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Abstract

This paper examines the development of cooperative strategies between 12 countries exporting Liquefied Natural Gas (LNG) and belonging to the Gas Exporting Countries Forum (GECF). This economic study is more specifically focused on a scenario often raised: that of the emergence of a cooperative approach designed with the sole aim of logistic rationalization, and which would not have any effect on LNG prices. As this is a standard transportation problem, we first assess the gains that may result from this cooperative approach using a simple static model calibrated on the year 2007. The numerical results obtained suggest that, in the absence of a gain redistribution policy, this cooperative strategy will probably not be adopted because cooperation would not be a rational move for some exporters. The problem of gain sharing is then formulated using cooperative game theory concepts. Several gain sharing methods have been studied, including the Shapley value and various nucleolus-inspired concepts. Our results suggest that the choice of a redistribution policy appears relatively restricted. Out of the methods studied, only one – the per capita nucleolus - satisfies two key requirements: core belonging and monotonicity (in the aggregate). Lastly, coordination costs are considered and we determine the maximum amount that can be tolerated by such a cooperation. In view of the low level of this amount and the relative complexity of the sharing method implemented, we consider that the credibility of a logistic cooperation scenario exempt from market power should be reappraised.

JEL Classification codes: L71, C71

Keywords: Liquefied Natural gas; Cooperative game theory; Linear programming problem.

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Introduction

In the gas industry, the establishment of the Gas Exporting Countries Forum, (GECF), founded in 2001 in Tehran, is undoubtedly one of the key events of the last few years. For the first time in history, the main gas exporting states, existing or emerging, got over the first steps to implement a cooperative approach. It is no surprise that all the meetings of this informal inter-ministerial assembly (Hallouche, 2006) have given rise to plenty of comments. It is true that the concentration of reserves[1], the precedent constituted by the OPEC (to which several GECF member states also belong) and the similarities between oil and natural gas (comparable technologies used in the exploration and production phases, analogies in terms of concentration of reserves) are all familiar topics when examining the long-term future of this industry.

As far as the GECF is concerned, one of the major questions is how this group of exporters is going to behave. According to the dichotomy referred to by Mr. Mandil (former Director of the International Energy Agency), two possibilities can be envisaged, depending on whether the GECF will seek to exercise market power or not. In the first case, the GECF would behave like a cartel, while in the second, it would concentrate on promoting regional cooperation as *"a think tank for gas exporting countries, enabling them to consider the best possible conditions for the exercise of their mission"* (Mandil, 2008). In the first scenario, economic theory provides satisfactory models for analyzing the GECF profitability. For example, Jaffe and Soligo (2006) evoke of a monopoly confronted by a competitive fringe, a by now classical model used in numerous studies of the oil industry (Cremer and Weitzman, 1976; Pindyck, 1978). However, as yet, there has been no examination of the other alternative: cooperation conducted without market power. It is true that the history of the hydrocarbons industry does not support the case for rationalization, which was included as a lame excuse in the preliminary declaration of the Achnacarry agreement[2] (Giraud & Boy de la Tour, 1987, p.206). However, historical precedents do not constitute proof. There is therefore a need for a study of the economic rationales for such cooperation conducted without any effect on the prices paid by importing countries, i.e. at "iso market power". That is the aim of this paper.

It is no surprise to note a revival of an early literature dedicated to international trade in natural gas (Percebois, 1989 pp. 559-582) and more specifically the theme of cooperation between exporters. Some recent publications (Hallouche, 2006; Jaffe and Soligo, 2006; Wagbara, 2007; Tönjes and de Jong, 2007) offer an in depth description of the GECF and provide the "basic building blocks" required for more detailed analyses, such as those concerning (i) the attitude of each of the GECF

[1] Three countries – Russia, Iran and Qatar – alone hold 55% of the planet's proven reserves of natural gas (BP, 2008). According to Hallouche (2006), the countries represented at the 2004 GECF assembly collectively held 87% of global gas reserves.

[2] This agreement, signed on 17th September 1928, constituted the deed of foundation of the famous "Seven Sisters" cartel, which would dominate the oil industry until the 1960s. Simply reading through the details of this agreement provides a refutation of the theory of rationalization without market power, since it describes methods of price fixing!

member countries in relation to cooperation[3] or (ii) the effect that cartelization would have on the importing countries as in Percebois (2008). These contributions examine the subject against the broad perspective of geopolitics. In addition to this holistic treatment, it might be judicious to promote an analytical and a purely economic approach to international trade in natural gas.

This would mean simplifying the problem, which is treated solely from an economic point of view, independently of any consideration of a political or geostrategic nature. As Mathiesen et al. note (1987, p.28), *"Even if we restrict ourselves to the pure economics of the natural gas market, we face large complexities. To incorporate all aspects of the market in one, a comprehensive model seems neither manageable nor fruitful. We will adopt the well-known strategy of decomposing and simplifying in order to obtain a manageable model."* This approach has been used many times to analyze the gas industry. For example in their Baker Institute World Gas Trade Model, Hartley and Medlock (2006) analyze the long-term competitive equilibrium of a global gas market. Other works, developed following Mathiesen et al. (1987) by Golombek et al. (1995), Boots et al. (2004), Holz et al. (2008) and Egging et al. (2008), deal with imperfect competition among gas exporters with the help of a Cournot oligopoly model. While some practitioners may feel that such modeling approaches oversimplify the issue, we feel that it can offer a qualitative improvement in terms of understanding the GECF.

Our paper focuses on trade in gas in the form of Liquefied Natural Gas (LNG) since "*an association of some kind among LNG exporters*" is often perceived as likely (Yergin and Stoppard, 2003). It is true that GECF countries are in a privileged position in this respect as they collectively hold almost 90% of the world's liquefaction capacities (Hallouche, 2006, p. 25). This sector is undergoing accelerated growth, at an average of +7.44% a year since 2000, and now represents almost 30% of international trade in gas (BP, 2008). In recent years, it has seen some profound changes including the reduction in LNG transport costs (Greaker et al., 2008) and development of remote sources not previously exploited, the development of transoceanic exchanges between previously isolated markets (Jensen, 2003) and the appearance of opportunities for arbitration between importing regions (Yepes Rodríguez, 2007), etc. However, the "commoditization" of LNG is still only partial and long-term contracts remain the main form of trade. Despite the recent relaxation of the flexibility clauses in these contracts (Jensen, 2003), simple observation of recent trading flows suggests the existence of considerable arbitration opportunities. For example in 2007, Trinidad and Tobago sent nearly 2.7 bcm to Europe, while Algeria sent 2.1 bcm to the United States (BP, 2008). In view of their respective geographical positions, this appears to indicate the possibility of a profitable logistic coordination between these two LNG exporters (an "asset swap" in industry jargon). And this is by no means an isolated occurrence (see Table 11). Some observers (Wagbara, 2007) have suggested that the GECF could play an intermediation role by identifying opportunities for logistic rationalization between

[3] For example, Finon (2007) studies Russia's attitude to the GECF.

GECF members. In terms of the GECF countries as a group, determining a strategy for logistic rationalization is similar to resolving a standard transportation problem. This transportation problem has fuelled a wide literature in both economic theory (Koopmans, 1949; Kantorovich, 1960) and operational research with a famous formulation proposed by Dantzig (1951). Note that this logistic optimization has no impact on the price paid by the importing countries[4].

Several questions now arise. Firstly, what gain is likely to be achieved by such a coordination of exports within the GECF? If any collective gain were to prove positive and substantial, we could legitimately question the spontaneous formation of this coalition by studying the choice of cooperation from the point of view of its rationality for each exporter. Or can a collective gain-sharing incentive policy be introduced? If so, is it possible to identify a sharing mode likely to encourage all the stakeholders to cooperate within the GECF? Is the current composition of the GECF the best suited to this coordination, or would it be in the interest of certain participants to cooperate within the framework of a restricted coalition? All these questions suggest using the concepts and methods of the cooperative game theory, which analyzes the distribution of gains resulting from cooperation between economic players. This theory has been used in a wide variety of contexts. Applications linked to energy include such diverse examples as the regional cooperation in planning an electricity supply system between three states in India (Gately, 1974); the definition of subsidy-free prices for a regulated firm (Faulhaber, 1975); the measurement of market power in the Western American coal industry (Wolak and Kolstad, 1988); the sharing of joint costs in a distribution planning situation at the Logistics Department at Norsk Hydro (Engevall et al., 1998); the allocation of electricity transmission cost (Kattuman et al., 2004); and the allocation of a refinery's CO_2 emissions (Pierru, 2007)… In this paper, we propose to analyze the credibility of the so-called "rationalization" argument by studying the feasibility of a cooperation, which would focus solely on logistic optimization of LNG supply chains, without trying to exert any upward pressure on prices. Finally, we aim to discuss the credibility, in a purely economic sense, of such a cooperation that would be "market power neutral".

The next section details all the assumptions used in this study. Section 3 justifies the formulation of the problem of coordination in the form of a linear program and comments on the results of logistic cooperation involving twelve GECF countries. According to these results, such cooperation would be collectively profitable however some countries would not spontaneously adhere to this collectively optimal export policy. Given that a gain sharing rule is needed, section 4 discusses this issue with the help of the cooperative game theory concepts. It sets out what can be achieved in gain sharing using basic solutions as well as more advanced ones such as the Shapley value, the nucleolus and some of its derivatives. The last section concludes the paper.

[4] This is compatible with the medium-term price rigidity resulting from long-term contracts. In these contracts, prices and indexing formulas are negotiated then fixed for periods of approximately 3 years.

1. Assumptions

Our study is specifically focused on gas transport by LNG ships. A brief description of the LNG supply chain is therefore essential. For the sake of clarity, please note that the approach used here is static and relates only to the year 2007.

1.1 The framework

The exporters

In 2007, twelve LNG exporting countries participated in GECF meetings: Trinidad & Tobago, Oman, Qatar, the United Arab Emirates, Algeria, Egypt, Equatorial Guinea, Libya, Nigeria, Brunei, Indonesia and Malaysia (Hallouche, 2006). In this study, the countries that are likely to adopt coordination correspond to this group of twelve countries - i.e. all the LNG exporters that are not members of the OECD[5].

The importing countries

In 2007, seventeen countries imported natural gas. These are located in North America and the Caribbean region (USA, Mexico, Dominican Republic and Puerto Rico), in Europe (Belgium, France, Greece, Italy, Portugal, Spain, Turkey and the United Kingdom) and in Asia (China, India, Japan, South Korea and Taiwan).

1.2 Notations

- i, a country exporting LNG and member of the GECF;
- n, the number of GECF countries exporting gas in LNG form (here, n =12);
- j, a country importing gas in LNG form;
- s, the number of countries importing LNG (here, s =17)
- q_{ij}, the quantity of natural gas shipped in LNG form during the year from i to j;
- $\overline{Q_{ij}^{2007}}$, the quantity effectively shipped in 2007 (cf. Table 11 in the Appendix);
- $L_i\left(\sum_{j=1}^{s} q_{ij}\right)$, the cost function for natural gas extraction and liquefaction activities in i;
- $T_{ij}\left(q_{ij}\right)$, the cost of transporting quantity q_{ij} from i to j;
- $R_j\left(\sum_{i=1}^{n} q_{ij}\right)$, the cost of LNG regasification in the importing country j.

[5] Three OECD countries export LNG: Australia, Norway (which holds an observer status at the GECF) and the United States (Alaska). However, it is very unlikely that these countries would agree to join the GECF in a coordination operation (Tönjes and de Jong, 2007).

In order to simplify things, we assume that these three cost functions are linear and denote respectively L_i the unit costs of production and liquefaction in the country i, T_{ij} the unit costs of transport by LNG carriers from the region i to the importing region j, and R_j the unit costs of LNG regasification in the region j.

1.3 Empirical assumptions

Production and liquefaction costs

The unit costs of gas extraction and liquefaction L_i are shown in Table 1. We have assumed that a common liquefaction technology is used, resulting in a uniform unit cost of liquefaction at $1.00 per MMBtu (DTI, 2005).

