnam	149.1 (11.1)	142.1 (11.2)	104.3 (10.9)

Table 6 Myerson value (Unit: Million USD (%))

The Myerson value of each country becomes small as the trade is restricted. For example, on the Trade75, the Myerson value for Cambodia is about 212 million US dollars, but it reduces to 110 million US dollars on the Trade25. The numbers in parenthesis indicates a percentage of the Myerson value. As the Myerson value implies the marginal contribution, the percentage can be interpreted as a proportion of contribution. For instance, the contribution of Cambodia on the Trade75 is about 16% among countries.

In all scenarios, Thailand gets the largest percentage and Laos gets the second largest. It implies that these two countries play a key role in this region. Both Thailand and Laos have transmission lines connecting with three countries. As there is no country connecting with more than four countries, Thailand and Laos have the largest number of transmission lines. Although Cambodia also has three transmission lines, neither the generation capacity nor the power demand is large enough. On the contrary, Laos has an extra generation capacity on hydro which attracts other countries to import. Thailand has the largest power demand so that she is likely to save some cost by importing the power.

The Myerson values of Myanmar and Vietnam are almost similar in all scenarios. For example, Myanmar gets 121 million US dollars and Vietnam gets 136 million US dollars on the Trade50. Moreover, their percentage of contribution is almost same through scenarios. The percentage of Vietnam is 11.1% on the Trade75 and 10.9% on the Trade25.

Unlike with Myanmar and Vietnam, Cambodia's proportion of contribution is different depending on the scenarios. The highest percentage appears on the Trade75 and it reduces as the trade is restricted. Cambodia's proportion is just 11.5% on the Trade25. This implies that Cambodia is affected by trade restriction a lot. On the Trade25, Cambodia should restrict the amounts of import and use her own generation capacity. Thus, her participation in the program becomes small.

4.3 Core

To check the stability of grand coalition, we analyze the core. It turns out the core is empty in all scenarios. It follows that some countries have an incentive to go out of the grand coalition and form their own coalition to increase benefit for themselves. Then only few countries get benefit from the program by trading the power between them. The existence of nonempty core for all possible coalition is described on the Table 7.

Coalition	Trade75	Trade50	Trade25
$\|S\| = 2$	nonempty	nonempty	nonempty
$\|S\| = 3$	nonempty	nonempty	nonempty
CLMT	nonempty	nonempty	nonempty
CLMV	empty	empty	empty
CLTV	nonempty	nonempty	nonempty
CMTV	empty	empty	empty
LMTV	nonempty	nonempty	empty
CLMTV	empty	empty	empty

Table 7 Existence of nonempty core

According to the table, any coalition consisting of two or three countries has a nonempty core. If we increase a size of coalition to four, the core may empty or nonempty. On the Trade75 and Trade50, the coalition consisting of Cambodia, Laos, Thailand, and Vietnam has a nonempty core. Likewise, the coalition of Laos, Myanmar, Thailand, and Vietnam has a nonempty core. However, the other two coalitions consisting of four countries do not have a nonempty core. On the Trade25, the core of coalition consisting of Laos, Myanmar, Thailand, and Vietnam becomes empty as well. Since the grand coalition has an empty core through all scenarios, the Myerson value described on the Table 6 cannot be in the core.

We guess some reasons why the grand coalition has an empty core. Firstly, it may because of link formation. On the current network, some pairs of countries should use the same lines at the same period. Since the total amounts of transmission cannot exceed the capacity of transmission lines, countries may not trade as much as they would like to. If we add new links in the region, paths between countries become various so that the congestion on the transmission lines can be diminished. Also, due to new links, countries can shorten the path to reduce the transmission cost.

Secondly, it may because of the current transmission capacity of lines. We may find a nonempty core by expanding transmission capacity without adding a new link. By expanding the capacity, we also improve the congestion problem on the lines. Expanding existing transmission capacity is more feasible option than constructing another new link.

From this consideration, we assume two types of imaginary network in the GMS to find a nonempty core. Firstly, we add a new link in the region. A

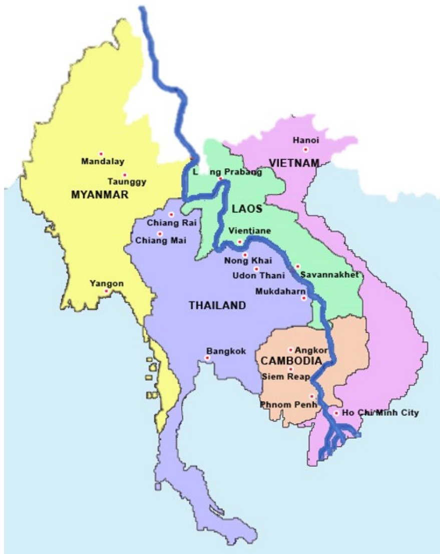

Figure 4.1 The Greatest Mekong Subregion

new link can be added between countries who share borders. As the Figure

4.1. shows, the only possible new link is between Laos and Myanmar. We define a new network $g' = g + \{\text{Laos, Myanmar}\}$, which has an additional link between Laos and Myanmar. However, we find that the result from g' is same with that from g. Thus, the core of grand coalition is still empty.