Table 1: Gas extraction and liquefaction costs in $ per MMBtu

	Extraction Cost $/MMBtu	Liquefaction Cost $/MMBtu	L_i $/MMBtu
Trinidad & Tobago	0.60	1.00	1.60
Oman	0.40	1.00	1.40
Qatar	0.30	1.00	1.30
UAE	0.35	1.00	1.35
Algeria	0.45	1.00	1.45
Egypt	0.60	1.00	1.60
Equatorial Guinea	0.50	1.00	1.50
Libya	0.50	1.00	1.50
Nigeria	0.50	1.00	1.50
Brunei	0.40	1.00	1.40
Indonesia	0.25	1.00	1.25
Malaysia	1.00	1.00	2.00

Source: OME (2001) and calculations by the authors based on Wood McKenzie data.

These costs correspond solely to technical operations and do not include either the effects of oil and gas taxation or the opportunity cost related to taking the exhaustible nature of gas resources into account. Care must therefore be taken with economic interpretation of the calculated profits, since these profits will incorporate costs that are not modeled.

Regasification costs

In practice, it will be assumed that the regasification service is uniformly invoiced R_j=$0.50 per MMBtu in all importing countries.

LNG transport costs[6]

The values of unit costs T_{ij} have been calculated in accordance with the simple approach described in Flood (1954). This method is based on a table of distances d_{ij} between the liquefaction plants in country i and the regasification plants in country j (cf. Table 13 in the Appendix) and some assumptions concerning the fleet of LNG carriers. We assume that the fleet is composed of standard ships with a capacity of 137,000 m^3 of LNG, i.e. the average value of the global fleet in 2007 (GIIGNL, 2008). The main characteristics of these ships are shown in Table 2.

Table 2: Characteristics of a standard ship – capacity: 137,000 m3 LNG

Effective capacity:	127,410 m^3 LNG *
Average vessel speed:	18 knots
Time required for loading operations:	2 days
Time required for unloading operations:	2 days
Cargo boil-off (used as a fuel in the ship's steam plant)**:	every day: 0.15% of the volume of LNG on the ship
Acquisition price:	\$165m (source: DTI, 2005)
Annual operating costs (fuel, crewing, annualized value of dry docking costs, insurance, etc.)	\$27.3m/year
Number of days' unavailability due to technical stoppages (maintenance, etc.) or contingencies (storms, etc.):	20 days/year

* *The rules of operation recommend: 1) filling the tanks to a maximum 98% of capacity and 2) maintenance of a "heel", i.e. a minimum quantity of LNG of 6,850 m^3 in order to maintain cryogenic conditions in the ship's tank on the outward and return journeys.*

** *Due to evaporation losses, the quantity of LNG delivered to the regasification plant is less than the quantity loaded on departure from the liquefaction plant. Losses increase with the distance covered.*

We assume that each ship is committed to a ij route. This enables us to calculate, for each route, the number of round trips made by a ship during a year, taking into account the return journey time and the time required for loading and unloading. For each ij route, we can therefore deduce the quantities transported during a year together with the evaporation losses. For the calculation of the unit cost, these losses are accounted for at the unit cost of gas production and liquefaction in the producing country. The calculation takes into account annual capital charges discounted at the rate of 10% over a useful life of 20 years. For each ij route, the unit cost values T_{ij} are shown in the Table 14 in the Appendix.

Gas prices in importing regions

The global economic integration of gas markets is far from perfect. We therefore follow the suggestion by Mazighi (2003, p. 319) who distinguishes "*three areas, or regions, for LNG: the European region,*

[6] All calculations have been performed using the following conversion assumptions: 1 MMBtu corresponds to 28.31684 m^3 of natural gas and 1 m^3 of LNG is equivalent to 600 m^3 of natural gas placed under normal temperature and pressure conditions.

that includes Europe and Africa; the Asian region, that includes Asia, the Middle East and Oceania; and the American region". Thus, we assume that the import price of natural gas, here regasified LNG, is uniform within each area. This is a strong assumption, but industrial reality suggests that the differences in intra-zone import prices are very limited compared to those of extra-zone prices. The prices used in this study are shown in Table 3.

Table 3: Import prices in 2007 in $ per MMBtu

	Asia (Japan CIF)	Europe (European Union CIF)	North America (US Henry Hub price)
Price ($/MMBTU)	7.73	8.93	6.01

Source: BP Statistical Review 2008

1.4 Discussion: The validity of assumptions

Clearly this is a simplistic representation of the real LNG industry and various important factors of fleet operations have not been considered: port charges, passage fees (Suez Canal)… It is thus natural to check whether this model can be considered as an acceptable representation. Two criterions seem relevant for that purpose.

The first concerns the technical credibility of this representation of the LNG chain. With the gas flows in 2007 $\overline{Q_{ij}^{2007}}$ solely from GECF countries, our assumptions suggest the use of a fleet of 204 ships[7] making a total of 2,848 trips. According to industry sources (GIIGNL, 2008), LNG trade involved effectively 237 ships in 2007 and these ships made a total of 3,325 trips during the year. Two points may explain the differences between our model and the statistics. The first one is obvious since three exporting countries: the USA (Alaska), Australia and Norway were not included in our modeling. Exports from these countries amounted to 21.6 Bcm in 2007, or approximately 9.5% of world trade in LNG (BP, 2008). The second point is related to the distances used for the calculation of LNG chains. It is clear that the quantity of LNG that can be carried by a vessel committed to a ij route during a whole year is a decreasing function of the maritime distance between the liquefaction plants in country i and the regasification plants in country j. The distances considered here are reduced "by construction" since they are based on the shortest maritime distance. However observation suggests that industrial reality can be more complex: the shortest distance is not necessarily preferred for each ij route. As an example, some of the LNG imported to France from Algeria crosses the Straits of Gibraltar to be regasified near Nantes on the Atlantic coast. In this case, a regasification on France's south coast would have obviously minimized the maritime distance. This simplification plays also a

[7] Calculation made assuming that each ship used remains committed to one ij route for the year, even if it is only partly used.

role in the observed differences. While conscious of these approximations, we assume that the technical representativeness of the LNG chain is sufficient for the purposes of this study.

The second criterion is that of the economic representativeness of the LNG chain. Using the 2007 gas flows $\overline{Q_{ij}^{2007}}$, we can build an aggregated representation of the economics of LNG trade from non-OECD exporters. In 2007, the revenue generated by this trade was approximately $57 billion. On these assumptions, the total yearly cost of these LNG chains is in the order of $21 billion enabling a nearly $35 billion rent. Table 4 illustrates this value chain. These orders of magnitude are in line with publicly available data. Activities linked to transport by LNG carriers represent nearly a third of this industry's costs.

Table 4: The LNG value chain for GECF exporting countries

		$ billion	%
E&P cost	Production	3.588	*16.6%*
LNG cost	Plant	7.234	*33.4%*
	Shipping	8.167	*33.3%*
	Re-gas	3.617	*16.7%*
Total cost		21.638	*100.0%*
Rent		34.870	
TOTAL revenue		57.476	

1.5 Some spatial considerations

In the preceding section, the unit cost of transport has implicitly been modeled as a monotonically increasing function of the maritime distance. The relative geographical position of the different exporters should thus have a significant influence on the costs of supplying LNG to the different importers. This point is illustrated in the figures below, which detail these costs for each of the main importing countries in North America, Europe and Asia.

Unsurprisingly, the distance factor makes a difference. No shipper dominates absolutely from the cost point of view; everything depends on the import zone. The LNG flows recorded in 2007 (cf. Table 11) show there are potential gains from logistic cooperation. Again, the example of Algeria and Trinidad and Tobago already mentioned in the introduction is sufficiently convincing. Given that transportation costs represent one third of the LNG industry costs, we conclude this section by noting that there seems to be ample room for the GECF exporters to perform a logistic optimization.

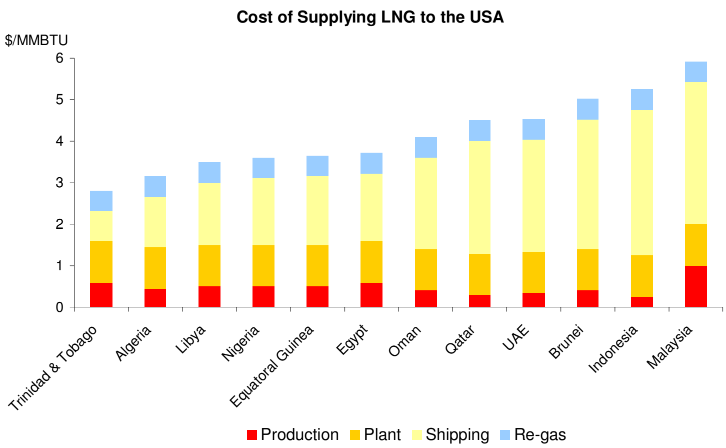

Figure 1 : Unit costs of imports of natural gas to the United States from exporting GECF countries ($/MMBtu)

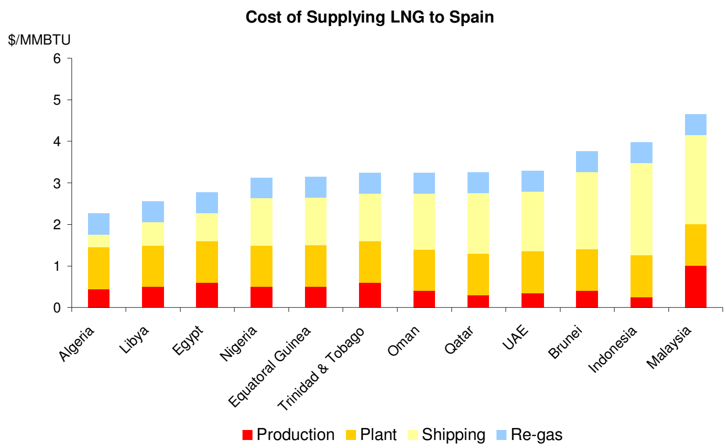

Figure 2 : Unit costs of imports of natural gas to Spain from exporting GECF countries ($/MMBtu)

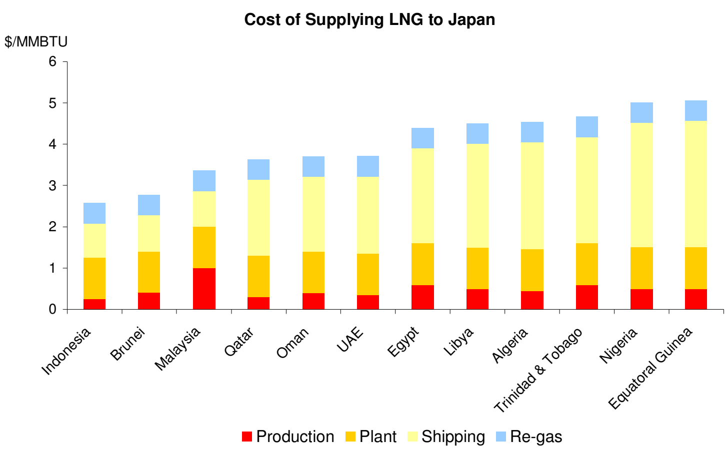

Figure 3 : Unit costs of imports of natural gas to Japan from exporting GECF countries ($/MMBtu)

2. Cooperation between LNG exporters

First and foremost, we assume that the exporting countries have total control over the shipment of LNG. This is an acceptable approximation, since most trades are governed by "delivered ex ship" clauses.

2.1 Formulation of the problem

In the work reported in this paper, the GECF is supposed to face a classic transportation problem. A homogeneous product, LNG, is to be shipped from n shipping origins to s shipping destinations. The cost of shipping a unit amount from the ith origin to the jth destination is known for all combinations (i, j). The problem is to determine the quantities q_{ij} to be shipped over all routes so as to maximize the GECF's collective profit. Apart from being non-negative, those variables have also to satisfy some constraints. Before explicitly writing them, it is worth noting that the context of the coordination dealt with here is that of a "nascent cooperation" between individual exporters who entrust the GECF with decisions on their shipment policy. As a result, it seems reasonable to assume that the GECF's decisions will have to take into account the following considerations:

- Natural gas extraction and liquefaction operations require considerable amounts of capital. It is normal practice for fund lenders to demand extensive guarantees in return for finance. In the case of liquefaction units, these guarantees include long-term contracts specifying a minimum production volume. Thus, it seems reasonable to postulate that each exporter request that the cooperative shipment policy will have to satisfy his previous commitments. In other words, for an exporter, it matters little where the gas goes as long as the total quantity shipped remains unchanged, which corresponds to the constraints: $\forall i,\ \sum_{j=1}^{s} q_{ij} = \sum_{j=1}^{s} \overline{Q_{ij}^{2007}}$
- As the present paper deals with a nascent cooperation solely focused on logistic matters, it is reasonable to assume that each exporter wants any coordination conducted at GECF level to preserve its reputation as a reliable supplier[8]. In other words, the rationalization conducted by the GECF has to be compliant with each exporter's contractual commitments. These individual requirements can be aggregated at the GECF level to translate as: whatever the sources of the gas supplied, each import region must receive a quantity exactly equal to the total of the individual commitments made by GECF exporters. This corresponds to the following constraints: $\forall j,\ \sum_{i=1}^{n} q_{ij} = \sum_{i=1}^{n} \overline{Q_{ij}^{2007}}$

[8] The history of the gas industry suggests that reputation matters. In the 1980s, Algeria unilaterally blocked its gas deliveries in an attempt to drive up prices. But this curtailing behaviour caused harm to the country's reputation and penalised the development of its exports in the subsequent years (Hayes and Victor, 2006).

Given that the quantities supplied to each importer j remain unchanged, the local price of gas P_j is not influenced by the GECF's conduct. Thus, those constraints are compatible with the GECF's supposed goal: promoting a purely logistic cooperation without trying to exert any collective market power.

We note $\pi_i\left(q_i\right)= \sum_j\left(P_j - L_i - T_{ij} - R_j\right)q_{ij}$ for all $i=1,2,...,n$, the profit of an exporting country i depending on its export policy $q_i := \left(q_{ij}\right)_{j=1}^{s} \in \mathbb{R}^s$, i.e. the quantities of gas shipped to the different importing regions. The GECF's transportation problem can thus be formulated as a familiar linear programming problem (Dantzig, 1951). Our problem amounts to seeking an optimal export policy named $q^* := \left(q_i^*\right)_{i=1}^{n} \in \mathbb{R}^{ns}$ that is a solution to the following problem:

<u>Programme 1:</u>

$$\underset{q_{ij}}{Max} \quad \sum_{i=1}^{n}\pi_i$$

$$\text{s.t.} \quad \sum_{j=1}^{s} q_{ij} = \sum_{j=1}^{s}\overline{Q_{ij}^{2007}} \qquad \left(\forall i = 1,2,...,n\right) \qquad (1)$$

$$\sum_{i=1}^{n} q_{ij} = \sum_{i=1}^{n}\overline{Q_{ij}^{2007}} \qquad \left(\forall j = 1,2,...,s\right) \qquad (2)$$

$$q_{ij} \geq 0$$

With those constraints, the GECF's objective relates clearly to a cost minimization problem. This problem contains ns =204 non-negative variables q_{ij} and $n+s$ =29 equality constraints type (1) and (2). In Dantzig (1951), it is shown that the optimal solution requires at most $n+s-1$ routes with positive shipments. This problem is obviously feasible: the observed trade flows for 2007 obviously satisfy all the constraints. But with a total of 77 positive flows, this obvious policy does not constitute an optimal policy! Thus, this particular instance of a transportation problem indicates that there is some room for a logistic optimization.

2.2 Results

An optimal policy q^* has been computed (cf. Table 12). Note that only 28 positive shipments are observed. Given that the solution might be non unique, it is not so interesting to spend too much time trying to comment those flows of LNG. Nevertheless, a quick look at the illustration proposed in Fig. 4 suggests that this optimal policy q^* clearly corresponds to a rationalization: Trinidad and Tobago only exports LNG to its neighboring importers in North America; Mediterranean exporters allocate almost all their gas to Europe… In South East Asia, the gas liquefied in Brunei, Indonesia and

Malaysia remains dedicated to Asian consumers. For those countries, the GECF's optimal policy can thus be viewed as an intra regional fine-tuning of their shipments.

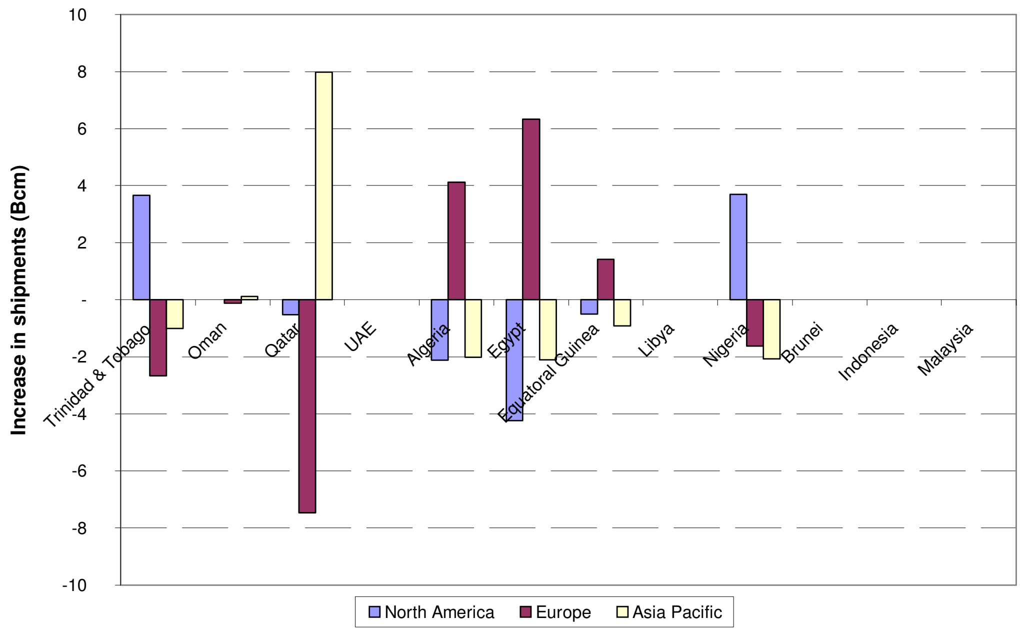

Figure 4: Comparison of the LNG destination between the GECF's optimal policy q^* and the 2007's case (a positive value corresponds to a shipment increase decided by the GECF)

Table 5: Impact of the optimal solution q^* on each exporter's profits (in M$)

	2007 Profits $\overline{\pi_i^{2007}}$	Profits attained with q^* $\pi_i\left(q_i^*\right)$	Gain from cooperation $\Delta\pi_i\left(q_i^*\right)=\pi_i\left(q_i^*\right)-\overline{\pi_i^{2007}}$
Trinidad & Tobago	2 761.87	2 650.93	-110.94
Oman	1 792.79	1 913.49	120.70
Qatar	6 299.10	5 674.21	-624.88
UAE	1 073.45	1 414.50	341.05
Algeria	5 269.89	5 781.20	511.31
Egypt	2 166.85	2 870.88	704.03
Equatorial Guinea	150.88	289.86	138.98
Libya	171.04	171.80	0.75
Nigeria	3 802.45	3 687.41	-115.04
Brunei	1 637.09	1 634.49	-2.60
Indonesia	5 085.04	5 047.17	-37.88
Malaysia	4 659.37	4 702.19	42.82
TOTAL	**34 869.82**	**35 838.12**	**968.31**

A closer look at the optimized shipments suggests that some countries may not individually benefit from this collective rationalization. For example, the GECF's optimized solution requires Qatar to increase its shipments to the distant Japan and cease its shipments to India and Spain… To analyze it, it is interesting to compute, for each country, the gains it derived from the optimized solution. For an exporter i, this gain is simply equal to the difference $\Delta\pi_i\left(q_i^*\right)=\pi_i\left(q_i^*\right)-\overline{\pi_i^{2007}}$ where $\overline{\pi_i^{2007}}$ is the profit received effectively in 2007 and $\pi_i\left(q_i^*\right)$ is the profit earned by i if q^* would have been implemented[9] in spite of the shipments observed in 2007. All those individual gains are presented in Table 5.

At the GECF level, this logistic cooperation is clearly collectively profitable: the collective gain $\sum_{i=1}^{n} \Delta\pi_i \left(q_i^*\right)$ derived from an optimal solution such as q^* amounts to $968.31 millions for 2007. Compared to the 2007 figures, it corresponds to an 11.9% reduction in the GECF's shipping cost and a 2.78% increase in the GECF's profits. But at an individual level, the attractiveness of the cooperation is not so clear-cut!

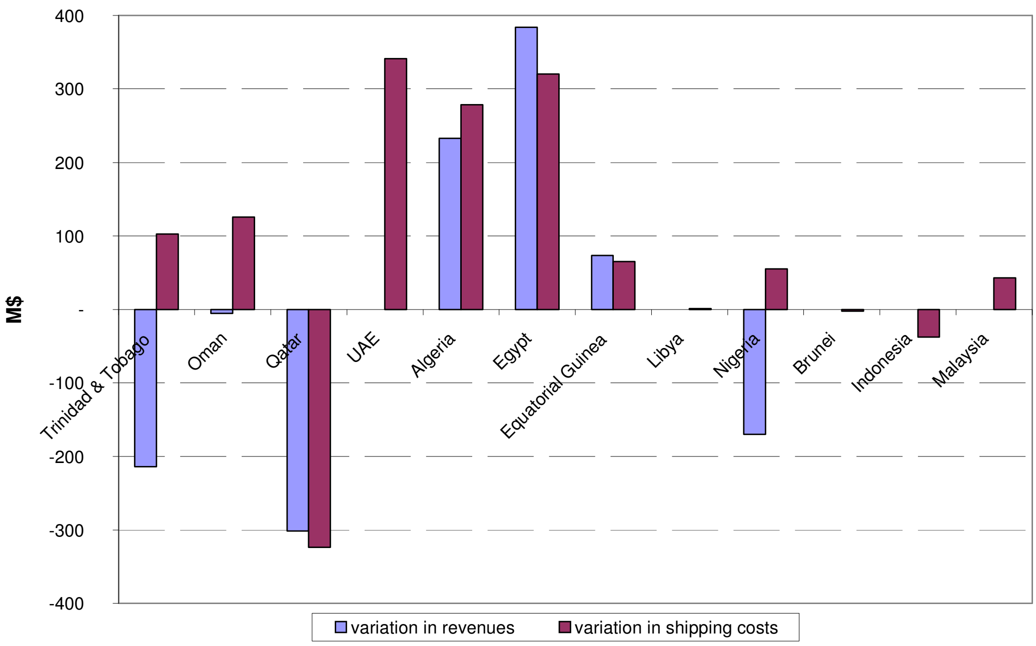

Figure 5 : Gains in cost and revenues derived from the adoption of the optimal solution (in M$)

Results presented in Table 5 suggest that Trinidad & Tobago, Qatar, Nigeria, Brunei and Indonesia face a negative variation in their individual profits. In fact, the implementation of q^* in spite of the shipments observed in 2007 can possibly have two effects on a country: a variation in its revenues and a variation in its shipping costs. Those variations in cost and revenues are presented in Figure 5. For both Trinidad & Tobago and Nigeria, the optimal policy induces a cost gain that is not sufficient to cover their revenue losses. As Brunei and Indonesia's exports remain directed to Asia, those exporters are not earning any revenue gain. But both countries are impacted from a cost increase attached to q^*. For Qatar, the situation is even worse since the GECF's optimal export policy induces both a revenue loss and a shipping cost increase… Obviously, joining the GECF is not a rational decision for each of those five countries. One interesting conflict emerges from those results: a rationalization motivated

[9] Here, we suppose that each country receives the unit price P_j for the gas it ships to country j. Thus, a shipment variation from an importing region to another induces a revenue variation.

GECF may look attractive at a collective level but this is not necessarily true at an individual level. If the GECF was to be organized so that each participant receives only its individual profits, there is little chance to observe those five countries spontaneously joining the GECF[10] in order to implement the optimal policy q^*. Such a decision would cause a decrease in their individual profits!