Secondly, we expand transmission capacity of existing links. While the transmission line between Myanmar and Thailand does not need to expand its capacity, other five transmission lines should be expanded to make countries trade without limitation. A required transmission capacity for each scenario is as below Table 8.

Project	Existing capacity	Trade75	Trade50	Trade25
CAM - LAO	300	337.57		
CAM - THA	2320	11343.8	11378.5	6874
CAM - VNM	865	11660	11660	7014.75
LAO - THA	8652	13597.1	13651.3	
LAO - VNM	4647	11324.3	11378.5	

Table 8 Expanding transmission capacity (Unit: MW)

For example, the current transmission capacity between Cambodia and Thailand is 2320 MW. It should be expanded to 11344 MW on the Trade75, 11378 MW on the Trade50, and 6874MW on the Trade25. In this case, the congestion on the lines is removed. We find, however, the core of grand coalition is still empty through all scenarios.

4.4 Pairwise Stability

Even though the core of grand coalition is empty, we find the current network is pairwise stable. To see this, we compare the current network g with adjacent network, g', which is constructed by adding a link or deleting a link. In the GMS, the adjacent network can be formed by adding a new link between Laos and Myanmar, or deleting one of the existing links. As there are six transmission lines exist, the possible adjacent networks are seven, $g' \in \{g+\mathrm{LM}, g-\mathrm{CL}, g-\mathrm{CT}, g-\mathrm{CV}, g-\mathrm{LT}, g-\mathrm{LV}, g-\mathrm{MT}\}$, where C is short for Cambodia, L is Laos, M is Myanmar, T is Thailand, and V is Vietnam.

	$u_i(g)$ and $u_i(g')$	$u_j(g)$ and $u_j(g')$
g+LM	$u_L(g) = u_L(g')$	$u_M(g) = u_M(g')$
g−CL	$u_C(g) = u_C(g')$	$u_L(g) = u_L(g')$
g−CT	$u_C(g) = u_C(g')$	$u_T(g) = u_T(g')$
g−CV	$u_C(g) = u_C(g')$	$u_V(g) = u_V(g')$
g−LT	$u_L(g) = u_L(g')$	$u_T(g) > u_T(g')$
g−LV	$u_L(g) = u_L(g')$	$u_V(g) = u_V(g')$
g−MT	$u_M(g) = u_M(g')$	$u_T(g) > u_T(g')$

Table 9 Pairwise stability

From the definition of cost function (2.1)) and utility function (2.8), the utility of net exporting country is zero in all networks. We find that the utility of importing country in the adjacent network is equal to or less than the current network. Since both Laos and Myanmar are net exporting countries, they cannot get benefit by connecting themselves. In the absence of any transmission line, countries use another path. This makes the congestion on the lines much more seriously and increases transmission costs because some trades need longer paths. Therefore, countries have no incentive to delete an existing line. Under any adjacent network, countries get same or worse result than the existing network, that implies the current network is pairwise stable.

5 Concluding Remarks

So far, we analyze the ASEAN Power Grid (APG) using the methodology developed in the cooperative game theory and the graph theory. Firstly, we construct the cost function for the APG. Our cost function considers not only the network structure but also peak demand and non-peak demand. Especially we adjust the load structure by constructing small games with respect to the duration of peak demand. From this process the cost function presented in this paper reflects the real world as much as possible. Also using the cost function, we derive the cost savings function and apply various tools from the cooperative game theory and the graph theory.

We agree with the statement that the APG is beneficial for the Greatest Mekong Subregion(GMS). We consider four different scenarios depending on the level of trade restriction. We can achieve the largest total cost savings by allowing at least 60% of domestic power demand to be met by trade for all countries. The benefit decreases in the cases of trading up to 50% and 25%, but these cases still maintain positive amounts of benefit comparing to a non-trading case.

The Myerson value shows the marginal contribution of each country. Due to its good implication, the Myerson value can be useful rule when countries allocate benefit. We find that Laos and Thailand are the key countries in the GMS. Both of them have many transmission lines connecting with other countries and also have either large generation capacity or demand. The contribution of Myanmar and Vietnam is similar in all scenarios. Cambodia contributes more in Trade75 and Trade50, comparing to Trade25.

It implies her participation in the program decreases because of trade restriction.

We check the stability of the program in the GMS by two concepts, the core and the pairwise stability. The core is developed in the cooperative game theory and the pairwise stability is came from the graph theory. Thus, the core checks the stability in the context of coalition formation and the pairwise stability focuses on the network formation. We find the core of grand coalition is empty but the current network structure is pairwise stable through all scenarios.