Cooperative game theory concepts might pave the way to a solution for this conflict. Given that the collective gain obtained thanks to the cooperation is positive and substantial, implementing a gain sharing method could potentially create the conditions for an incentive compatible participation of each of the twelve countries. The next section clearly study this issue

3. An 'incentive compatible' gain sharing

Supposing that the twelve players agree to work together, we assume that the total gain earned through the cooperation can be divided among the members of the coalition. To implement this reallocation of the benefits, we have to suppose that money has the properties of a "transferable utility" so that the problem at hand can be analyzed as a transferable utility game. This is a strong hypothesis but looking at the industrial reality suggests the existence of side-payments among participants in a logistic cooperation[11].

3.1 A game theory background

Context

It is now time to introduce some notations. A cooperative game with transferable utility (TU-game) is a pair (N,v), where $N := \{1,...,n\}$ is a finite set (the set of *players*) and $v : 2^N \to \mathbb{R}$ is a function assigning, to each coalition $S \subseteq N$, its worth $v(S)$. By convention, $v(\varnothing)=0$. Let $|S|$ be the number of elements of coalition S. To simplify the notations, when no ambiguity arises, we use i to denote $\{i\}$ a particular element in N.

In our particular case, N represents the group of prospective participants in a cooperative organization named GECF. There are twelve elements in N: all the non-OECD exporters of LNG. The GECF, as an organization, is supposed to implement the logistic coordination described in the

[10] Note that Figure 5 suggests that this results also holds if the GECF was to be organized so that to avoid any revenue variations. For example: if all the countries manage to keep their 2007 revenues unchanged and to organize a pure shipping cost optimization, q^* remains an optimal policy. In this case, Qatar, Brunei and Indonesia would face an increase in their costs.

[11] In the 1990's, the Italian ENEL and the French GDF signed a swap deal under which Nigerian LNG is delivered in France and GDF diverts an equivalent volume of its imports to Italy. In fact, this swap agreement generated a logistic optimization and transfer prices were used to provide some side-payments with the aim to create the incentives for each participant to cooperate.

previous section. Thus, we can define the worth $v(N)$ to be equal to the maximum profit gain that can be attained by those twelve countries: \$968.31 million. For each coalition S, the gains $v(S)$ to be apportioned among its members are measured by the difference between the maximum total profits to its members when they cooperate and when they don't. Such a coordination policy is strictly limited to S and has thus no impact on the shipments decided by the others $|N \setminus S|$ countries. In other words, $v(S)$ is simply the gain obtained from the creation of a smaller GECF-like organization that implements an optimal shipment policy specifically computed for the coalition S. The gains of operating a shipping coordination for each of the assumption about the degree of cooperation can be estimated from the solution of a linear programming model. If we denote $\delta_i(S)$, the function whose value is equal to 1 if $i \in S$ and is equal to 0 otherwise, a simple adaptation of the previous linear programming model is sufficient to compute the worth of each of the $2^{12} = 4096$ coalitions that can be formed in N:

Programme n°2

$$v(S) = \underset{q_{ij}}{Max} \quad \sum_{i=1}^{n} \delta_i(S).\left(\pi_i - \overline{\pi_i^{2007}}\right)$$

$$\text{s.t.} \quad \sum_{j=1}^{s} q_{ij} = \sum_{j=1}^{s} \overline{Q_{ij}^{2007}} \qquad (\forall i = 1,2,...,n)$$

$$\sum_{i=1}^{n} q_{ij} = \sum_{i=1}^{n} \overline{Q_{ij}^{2007}} \qquad (\forall j = 1,2,...,s)$$

$$\left(1\text{-}\delta_i(S)\right) q_{ij} = \overline{Q_{ij}^{2007}} \qquad \left(\forall (i,j) \in \{1,2,...,n\} \times \{1,2,...,s\}\right) \qquad (3)$$

$$q_{ij} \geq 0$$

We can remark here that the type-(3) constraints clearly precise that this shipment optimization has no impact on the shipments decided by the others $|N \setminus S|$ countries. Thus, the game at hand is a cooperative game without externalities.

It is worth noting here that the gains from cooperation are always positive. Moreover, this function is 0-normalized: $v(i) = 0$, $\forall i$. On top of that, v has a nice property: by construction, v is super-additive since for all coalitions A, B with $A \cap B = \varnothing$, we clearly have $v(A \cup B) \geq v(A) + v(B)$. This feature suggests that countries have real incentives to cooperate since the union of any two disjoint groups of players can only improve their total gains. Thanks to super-additivity, it pays to cooperate in the largest coalition. Thus the problem may turn to be the sharing of the overall gain among the twelve countries.

Formulation of a gain sharing problem

In this TU-game (N,v), the redistribution problem faced by the GECF can be formulated as finding a vector $x \in \mathbb{R}^n$ where the i^{th} coordinate named x_i is simply equal to the benefit allocated to country i. Here again, to simplify the notations, when no ambiguity arises, we use x to denote $x(v)$. It seems natural to expect that x allows a full distribution of the gains created by the GECF. Equivalently, x is expected to be *efficient,* that is to satisfy $\sum_{i=1}^{n} x_i = v(N)$.

For the GECF, the goal of a redistribution policy is to encourage the cooperation of the twelve countries. Thus a reasonable test of the method is to check whether the participants agree in principle to the proposed allocation of benefits. A natural requirement for x is to be *individually rational;* that is, for each $i \in N$, $x_i \geq v(i)$. This individual rationality condition basically states that no country should receive less in the joint operation proposed by the GECF than it would receive on its own. Finding an allocation satisfying this property is fundamental since it constitutes the minimum incentive for an individual country to join the GECF. The set of all efficient and individually rational allocations is named the *imputation set* $I(v)$. Choosing an allocation in $I(v)$ can be viewed as a minimal requirement for the GECF.

One step ahead, it is worth noting that a similar analysis can be extended to coalitions of countries as well as to individual exporters. The condition that no group receives less than the value it could generate on its own is the principle of *group rationality*. An allocation x satisfies group rationality if there is no coalition $S \subseteq N$ such that $\sum_{i \in S} x_i < v(S)$. Group rationality obviously implies individual rationality. Now, the notion of the core (Gillies, 1953) can be introduced. Denote $C(v)$ the core of a game (N,v); it is defined as the set of all efficient and group rational allocations, i.e., $C(v) := \left\{ x \in \mathbb{R}^n : \sum_{i=1}^{n} x_i = v(N) \text{ and, for each } S \subset N, \sum_{i \in S} x_i \geq v(S) \right\}$. In this GECF's case, selecting an allocation within the core constitutes an appealing requirement since it ensures that no participant, or subgroup of participants, can complain about the proposed distribution. In fact, each coalition prefers to cooperate within the grand coalition N – and earns its share of the total gain – rather than choosing a 'stand alone' attitude that yields a lower gain.

However, there is always the adverse possibility that there may be no core imputations: that is, no gain allocations that are group rational. Thus, we have to check whether the core of this gain sharing game is void or not. In some cases, it can be relatively easy to show that the core is non void. For example, in a convex game[12], the core is always non-void. Unfortunately, the gain sharing game considered here is not convex (see the example presented in Table 6).

Table 6: An illustration of the non-convexity of the game (N,v) (figures are in M$)

S	$v(S)$
A := {Brunei, Indonesia}	9.445
B := {Oman, UAE, Equatorial Guinea, Indonesia}	50.100
$A \cup B$:= {Oman, UAE, Equatorial Guinea, Brunei, Indonesia}	50.366
$A \cap B$:= {Indonesia}	0

Thus:

$$v(A) - v(A \cap B) = 9.445 > 0.266 = v(A \cup B) - v(B)$$

However, the super-additive nature of v suggests that a large cooperation can be appealing. Thus, the existence of a non-void core has to be checked using a linear program as follows:

<u>Programme n°3</u>

$$\max_{x_i, \varepsilon} \quad \varepsilon$$

$$\text{s.t.} \quad \sum_{i=1}^{n} x_i = v(N) \qquad (4)$$

$$\sum_{i \in S} x_i - \varepsilon \geq v(S) \qquad (\forall S \subset N) \qquad (5)$$

$$x_i \geq 0 \qquad (\forall i = 1, 2, \ldots, n)$$

$$\varepsilon \geq 0$$

A non void solution to this problem basically shows that a non void core exists since a positive value for ε guarantee that it is possible to find at least one allocation $x \in \mathbb{R}^n$ that satisfy all the constraints attached to the definition of the core. Fortunately for the GECF, we find a solution to that problem (ε is equal to \$360.469 at the optimum). Moreover, the core is not reduced to a unique vector since we found that several $x \in \mathbb{R}^n$ provide this value for ε.

The core provides a "preliminary criterion of a satisfactory allocation". Given that it is neither void nor reduced to a singleton, the core offers an attractive guideline for choosing an allocation since it narrows down the set of acceptable imputations. So it is now time to verify whether some classic gain sharing rules verify this requirement.

[12] A game (N,v) is called convex if for all coalitions A and B in N: $v(A \cup B) - v(B) \geq v(A) - v(A \cap B)$. A classic characterization shows that for convex games, the gain made when individuals or groups join larger coalitions is higher than when they join smaller coalitions (Branzei et al., 2008 p. 46)

3.2 Presentation of some gain sharing methods

Many gain sharing methods can be envisaged for the GECF. In this article, we limit ourselves to a limited sample that includes most of the most popular ones. The first three rules propose to share the collective gain in proportion of the total of a given quantitative criteria. Those naïve rules could typically be inspired by some accounting considerations. A second type of rule is then presented; those two methods explicitly take into account the marginal contribution of each participant. Last but not least, four methods developed in game theory are presented.

Method 1: Equal Repartition of the Total Gain

The logistic gain is basically divided in twelve equal shares: $x_i = \frac{v(N)}{|N|}, \quad \forall i \in N$.

Method 2: Proportional to non-cooperative profits

Here, the total gain $v(N)$ is shared in proportion to the profits earned in 2007, so that exporter's profits are all impacted by an identical rate of increase that is equal to: $1 + \frac{v(N)}{\sum_{i=1}^{n} \overline{\pi_i^{2007}}} \approx 1.0278$.

Hence, $x_i = \frac{\overline{\pi_i^{2007}}}{\sum_{i=1}^{n} \overline{\pi_i^{2007}}} . v(N), \quad \forall i \in N$.

Method 3: Proportional to shipments

Information on LNG shipped quantities is presented in numerous publicly available sources. In this third proportional rule, the total gain $v(N)$ is simply shared in proportion to the total quantities shipped by each exporter in 2007 : $x_i = \frac{\sum_{j=1}^{s} \overline{Q_{ij}^{2007}}}{\sum_{i=1}^{n} \sum_{j=1}^{s} \overline{Q_{ij}^{2007}}} . v(N), \quad \forall i \in N$.

Method 4: A marginal contribution scheme

By definition, the *marginal contribution* m_i of a participant i is equal to $v(N) - v(N \setminus i)$. For a given exporter i, m_i is the gain created by i when joining the coalition of the 11 other participants. Without anticipating too much on the results presented in the next section, it is important to note that this method is not necessarily efficient (and thus do not belong to $I(v)$). In the present case, this method clearly overestimates the total gain to be shared $\sum_{i=1}^{n} m_i > v(N)$.

Method 5: A scheme inspired by the Alternative Cost Avoided method (ACA-method)

This method is inspired by a technique developed during the 1930's by the economists of the Tennessee Valley Authority to allocate the joint costs of multipurpose water development projects (Tijs and Driessen, 1986). In this adaptation to a gain sharing problem, it can simply be viewed as a two-step procedure. In the first step, each player i receives a payment based on its marginal contribution m_i. But, for many value functions, the sum of these marginal contributions is greater than the total value created by the grand coalition. As a result, a total of $\sum_{i=1}^{n} m_i - v(N)$ has to be subtracted from individual's allocations based on m_i. Here comes the second step of the procedure. In the ACA-method, this difference is simply shared in proportion to the total of $(m_i - v(i))$, the differences between the i's marginal value and its value in a stand alone case:

$$x_i = m_i - \left(\sum_{i=1}^{n} m_i - v(N) \right) \frac{m_i - v(i)}{\sum_{l=1}^{n} (m_l - v(l))}, \quad \forall i \in N .$$

Here $v(i)$ is normalized to zero. As a result, the total $\sum_{i=1}^{n} m_i - v(N)$ is simply shared in proportion to the marginal values.

Method 6: The Shapley value

The Shapley value is a well-known game theoretic allocation that has been defined as the unique allocation that satisfies a consistent set of three axioms (Shapley, 1953). An intuitive interpretation of the Shapley value can be presented as follows: as the grand coalition is formed by the sequential addition of exporters, each participant i receives a benefit equal to the entire value $(v(S) - v(S \setminus i))$ he offers to the coalition $S \setminus i$ formed just before him. The Shapley value is i's average benefit if all orders of formation of N - the permutations of the grand coalition - are considered and intervene with the same weight $1/|N|!$ in the computation. The Shapley value is defined as:

$$x_i = \sum_{\substack{S \subseteq N \\ i \in S}} \frac{|S \setminus i|! \times |N \setminus S|!}{|N|!} (v(S) - v(S \setminus i)), \quad \forall i \in N .$$

The Shapley value has an attractive property since this allocation always belongs to the core of a convex game. Unfortunately, there are not so clear-cut results for super-additive games. For our particular instance of our GECF game, we will thus have to test if it belongs to the core.

Method 7: The nucleolus

Another game theoretical concept is the nucleolus proposed by Schmeidler (1969). He defined the unhappiness of a coalition S with respect to a proposed allocation x and proposed to measure it with $e(S,x) = v(S) - \sum_{i \in S} x_i$, the *excess* of the non-trivial coalitions $S \subset N \quad (S \neq \varnothing, N)$ with respect to an allocation x. This excess can simply be viewed as an index of that coalition's objections to the payoffs its members are receiving in the grand coalition. The coalition which objects most strongly to the proposed allocation x is the one with the greatest excess. If this greatest excess is positive, the proposed allocation is outside the core; if it is negative, the allocation is acceptable, but the coalition nevertheless has an interest in obtaining the smallest possible excess. Thus, it is appealing to look for an allocation that minimizes the maximum unhappiness. Schmeidler (1969) went one step ahead and proposed a new solution concept: the nucleolus of the game.

Let $e(x) = \{e_1(x), \ldots, e_{2^n-2}(x)\}$ be a vector in $\mathbb{R}^{2^n-2}$ the components of which are the excess sorted in a decreasing order, where S runs over the subset of $N \ (S \neq \varnothing, N)$. Thus, $e_1(x)$ is the maximum unhappiness created by the proposed allocation x. Thanks to these vectors, two allocations $x, y \in I(v)$ can be compared: x is preferred to y if $e(x)$ is lexicographically smaller[13] than $e(y)$, this is noted $e(x) \leq_l e(y)$. Schmeidler (1969) named nucleolus of the game the set $Nu(v) := \{x \in I(v); e(x) \leq_L e(y) \text{ for all } y \in I(v)\}$ and he proved that the nucleolus is a unique allocation. An appealing property of the nucleolus as an allocation method is that it always belongs to the core when it is nonempty. As a result, the nucleolus has received a great attention that span beyond the strict boundaries of cooperative game theory. For example, Hamlen et al. (1977) precise that: the nucleolus has its analogy with the theory developed by Rawls (1971) in the welfare economic literature.

From a strict practical perspective, Kopelowitz (1967) presented an algorithm for calculating the nucleolus by means of a sequence of linear programs. The procedure used in this article relies on Granot and al. (1998). It is based on the subsequent ideas. Denote Σ^0 the set of $2^n - 2$ coalitions $S \subset N \quad (S \neq \varnothing, N)$ that can be formed in N and k an index that count the number of iterations. The first iteration $k = 1$ of the procedure consists in solving a first linear program named LP_1:

Programme n°4 (LP_1)

$$\underset{x_i,\varepsilon}{Min} \quad \varepsilon$$

$$\text{s.t.} \quad \sum_{i=1}^{n} x_i = v(N) \qquad (6)$$

$$\varepsilon + \sum_{i \in S} x_i \geq v(S) \quad (\forall S \in \Sigma^0) \qquad (7)$$

$$x_i \geq 0 \quad (\forall i = 1,2,...,n)$$

If the game has a non-void core, this problem has a non-void solution set and ε has a negative value at the optimum. Denote e_1 this optimal value of ε. From the outcome of LP_1, we can define X_1 the set of all the allocations x that, combined with e_1, are an optimal solution to LP_1. If the game has a non-void core, the nucleolus is contained in X_1. If the outcome of this problem is a singleton set, then it is clear that the nucleolus has been found and that the algorithm is terminated. But in general, it is not the case and some number of further iterations $k > 1$ of the algorithm are required. The key idea is to get a narrower set X_k that still contains the nucleolus. Thus, a nested sequence $X_1 \supset X_2 \supset ... \supset X_k$ of sets of coalitions has to be constructed.

To initiate a second iteration, we have to identify Σ_1 the collection of all the coalitions $S \in \Sigma^0$ for which the type (7) constraints holds with equality: $e_1 + \sum_{i \in S} x_i = v(S)$ for all optimal solutions of LP_1. We denote Σ^1 the set of all the other coalitions: $\Sigma^1 = \Sigma^0 \setminus \Sigma_1$. Duality theory is helpful to identify the coalitions in Σ_1 since a non-zero dual variable indicates that the corresponding constraint in binding in the primal problem. Then, a new a linear programming problem LP_2 can be implemented. LP_2 is simply derived from LP_1 by converting all the constraints of coalitions in Σ_1 into equalities of the form $e_1 + \sum_{i \in S} x_i = v(S)$.

[13] It means that there are no index $u \in \{1,...,2^n - 2\}$ so that $e_u(x) \geq e_u(y)$ and $e_t(x) = e_t(y)$ for all $t < u$.

Programme n°5 (LP_2)

$$\min_{x_i,\varepsilon} \quad \varepsilon$$

$$\text{s.t.} \quad \sum_{i=1}^{n} x_i = v(N) \qquad (8)$$

$$\sum_{i \in S} x_i = v(S) - e_1 \qquad (\forall S \in \Sigma_1) \qquad (9)$$

$$\varepsilon + \sum_{i \in S} x_i \geq v(S) \qquad (\forall S \in \Sigma^1) \qquad (10)$$

$$x_i \geq 0 \qquad (\forall i = 1, 2, ..., n)$$

Denote e_2 this optimal value of ε. If the optimal solution is still not unique, then a third-stage problem has to be formed. This third problem LP_3 is defined similarly to LP_2 : we identify Σ_2 the collection of all the coalitions $S \in \Sigma^1$ for which the type (10) constraints hold with equality, convert all the corresponding constraints into equalities of the form $\sum_{i \in S} x_i = v(S) - e_2$ and so on… At each stage, at least one additional linear equality is imposed on the n dimensional allocation vector. After a finite number of steps, the procedure terminates with a unique outcome: the nucleolus.

Method 8: The "per capita" nucleolus

The nucleolus is entirely based on a measure of the unhappiness of a coalition with respect to a proposed allocation. But there is some arbitrariness in the definition of the metric. This led Grotte (1970) to define a variant named the per capita nucleolus (also named normalized nucleolus) and obtained thanks to a lexicographic construction based on a per capita measure of the excesses in spite of the previous excesses. In this allocation, the unhappiness of a coalition S with respect to a proposed allocation x is simply measured with $e(S,x) = \dfrac{v(S) - \sum_{i \in S} x_i}{|S|}$.

Method 9: The disruptive nucleolus

This other variant of the nucleolus has its roots in Gately (1974). The two allocations presented in Table 7 provide a good illustration of Gately's ideas.

Table 7: example of two allocations in the core of the cooperative game (in M$)

Trinidad & Tobago	Oman	Qatar	UAE	Algeria	Egypt	Equatorial Guinea	Libya	Nigeria	Brunei	Indonesia	Malaysia	$\sum_{i=1}^{n} x_i$
123.695	20.151	453.897	-	153.649	146.268	2.991	2.149	21.987	0.721	26.958	15.839	968.306
123.592	20.253	452.884	6.935	153.101	147.860	2.322	-	23.488	-	20.855	17.013	968.306

Both allocations belong to the core of our 12-players GECF game and could *a priori* be considered as good candidates to allocate the gains. But, in both cases, there is at least one country that receives absolutely no share of these gains and it is clear that those countries are thus perfectly indifferent between cooperating or staying on their own. In fact, choosing an allocation in the core does not guarantee that each country will receive a positive share of the gains from cooperation.

To eliminate those allocations, Gately (1974) proposed an additional concept named "propensity to disrupt" that was latter extended by Littlechild and Vaidya (1976). For a given allocation vector x, the propensity to disrupt, denoted $d(x,S)$, of any coalition $S \subset N \quad (S \neq \emptyset, N)$, is defined as the ratio of the total amount which the complementary coalition $N \setminus S$ would lose if the grand coalition broke up, to the loss incurred by the coalition S itself if that coalition refuse to cooperate, i.e. :

$$d(x,S) = \frac{\sum_{l \in N \setminus S} x_l - v(N \setminus S)}{\sum_{i \in S} x_l - v(S)}.$$

Suppose that only core allocations are proposed to the members of the grand coalition. It is clear that the propensity of a given subgroup S to disrupt this grand coalition becomes larger when its payment becomes smaller (in such a case, the payment received by other $|N \setminus S|$ increases). It can even rise to infinity, reflecting an aspiration to quit the agreement, as the gain share of S approaches its minimum $v(S)$.

In his 3-person game, Gately (1974) proposed to use an allocation in which every player's propensity to disrupt is identical. Unfortunately, in a n-person game, Littlechild and Vaidya (1976) proved that such an allocation does not necessarily belong to the core. But, Littlechild and Vaidya (1976) proposed an adaptation of the nucleolus where the propensity to disrupt is used as a dissatisfaction measure to be minimized in a lexicographic sense. In the same way as in the nucleolus, let $d(x) = \{d_1(x), \dots, d_{2^n-2}(x)\}$ be a vector in $\mathbb{R}^{2^n-2}$ the components of which are the propensities to disrupt sorted in a decreasing order, where S runs over the subset of $N \ (S \neq \emptyset, N)$. If the strict core $\left\{x \in C(v) : \sum_{i \in S} x_i > v(S), S \subset N, S \neq \emptyset \text{ and } \sum_{i \in N} x_i = v(N)\right\}$ is non-empty, two allocations x, y chosen in the strict core can be compared: x is "less disruptive" than y if $d(x) \leq_l d(y)$. The disruptive nucleolus x_{dn} is the unique allocation in the strict core so that $d(x_{dn}) \leq_l d(x)$ for all other allocation x chosen in the strict core of the game. From a computational perspective, the simple transformation described in Littlechild and Vaidya (1976, p.155) allows to compute this disruptive nucleolus with a sequence of linear programs. Before looking at the results, it is interesting to note here that the reference to the strict core is imposed by the need to keep finite values for $d(x)$. As acknowledged by Littlechild and Vaidya (1976), some difficulties may arise when the core is not sufficiently "large" and this problem led Charnes and al. (1978) to propose an alternative definition of the propensity to disrupt. But in the particular game studied here, we applied the procedure described in Littlechild and Vaidya (1976) and did not experience any computational problem related to those boundaries issues.

4. Results

In this section, the methods developed in the preceding section are applied to analyze the distribution of the gain obtained by the twelve exporters when implementing a logistic cooperation. Based on the previous hypothesis, a total of $968.306 millions is thus to be shared.

4.1 Preliminary comments

Numerical results for the methods described above are given in Table 8. As a first remark, it is important to note that the marginal contribution scheme is not an efficient rule for the GECF and cannot be considered as a workable allocation mechanism. However, this method provides an indication of the relative importance of the different actors. And there are large differences among them, since their marginal contribution vary from a limited $0.7 million for Brunei to $459 millions for Qatar - more than 47% of the total gains when the second largest marginal contribution only gives 25% of those gains. Those results suggest that Qatar's participation seems very important for the whole cooperation and have thus to be rewarded. Those differences obviously depend on factors such as pre-cooperation exports policy, costs and the total volumes to be shipped.