The core of grand coalition is empty for all scenarios. It implies some countries have an incentive not to trade in the grand coalition but to form their own coalition and trade with each other. To recover the nonempty core, we suggest two alternatives. One is adding a new link and the other is expanding the existing transmission capacities. Both alternatives are expected to relieve the congestion on the transmission lines and decrease transmission cost. However, we find that the core of grand coalition is still empty on both alternatives.

Even though we cannot recover the nonempty core for grand coalition, we find that the current network is pairwise stable. We compare the existing network with seven kinds of adjacent networks, came from adding a link or deleting a link. Under any adjacent network, the countries get equal or less utility than the current network. Therefore, the network is pairwise stable, that is no two countries both want to add a link and no country wants to delete a link.

Another possible reason of empty core is the competition between importing countries to import the power. It can be a hint for recovering the nonempty core. The core may become nonempty if exporting countries increase their generation capacity. Especially, It is reported that Laos and Cambodia have a huge amount of unused hydro resource. The future work can test whether the nonempty core is recovered by investing hydro power plants in two countries.

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Appendices

A. The Cost Savings of Coalition on the Trade75

S	Y^{MV}	S	Y^{MV}
C	0	CLM	292.2
L	0	CLT	782.7
M	0	CLV	477.8
T	0	CMT	695.4
V	0	CMV	277.8
CL	292.2	CTV	712.8
CM	0	LMT	905.2
CT	257.1	LMV	196.5
CV	277.8	LTV	836.1
LM	0	MTV	422.1
LT	521.7	CLMT	1167.4
LV	196.65	CLMV	477.8
MT	422.1	CLTV	1158.3
MV	0	CMTV	790.8
TV	0	LMTV	1138.1
		CLMTV	1333.7

Table 10 Cost Savings of Coalition on the Trade75 (Unit: Million USD)

C: Cambodia, L: Laos, M: Myanmar, T: Thailand, V: Vietnam

B. The Cost Savings of Coalition on the Trade50

S	Y^{MV}	S	Y^{MV}
C	0	CLM	274.2
L	0	CLT	754.1
M	0	CLV	446.4
T	0	CMT	666.8
V	0	CMV	246.8
CL	274.2	CTV	683.9
CM	0	LMT	870.5
CT	228.9	LMV	196.6
CV	246.8	LTV	712.0
LM	0	MTV	422.1
LT	521.7	CLMT	1104.8
LV	196.6	CLMV	446.4
MT	422.1	CLTV	1075.3
MV	0	CMTV	762.2
TV	0	LMTV	1189.5
		CLMTV	1267.8

Table 11 Cost Savings of Coalition on the Trade50 (Unit: Million USD)

C: Cambodia, L: Laos, M: Myanmar, T: Thailand, V: Vietnam

C. The Cost Savings of Coalition on the Trade25

S	Y^{MV}	S	Y^{MV}
C	0	CLM	137.1
L	0	CLT	595.8
M	0	CLV	321.5
T	0	CMT	527.5
V	0	CMV	123.3
CL	137.1	CTV	568.5
CM	0	LMT	754.3
CT	114.5	LMV	196.5
CV	123.3	LTV	710.9
LM	0	MTV	396.8
LT	479.1	CLMT	846.1
LV	196.5	CLMV	321.5
MT	396.8	CLTV	835.3
MV	0	CMTV	567.1
TV	0	LMTV	828.3
		CLMTV	955.1

Table 12 Cost Savings of Coalition on the Trade25 (Unit: Million USD)

C: Cambodia, L: Laos, M: Myanmar, T: Thailand, V: Vietnam

국문 초록

아세안 전력 그리드(ASEAN Power Grid, APG)는 동남아시아 지역 내 통합 전력 그리드를 목표로 하는 프로그램이다. APG를 통해 참가국들이 이익을 누릴 수 있음은 기존 문헌에서 확인되었다. 이 글에서 필자는 협조적 게임 이론과 그래프 이론의 여러 개념을 응용하여 APG에 관한 분배문제와 안정성을 다룬다. 특히 캄보디아, 라오스, 미얀마, 태국, 베트남이 포함된 메콩강 유역(Greatest Mekong Subregion, GMS) 관련 데이터 분석을 시행하였다. 각국의 한계기여도를 보여주는 마이어슨 밸류(Myerson value)는 라오스와 태국이 가장 중요한 참가국임을 보여주었다. 필자는 코어(core)와 쌍별 안정성(pairwise stability)을 활용하여 APG의 안정성 여부를 파악하였다. 그 결과 전체 연합에서의 코어는 공집합이나, 현 네트워크 구조는 쌍별 안정성을 띠고 있음을 확인하였다.

주제어 : 아세안 전기 그리드, 협조적 게임, 마이어슨 밸류, 코어, 쌍별 안정성

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