Table 8: allocation of the GECF's gains obtained by the previous methods (M$)

	Marginal Contribution	Equal Repartition	Proportional to profits	Proportional to quantities	An « ACA » inspired method	Shapley Value	Nucleolus	Per Capita Nucleolus	Disruptive Nucleolus
Trinidad & Tobago	123.695	80.692	76.695	85.793	94.130	117.062	81.577	78.334	93.630
Oman	20.253	80.692	49.784	57.479	15.413	20.445	17.195	16.868	16.541
Qatar	459.779	80.692	174.921	181.938	349.885	289.67	386.845	398.619	351.103
UAE	8.386	80.692	29.809	35.688	6.382	8.332	5.306	5.000	6.832
Algeria	205.191	80.692	146.34	116.613	156.147	161.099	144.886	144.776	155.629
Egypt	245.722	80.692	60.172	64.333	186.991	174.970	188.052	185.307	187.873
Equatorial Guinea	6.663	80.692	4.190	6.712	5.071	20.568	3.604	3.277	5.442
Libya	2.149	80.692	4.750	3.592	1.636	3.051	1.075	0.280	0.922
Nigeria	134.774	80.692	105.591	100.021	102.561	121.775	92.220	89.413	102.845
Brunei	0.721	80.692	45.461	44.197	0.549	3.221	0.360	0.060	0.313
Indonesia	30.113	80.692	141.207	131.124	22.916	21.738	27.055	26.728	24.594
Malaysia	34.99	80.692	129.387	140.814	26.627	26.377	20.132	19.643	22.581
TOTAL	*1272.43*	*968.306*	*968.306*	*968.306*	*968.306*	*968.306*	*968.306*	*968.306*	*968.306*

To ease comparisons, Figure 6 illustrates, for each method, the shares of the collective gain attributed to each exporters. As a preliminary remark, we can underline that results obtained with proportional methods differ significantly from the others. These differences are particularly noteworthy for Qatar, Egypt, Indonesia and Malaysia. With proportional methods, Qatar's share is not that different from those received by other exporters, which seem astonishing given the importance of Qatar for the grand coalition (cf. our previous discussion on marginal contributions). By contrast, these allocations provide large gains to South East Asian exporters (Brunei, Malaysia and Indonesia). Regarding the outcome of the three "lexicography inspired" methods, we can naively note that they all provide an equal ranking with Qatar receiving the largest share, followed by Egypt, Algeria, Nigeria, Trinidad & Tobago, Indonesia, Malaysia, Oman, UAE, Equatorial Guinea, Libya and Brunei. Moreover, the nucleolus and the per capita nucleolus schemes provide very similar numerical results.

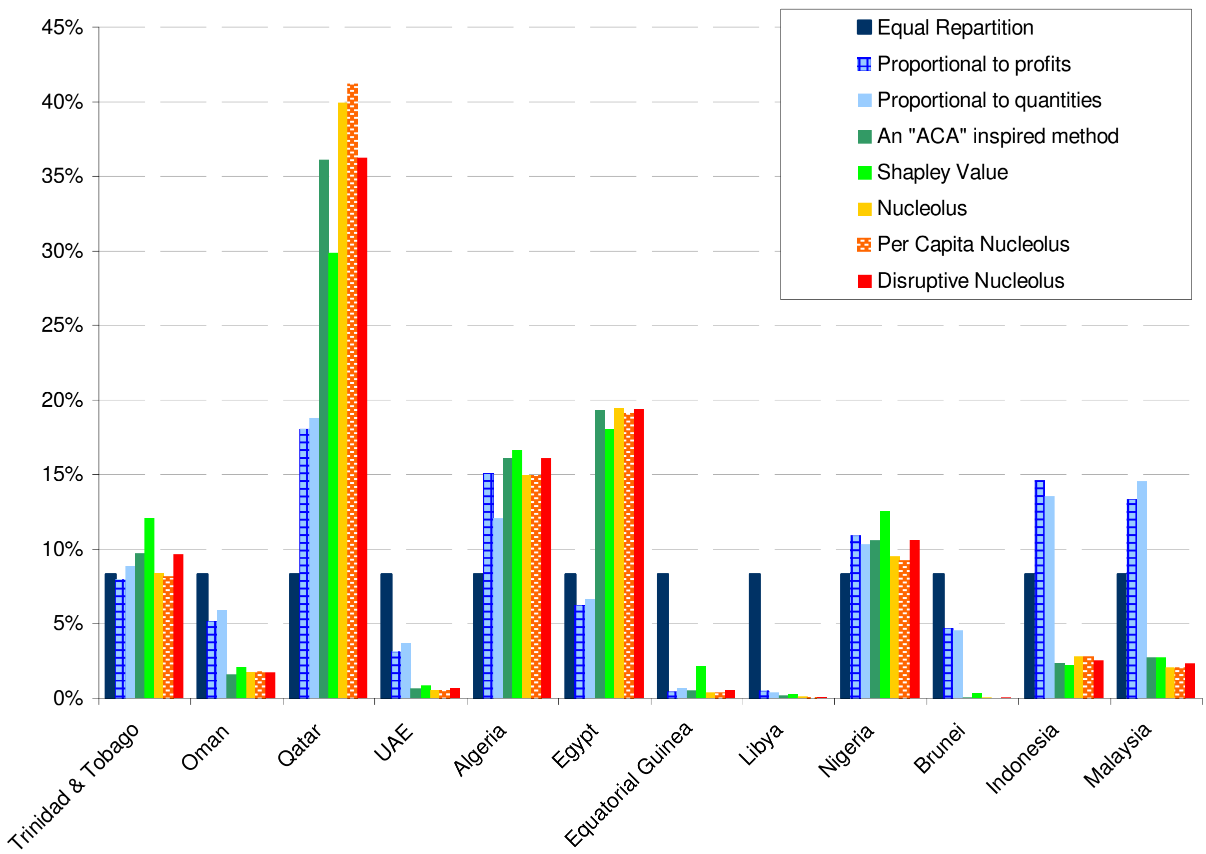

Figure 6 : The shares of the total gain allocated to each country by the eight allocation methods (in %)

4.2 Checking the method's properties

<u>Group rationality</u>

Clearly, all the methods pictured in Figure 6 are elements of the imputation set $I(v)$ and individual exporters have thus an incentive to join the cooperation. But do those allocations provide an incentive to cooperate for each of the 4094 non-trivial subgroups that can potentially be formed? To answer it, an enumeration is necessary and results of this investigation are presented in Table 9.

Clearly, this verification was obviously not necessary for the nucleolus-inspired allocations given that core non-emptiness is sufficient to prove core belonging. But for the other allocations, core belonging is never observed and any GECF agreement based on them would be rationally rejected by some subgroups. Taking proportional methods as an example, a simple comparison with the marginal contributions m_i presented in Table 8 is sufficient to gain confidence in this last affirmation. Those basic allocations provide a share of the gain to some particular individual participants i like Oman, Libya, Brunei, Indonesia and Malaysia that is too large as it is higher than those i's marginal contributions. Framed with a cross-subsidy's vocabulary (Faulhaber, 1975), it simply means that those allocations would "unduly" favor each of those particular exporters i at the expense of the participants involved in the complementary coalitions $N \setminus i$ since each of those complementary coalitions $N \setminus i$ could rightly prefer to stay away from the GECF agreement. Results presented in Table 9 suggest that a similar line of arguments can also be developed for numerous non-trivial coalitions. By contrast, the Shapley Value or the ACA inspired method could be considered as more suitable rules since the number of "unhappy" coalitions is significantly reduced. But, those two schemes are still unable to provide an unanimously accepted gain sharing.

Table 9: Results of core belonging tests

	Equal Repartition	Proportional to profits	Proportional to quantities	An « ACA » inspired method	Shapley Value	Nucleolus	Per Capita Nucleolus	Disruptive Nucleolus
Core membership?	No	No	No	No	No	Yes	Yes	Yes
Number of coalitions likely to refuse the GECF agreement?	981	756	748	2	52	0	0	0

As a first conclusion, we can note that, among the methods studied in this article, only three: the nucleolus, the per capita nucleolus and the disruptive nucleolus methods are able to provide an appropriate gain allocation. But can we go further and find a criterion that could be used to discriminate one method among the three remaining one?

Aggregate-monotonicity

Following Young et al. (1980), we can note that the allocation method is usually chosen before the cooperation has been started, at a time when the total gains obtained from cooperation are yet to be earned and can only be estimated. As a consequence, it is not unrealistic to imagine that each potential participant in the GECF will actively consider various gain scenarios and check allocations outcomes before committing to the GECF. As a result, it would not be surprising to observe that participants collectively require the allocation method to satisfy an elementary monotony property named *aggregate-monotonicity* property (Megiddo, 1974). Denote $x(v)$ - respectively $x(\bar{v})$ - the outcome of a given allocation method computed for the game (N,v) - respectively $(N,\bar{v})$. An allocation $x \in \mathbb{R}^n$ is monotonic in the aggregate if (Young, 1985, p.17) for all v, $\bar{v}$ and N :

$$v(N) \geq \bar{v}(N) \text{ and } v(S) = \bar{v}(S) \text{ for all } S \underset{\neq}{\subset} N$$
$$\text{implies } x_i(v) \geq x_i(\bar{v}) \text{ for all } i \in N$$

For the GECF's case, aggregate-monotonicity is desirable since it basically assures the participants, after committing themselves to an allocation, that if the total gain was to decrease then no participant would receive more; conversely, if total gain increases, no individual payments will decrease.

As an illustration, let us assume that the total gain obtained from cooperation is reduced by $720,939 (the total gain is reduced to $967.585 million). New allocations outcomes have been computed for the three remaining methods and those results are presented in Table 10.

Table 10: Allocations results get under decreased gain (in M$).

	Nucleolus	Per Capita Nucleolus	Disruptive Nucleolus
Trinidad & Tobago	81.640	78.274	93.272
Oman	17.099	16.808	16.590
Qatar	386.698	398.559	352.420
UAE	5.232	4.940	6.447
Algeria	145.232	144.716	155.340
Egypt	187.942	185.247	187.977
Equatorial Guinea	3.509	3.217	4.974
Libya	0.714	0.220	0.904
Nigeria	92.378	89.353	102.528
Brunei	-	-	-
Indonesia	26.959	26.668	25.017
Malaysia	20.180	19.583	22.116
TOTAL	*967.585*	*967.585*	*967.585*

A simple comparison with previous results (cf. Table 8) clearly suggests the per capita nucleolus rule appears to be monotonic in the aggregate, which is not a surprise since a simple demonstration of this result can be found in Young et al. (1980). On the other hand, neither the nucleolus nor the disruptive nucleolus are monotonic in the aggregate. For the nucleolus, this is also a well-known result established by Megiddo (1974). Thus, considering both core belonging and monotonicity in the aggregate clearly narrows the set of possible allocations for the GECF. Among all the methods considered in this article, the per capita nucleolus is the only one that verifies both requirements... In the next subsection, we thus assume that the per capita nucleolus is selected and implemented.

4.3 Dealing with a costly coordination

In the previous subsection, we have assumed that coordination can be organized at a zero cost so that there is a complete redistribution of the gains earned thanks to the GECF. However, it is highly likely that such a cooperation will induce a coordination cost. In the oil industry, OPEC's coordination requires a General Secretariat based in Vienna whose cost is probably limited but obviously not equal to zero. As far as the GECF is concerned, the creation of a dedicated Liaison Office to be located in Qatar is considered (Hallouche, 2006, p. 15). Moreover the formulation of a logistic model, the gathering the data, and the numerical analysis are time-consuming and possibly expensive activities. If the coordination becomes a costly activity, two questions arise. Firstly, how does the existence of an annual coordination cost denoted $\omega > 0$ influence the gain-sharing outcome? Secondly, what is the maximum amount, denoted $\bar{\omega}$, that can be tolerated by the participants without calling into question the advantages of cooperation via the GECF?

Incidence on the gain-sharing outcome

Regarding the impact on the per capita nucleolus outcome, the demonstration in Young et al. (1980) provides a nice answer. If we assume that a costly GECF can be described by the game $\left(N,\bar{v}\right)$ with a reference to the zero-cost case $\left(N,v\right)$ so that $\bar{v}$ is defined as: $\bar{v}\left(N\right)=v\left(N\right)-\omega$ and $v\left(S\right)=\bar{v}\left(S\right)$ for all $S \underset{\neq}{\subset} N$, the per capita nucleolus $x\left(\bar{v}\right)$ of the game $\left(N,\bar{v}\right)$ can also be described from those of game $\left(N,v\right)$. In the costly case, each country i receives $x_i\left(\bar{v}\right)=x_i\left(v\right)-\frac{\omega}{n}$, which corresponds to an equal repartition of the coordination costs. In passing, we can note that applying an OPEC-inspired institutional organization to the GECF is an issue frequently raised by GECF observers and it is interesting to remark that this coordination cost sharing rule is precisely the one used by the OPEC (OPEC Statute, 2008, art. 37, p.21).

The maximum coordination cost

The second question can be reframed as finding the maximum $\bar{\omega}$ compatible with a non-empty core for the game $\left(N,\bar{v}\right)$. Again, solving a simple linear programming problem provides the answer :

Programme n°6

$$\overline{\omega} = \underset{x_i,\omega}{Max} \quad \omega$$

$$\text{s.t.} \quad \omega + \sum_{i=1}^{n} x_i = v(N)$$

$$\sum_{i \in S} x_i \geq v(S) \qquad (\forall S \subset N, S \neq N)$$

$$\omega \geq 0 \ , \ x_i \geq 0 \ , \qquad (\forall i = 1, 2, ..., n)$$

With previous assumptions, a particularly low value of \$720,939 was found for $\overline{\omega}$ (as a order of magnitude, \$97,000 is the average annual salary offered to new Ph.D.s in economics from MIT in an international organization). Any greater amount can be considered as unsustainable because it corresponds to an empty core situation. In our case: with $\overline{\omega}$=\$720,939 the complementary coalition to Brunei has an infinite propensity to disrupt and is perfectly indifferent between cooperating within the GECF and staying on its own. Of course, this observation corresponds to a particular case since, in this linear program, a zero coordination cost is assumed for the subgroups $S \subset N, S \neq N$. Hence, we are supposing that subgroups S are able to earn $v(S)$ and thus do not incur any coordination cost even if the cardinality $|S|$ is large. Framed with basic algebra, it means that the coordination cost $Cc(S)$ of a given subgroup $S \subseteq N$ is equal to $\overline{\omega}$ if $S = N$ and to zero when $S \subset N$ $(S \neq \varnothing, N)$. An assumption on the amount of coordination costs incurred by S as a function of $|S|$ could certainly be needed to get a more realistic representation[14]. Nevertheless, this very low amount suggests that: even a limited coordination cost can be enough to get an empty core situation. In this unfortunate situation, whatever the proposed gain sharing method, there is always at least one coalition that can rightly protest against the allocation outcome.

Conclusions

Since the mid-2000s we are seeing heightened concern about the future of the GECF and the possible emergence of a cartel in the gas industry. These debates have received considerable publicity especially for the trade of LNG. As a consequence, many authors have proposed a detailed description of the GECF. To our knowledge, most of those contributions present a strict geopolitical approach and lack a clear economic analysis. This paper represents no more than a modest attempt to illustrate how some quantitative techniques can be used to address an important issue: what could be the future GECF's behavior?

[14] Various functional forms have also been considered to describe coordination costs as a function of a subgroup's cardinality. But results indicate that the GECF cannot afford large coordination costs. As an example: with a quadratic form $Cc(S) = \rho.(|S|-1)^2$ where $\rho = \overline{\omega}/(n-1)^2$ for $S \subseteq N$ $(S \neq \varnothing)$, the amount of $\overline{\omega}$ is as low as \$4.153 millions, which corresponds to a limited \$356 thousand per participant.

Many experts and industrial observers share an idealized view of how cooperation among LNG exporters could be entirely devoted to the promotion of a purely logistic cooperation. In most cases, there is no room for market power issues in those mental constructions. We thus adopted this strong behavioral assumption and supposed that the GECF's objective can be reframed as the identification of optimum routes and schedules for a fleet of vessels carrying participant's LNG throughout the world. This paper investigates meticulously the rationale of such an association of LNG exporters by means of a simple transportation model. In this particular instance of a transportation problem, cooperation is found to be collectively profitable since there is a potential for a reduction of the lengths of actual supply chains. But, results indicate also that some countries could rationally prefer to stay away from the GECF unless a redistribution mechanism is implemented. Thanks to a cooperative game theory framework, we show that this logistic cooperation at hand corresponds to a super-additive game whose core is non-empty. Several classic allocation concepts (basic sharing methods, the Shapley value and nucleolus-inspired methods) have been implemented and analyzed in the light of two desirable axiomatic properties. Firstly, core belonging is considered as an imperative prerequisite since it eliminates possible contestation to the proposed redistribution scheme. Then, aggregate-monotonicity is checked so that to promote the methods that are able to adapt to changing conditions on the total value to be shared. Out of the methods studied, only one - the per capita nucleolus – satisfies both criterions. Thus, the range of conceivable methods appears significantly narrower than expected. Moreover, this nucleolus-inspired method is somewhat complicated and requires detailed information on costs, distances... From a strict practical perspective, some doubts can be raised on the capability of the GECF to implement such a non-trivial allocation. Lastly, coordination costs were considered. Our results indicate that a limited amount of coordination costs could be sufficient to deny the possibility to find a core-belonging allocation of the gains thus creating some incentive for a split up of the grand coalition.

Of course, there are several improvements that could be included in this simple model, notably the existence of potentially large LNG exporters such as Russia, Iran and Venezuela. All these countries do not export yet any volume of LNG but are expected to do so and are already involved in GECF's meetings. Compared to the simple static model presented in this paper, the number of participants would climb to at least 15 players and a dynamic framework would have to be implemented so as to capture the essence of the potentially complex interactions among those players. Moreover, such a dynamic approach would enable us to see how the existence of heterogeneous reserve endowments could have affect cooperation outcomes. Of course, it would result in an increased complexity that would also be reflected in the gain sharing issue.

As a consequence, it is now clear that a pure logistic cooperation in the LNG industry faces a complicated gain-sharing problem that can hardly be tackled by trivial methods. As far as we are concerned, this conclusion makes us think that this strong behavioral assumption is not so realistic for the GECF and thus has be reconsidered. As an alternative, the ability to exert some market power, so as to raise prices in consuming regions, can be posited. Such a behavior would obviously enlarge the collective gains of "the conspirators" but there is no free lunch since well-known cartel problems would emerge as well: 1) predicting and if possible, discouraging production by nonmembers; 2) finding a unanimously accepted contract to share the gains; 3) detecting and deterring cheating. Further research is thus needed to analyze GECF's possible behaviors in an imperfect competition framework.

References

Boots M.G., Rijkers F.A.M., Hobbs B.F., 2004. Trading in the downstream European gas market: a successive oligopoly approach. Energy Journal 25(3), 73–102.

BP, 2008. BP Statistical Review of World Energy. BP, London.

Charnes A., Rousseau J., Seiford L., 1978. Complements, Mollifiers and the Propensity to Disrupt. International Journal of Game Theory 7(1), 37-50.

Cremer J., Weitzman M., 1976. OPEC and the Monopoly Price of World Oil. European Economic Review 8, 155-164.

Dantzig, G. B. 1951. Application of the simplex method to a transportation problem. In Koopmans, T. C. (ed.), Activity Analysis of Production and Allocation, John Wiley& Sons:NY; 1951. 359-373.

DTI, 2005. UK Capability in the LNG Global Market. Department of Trade and Industry, Energy Technologies and Industries Unit. London.

Egging R., Gabriel S.A., Holz F., Zhuang J., 2008. A complementarity model for the European natural gas market. Energy Policy 36(7), 2385-2414.

Engevall S., Göthe-Lundgren M., Värbrand P., 1998. The traveling salesman game: An application of cost allocation in a gas and oil company. Annals of Operations Research 82(1), 453-472.

Faulhaber G.R., 1975. Cross-subsidization: pricing in public enterprises. American Economic Review 65(5), 966-977.

Finon D., 2007. Russia and the "Gas-OPEC". Real or Perceived Threat? IFRI Russia/NIS Center, Paris.

Flood M. M., 1954. Application of Transportation Theory to Scheduling a Military Tanker Fleet. Journal of the Operations Research Society of America 2(2), 150-162.

Gately D., 1974. Sharing the games from regional cooperation: a game theoretic application to planning investment in electric power. International Economic Review 15, 195-208.

GIIGNL, 2008. The LNG Industry. GIIGNL, Paris.

Gillies, D.B. (1953) "Some theorems on n-Person games". Ph.D. Thesis, Princeton.

Giraud A., Boy de la Tour X. Géopolitique du Pétrole et du Gaz. Editions Technip: Paris; 1987.

Golombek R., Gjelsvik E., Rosendahl K.E., 1995. Effects of liberalizing the natural gas markets in Western Europe. Energy Journal 16, 85–111.

Granot, D., F. Granot, Zhu W.R., 1998. On Characterization Sets for the Nucleolus, International Journal of Game Theory 27, 359-374.

Greaker M, Lund Sagen E., 2008. Explaining experience curves for new energy technologies: A case study of liquefied natural gas. Energy Economics 30, 2899–2911

Grotte, J.H., 1970. Computation of and Observations on the Nucleolus, and the Central Games. M.Sc. Thesis, Cornell University.

Hallouche H., 2006. The Gas Exporting Countries Forum: Is it really a Gas OPEC in the Making, Oxford Institute for Energy Studies, NG 13, Oxford.

Hamlen S., Hamlen J., Tschirhart W., 1977. The Use of Core-Theory in Joint Cost Allocation. The Accounting Review 52(3), 616-27.

Hartley P., Medlock. K.B., 2006. Political and economic influences on the future world market for natural gas. In Victor, D.G., Jaffe, A.M., Hayes, M. H. (Eds), Natural Gas and Geopolitics: From 1970 to 2040, chapter 12, Cambridge University Press; 2006.

Hayes M. H., Victor D. G., 2006. Politics, Markets and the Shift to Gas: Insights from the Seven Historical Case Studies. In Victor, D.G., Jaffe, A.M., Hayes, M. H. (Eds), Natural Gas and Geopolitics: From 1970 to 2040, chapter 10, Cambridge University Press; 2006.

Holz F., Hirschhausen C.v., Kemfert C., 2008. A Strategic Model of European Gas Supply (GASMOD), Energy Economics 30(3), 766–788.

Jaffe A.M., Soligo R. 2006. Market Structure in the New Gas Economy: Is Cartelization Possible? In Victor, D.G., Jaffe, A.M., Hayes, M. H. (Eds), Natural Gas and Geopolitics: From 1970 to 2040, chapter 11, Cambridge University Press; 2006.

Jensen J.T., 2003. The LNG revolution. The Energy Journal 24 (2), 14-58.

Kantorovich L. V., 1960. Mathematical Methods of Organizing and Planning Production. Management Science 6(4), 366-422.

Kattuman P.A., Green R.J., Bialek J.W., 2004. Allocating electricity transmission costs through tracing: a game-theoretic rationale. Operations Research Letters 32 (2), 114-120.

Koopmans T., 1949. Optimum Utilization of the Transportation System. Econometrica 17, 136-145.

Kopelowitz A., 1967. Computation of the kernels of simple games and the nucleolus of n-person games. RM-131, Mathematics Department, The Hebrew University of Jerusalem, Israel.

Littlechild S.C., Vaidya K.G., 1976. The propensity to disrupt and the disruption nucleolus of a characteristic function game. International Journal of Game Theory 5, pp. 151–161.

Mandil C., 2008. Interview by the Challenges magazine's website published in "Bientôt une OPEP du gaz" an article posted on 22nd September 2008; http://www.challenges.fr/actualites/finance_et_marches/20080922.CHA6616/bientot_une_opep_du_gaz_.html

Mathiesen L., Roland K., Thonstad K., 1987. The European Natural Gas Market. Degrees of Market Power on the Selling Side. In Golombek and Hoel (eds.), Natural Gas Markets and Contracts, North Holland Publ. Co., Amsterdam, 1987.

Mazighi A. E. H., 2003. An examination of the international natural gas trade, OPEC Review 27 (4), 313-329.

Megiddo N., 1974. On the nonmonotonicity of the bargaining set, the kernel, and the nucleolus of a game. SIAM Journal of Applied Mathematics 27, 355-358.

OME. Assessment of Internal and External Gas Supply Options for the EU - Evaluation of the Supply Costs of New Natural Gas Supply Projects to the EU and an Investigation of Related Financial Requirements and Tools. Observatoire Méditerranéen de l'Energie: Sophia-Antipolis; 2001.

OPEC (Organization of Petroleum Exporting Countries). OPEC Statute 2008, OPEC Secretariat: Vienna; 2008.

Percebois J. L'économie de l'énergie, Editions Economica: Paris; 1989.

Percebois J., 2008. The supply of natural gas in the European Union—strategic issues, OPEC Energy Review 32 (1), 33-53

Pindyck R.S., 1978. Gains to Producers from the Cartelization of Exhaustible Resources, The Review of Economics and Statistics 60(2), 238-251.

Pierru A., 2007. Allocating the CO2 emissions of an oil refinery with Aumann–Shapley prices. Energy Economics 29(3), 563-577.

Rawls J. A Theory of Justice. Harvard University Press: Cambridge; 1971.

Schmeidler D., 1969. The nucleolus of a characteristic function game. SIAM Journal on applied mathematics 17, 1163-1170.

Shapley, L.S., 1953. A Value for n-Person Games. In Kuhn, H.W. and Tucker, A.W. (eds.) Contributions to the Theory of Games, n. II, Annals of Math. Studies, 28. Princeton University Press; 1953. pp. 307-317.

Tijs S. H., Driessen T. S. H., 1986. Game Theory and Cost Allocation Problems, Management Science 32(8), 1015-1028.

Tönjes C., de Jong J. Perspectives on security of supply in European natural gas markets, CIEP, Clingendael Institute:The Hague; 2007.

Wagbara O.N., 2007. How would the gas exporting countries forum influence gas trade? Energy Policy 35(2), 1224-1237.

Wolak F.A., Kolstad C.D., 1988. Measuring Relative Market Power in the Western US Coal Market Using Shapley Values. Resources and Energy 10, 293-314.

Yepes Rodríguez R., 2008. Real option valuation of free destination in long-term liquefied natural gas supplies. Energy Economics 30(4), 1909-1932.

Yergin D., Stoppard M., 2003. The next prize. Foreign Affairs 82(6), 103-114.

Young H.P., Okada N., Hashimoto T., 1980. Cost Allocation in Water Resources Development. A Case Study of Sweden. IIASA Research report, Laxenburg.

Young H.P., 1985. Methods and principles of cost allocation. In. H. Young. (Ed.) Cost Allocation: Method, principles, applications. North-Holland: Amsterdam; 1985.

Appendix

Table 11: Observed LNG trade movements $\overline{Q_{ij}^{2007}}$ *from GECF countries in 2007 (Bcm)*

From \ to	North America				Europe								Asia					Total Export
	US	**Mexico**	**Dominican Republic**	**Puerto Rico**	**Belgium**	**France**	**Greece**	**Italy**	**Portugal**	**Spain**	**Turkey**	**United Kingdom**	**China**	**India**	**Japan**	**South Korea**	**Taiwan**	
Trinidad & Tobago	12.76	0.62	0.36	0.74	0.07	0.06	-	-	-	2.09	0.06	0.39	-	0.21	0.57	0.22	-	-
Oman	-	-	-	-	-	-	-	-	-	0.12	-	-	-	0.21	4.81	6.74	0.21	**12.16**
Qatar	0.52	-	-	-	2.75	-	-	-	-	4.45	-	0.27	-	8.27	10.87	10.79	0.57	**38.49**
UAE	-	-	-	-	-	-	-	-	-	-	-	-	-	0.07	7.41	0.07	-	-
Algeria	2.11	-	-	-	0.35	7.85	0.5	2.43	-	4.32	4.45	0.64	0.42	0.44	0.78	0.24	0.14	**24.67**
Egypt	3.24	0.99	-	-	-	1.21	0.31	-	-	4.04	0.08	0.16	-	0.07	1.62	1.48	0.41	**13.61**
Equatorial Guinea	0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	0.36	-	0.56	**1.42**
Libya	-	-	-	-	-	-	-	-	-	0.76	-	-	-	-	-	-	-	**0.76**
Nigeria	2.69	0.56	-	-	-	3.78	-	-	2.31	8.33	1.42	-	0.08	0.64	0.88	0.24	0.23	**21.16**
Brunei	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8.57	0.78	-	**9.35**
Indonesia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.07	5.12	4.55	**27.74**
Malaysia	-	-	-	-	-	-	-	-	-	-	-	-	-	0.07	17.65	8.15	3.92	**29.79**
Total imports	**21.82**	**2.17**	**0.36**	**0.74**	**3.17**	**12.9**	**0.81**	**2.43**	**2.31**	**24.11**	**6.01**	**1.46**	**0.57**	**9.98**	**71.59**	**33.83**	**10.59**	**204.85**

Source: BP Statistical Review 2008

Table 12: Optimized LNG trade movements q^* *from GECF countries in 2007 (Bcm)*

From \ to	North America				Europe								Asia					Total Export
	US	**Mexico**	**Dominican Republic**	**Puerto Rico**	**Belgium**	**France**	**Greece**	**Italy**	**Portugal**	**Spain**	**Turkey**	**United Kingdom**	**China**	**India**	**Japan**	**South Korea**	**Taiwan**	
Trinidad & Tobago	14.88	2.17	0.36	0.74	-	-	-	-	-	-	-	-	-	-	-	-	-	**18.15**
Oman	-	-	-	-	-	-	-	-	-	-	-	-	-.57	2.43	-	9.16	-	**12.16**
Qatar	-	-	-	-	-	-	-	-	-	-	-	-	-	-	27.9	-	10.59	**38.49**
UAE	-	-	-	-	-	-	-	-	-	-	-	-	-	7.55	-	-	-	**7.55**
Algeria	-	-	-	-	-	9.26	-	-	-	15.41	-	-	-	-	-	-	-	**24.67**
Egypt	-	-	-	-	-	3.64	0.81	1.67	-	-	6.01	-	-	-	1.48	-	-	**13.61**
Equatorial Guinea	-	-	-	-	-	-	-	-	-	1.42	-	-	-	-	-	-	-	**1.42**
Libya	-	-	-	-	-	-	-	0.76	-	-	-	-	-	-	-	-	-	**0.76**
Nigeria	6.94	-	-	-	3.17	-	-	-	2.31	7.28	-	1.46	-	-	-	-	-	**21.16**
Brunei	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9.35	-	-	**9.35**
Indonesia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	27.74	-	-	**27.74**
Malaysia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.12	24.67	-	**29.79**
Total imports	**21.82**	**2.17**	**0.36**	**0.74**	**3.17**	**12.9**	**0.81**	**2.43**	**2.31**	**24.11**	**6.01**	**1.46**	**0.57**	**9.98**	**71.59**	**33.83**	**10.59**	**204.85**

Table 13: Shortest maritime distances d_{ij} between an exporter i and the regasification plants located in j (km)

to	North America				Europe								Asia				
From	US	Mexico	Dominican Republic	Puerto Rico	Belgium	France	Greece	Italy	Portugal	Spain	Turkey	United Kingdom	China	India	Japan	South Korea	Taiwan
Trinidad & Tobago	3130	4074	1037	1258	7214	6945	9743	7977	6300	6328	10640	7114	14816	15609	16501	17505	18842
Oman	14042	16607	13380	13142	10892	7701	4469	7438	8430	7888	4389	11171	7799	1408	11232	9816	8740
Qatar	17613	20178	16951	16713	11625	8490	5492	8227	9830	8723	5412	11905	9060	2289	11449	11077	9371
UAE	17478	20043	16816	16578	11575	8382	5358	8119	9780	8588	5278	11855	9260	2200	11649	11277	9571
Algeria	6799	9364	6137	5899	2871	741	1704	845	1076	209	2600	3102	15098	8843	16783	17172	15423
Egypt	9680	12245	9019	8780	5886	2658	1000	2517	4091	2761	1119	5986	11938	6062	14592	14012	12638
Equatorial Guinea	10053	11894	8875	8500	8253	7501	10253	7870	6458	6351	10403	8353	17594	13171	19981	19235	17885
Libya	8897	11462	8235	7997	4963	1982	2030	1769	3169	1978	2130	5195	13383	7062	16114	15457	13927
Nigeria	9667	11508	8600	8300	8123	7371	9219	7740	6328	6221	9369	8223	17275	13062	19635	19176	17483
Brunei	20435	23000	19773	19535	14670	11479	8455	11216	12875	11545	8375	14949	2778	3895	4426	3730	3769
Indonesia	23154	25719	22492	22254	17388	14186	11173	13934	15594	14264	11093	17668	2852	6584	4095	3784	2695
Malaysia	22133	24698	21472	21233	16368	13177	10153	12914	14573	13244	10073	16648	2778	5593	3984	3100	2500

Sources: GIIGNL. Barry Rogliano Salles and author's estimates.

Table 14: Unit shipping costs T_{ij} for LNG ($/1000m^3)

to	North America				Europe								Asia				
From	US	Mexico	Dominican Republic	Puerto Rico	Belgium	France	Greece	Italy	Portugal	Spain	Turkey	United Kingdom	China	India	Japan	South Korea	Taiwan
Trinidad & Tobago	25.24	29.76	15.29	16.33	44.89	43.59	57.23	48.6	40.47	40.61	61.62	44.41	82.32	86.29	90.77	95.82	102.59
Oman	77.87	90.67	74.59	73.41	62.32	46.77	31.21	45.49	50.31	47.67	30.82	63.69	47.24	16.64	63.99	57.05	51.81
Qatar	95.4	108.36	92.08	90.89	65.65	50.34	35.88	49.07	56.86	51.47	35.49	67.02	53.11	20.61	64.78	62.96	54.63
UAE	94.88	107.84	91.56	90.37	65.54	49.95	35.35	48.67	56.75	50.94	34.97	66.92	54.21	20.29	65.91	64.08	55.73
Algeria	42.52	54.98	39.33	38.18	23.69	13.59	18.15	14.08	15.18	11.09	22.4	24.79	83.27	52.44	91.71	93.66	84.9
Egypt	56.92	69.54	53.68	52.52	38.47	22.99	15.11	22.32	29.84	23.48	15.67	38.95	68.02	39.32	81.2	78.31	71.49
Equatorial Guinea	58.48	67.52	52.72	50.9	49.69	46.04	59.46	47.83	41	40.48	60.19	50.18	95.95	73.84	108.04	104.25	97.42
Libya	52.72	65.33	49.57	48.35	33.8	19.57	19.79	18.55	25.21	19.55	20.27	34.91	74.89	43.92	88.51	85.22	77.59
Nigeria	56.59	65.63	51.38	49.92	49.06	45.41	54.4	47.2	40.37	39.85	55.14	49.55	94.35	73.3	106.28	103.95	95.39
Brunei	110.02	123.13	106.65	105.44	81	65.21	50.43	63.92	72.09	65.54	50.04	82.39	23.14	28.46	31	27.68	27.86
Indonesia	123.39	136.61	120	118.78	94.13	78.16	63.31	76.91	85.15	78.54	62.91	95.53	23.18	41.02	29.09	27.61	22.44
Malaysia	120.83	134.16	117.42	116.19	91.36	75.32	60.31	74.01	82.32	75.66	59.91	92.77	24.41	37.99	30.21	25.96	23.08

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