Spatial Price Equilibrium in the World Natural Gas Market

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Abstract
Characteristic for the world natural gas market is that the markets in different continents are not completely integrated. In some cases, this leads to exceptionally large price differences. There are two reasons for this; first the technical difficulties related to shipping natural gas, second the pricing mechanism of the natural gas market.

The purpose of this thesis is to use the Spatial Price Equilibrium (SPE) theory to describe the world market for natural gas and to predict how it will react to the recent disturbances in trade following the Russian invasion of Ukraine in 2022.

We include data from all countries in the world with an import or export exceeding 10 000 terajoule of natural gas into a SPE model implemented in the GAMS programming language. The result from the model tells what world gas trade flows would be if arbitrage possibilities were utilized and find that it partially differs from real trade flows. Thus, our thesis concludes that the world market for natural gas is only partially integrated, which is also in line with the current economic research in the field.

Using the model, a scenario is simulated where sanctions limit trade of Russian gas. In this scenario Europe will experience higher prices and less consumption of gas. In the long run given that the capacity of shipping LNG is increased, Europe will compensate with imports from other sources and the price and consumption levels will return to normal, while Russia will also find new export markets for its gas and return towards, but not quite reach, pre-sanctions export levels.

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1 Introduction

The price of natural gas for households in Europe was stable around approximately 0.04-0.06 €/kwh between 2010 and 2021 (Eurostat, 2022). In December 2021 energy markets reacted to the reports of a potential Russian invasion of Ukraine with sharply increasing prices. Two weeks after the invasion the prices of gas went up by 180% (Adolfsen et al., 2022). Since then the price of natural gas has declined during the first half of 2022, but was still high compared to the past ten years (Eurostat, 2022).

In the past, gas prices have typically been determined on regional markets. This is due to the difficulties related to the transportation of gas between regions. Natural gas pipelines are costly to build, energy markets are often heavily regulated, geopolitical tensions hinders trade and pricing in the gas market is unconventional due to long term contracts and so-called oil index pricing that ties the gas price to oil. In recent years, expanding volumes of natural gas have been traded due to the increased capacity to ship gas long distances in the form of Liquefied Natural Gas (LNG). Thus, the market for natural gas shows signs of becoming more integrated throughout the world (Hafner & Luciani, 2022).

Given a more integrated world market for natural gas, many studies have tried to describe the markets and the integration between them using different empirical methods like correlation, cointegration and price convergence (Dukhanina & Massol, 2018). However, since the end user price of natural gas consist to over 50% of transportation costs, Dukhanina and Massol (2018) argues that it is important to use a model which takes that important transportation costs into consideration. One such model is the Spatial Price Equilibrium (SPE) theory originally developed by Samuelsson in 1951, and Takayama and Judge in 1964. The basic idea of the SPE theory is that the price spread between two markets will equal the transportation cost, but only as long as the transportation cost is less than the price spread. If the transportation cost is larger than the price spread, then no trade will occur between the markets.

1.1 Purpose and research question

The purpose of this thesis is to explain the world market for natural gas by implementing the SPE model. Furthermore, we will make predictions about changes in gas prices and world trade flows related to the recent disturbance in the European gas import following the Russian invasion of Ukraine in 2022.

This thesis will therefore answer the following research questions:

- Is it possible to describe the world natural gas trade flows prior to 2022 using the SPE model?
- According to the SPE model, how will the European gas market react to the events that took place during the autumn in 2022 that lead to a complete stop of large gas imports through the Nordstream pipeline and a reduction of gas imports from Russia?
- How would world trade be affected by a large build-up of LNG shipping capacity?

To our knowledge we are the first to use the SPE theory in a computer model that includes all countries in the world with an import or export exceeding 10 000 terajoule of natural gas to describe the world market for natural gas, and to predict the effect of a large disturbance of the European natural gas import.

1.2 Background

The world market for natural gas has very special characteristics that make it different from normal markets, especially different from the oil market. This background will describe the technical aspects and the pricing mechanism of the natural gas market which are important to be aware of in order to understand how the market behaves.

1.2.1 Technical aspects of the natural gas market

Natural gas is the most expensive and challenging primary fuel to transport from the wellhead to the end user. This is based on the fact that natural gas has a low energy density on a volumetric basis, approximately 1000 times lower compared to crude oil. Internationally traded natural gas is transported either in gaseous form through pipelines or in the form of liquid natural gas on ships, so-called LNG carriers. The transportation accounts for over 50% of the cost incurred through the value chain for international natural gas trade. During the 1960s and 1970s, interregional natural gas trade emerged in connection with the opening of the first commercial LNG export facilities and the construction of the first long-distance pipelines (Hafner & Luciani, 2022).

In the past, pipelines have dominated the international gas trade, but since the beginning of the twenty-first century, LNG exports have more than tripled and corresponded to half of the international gas trade for the year 2018 (Hafner & Luciani, 2022).

1.2.2 Pipelines

Natural gas pipeline projects are capital intensive. The initial investment costs account for over 90% of the total cost incurred during the life of the pipeline, which corresponds to approximately 40 years. Operating costs are significantly lower and the equivalent of up to 5-10% of the total cost (Hafner & Luciani, 2022).

Apart from the construction costs, international pipelines that pass through several countries and borders must comply with different regulations, which mean that the costs related to administration and registration fees increase the total costs significantly (Hafner & Luciani, 2022).

The transportation is provided as a service by the operator to the shipper who is the owner of the gas. The transport cost of internationally traded natural gas through pipelines takes place through a gas transport agreement, which is a long-term contract that can extend over 20 years. The gas transport agreement has two parties; the transporter who operates the pipeline and the shipper who owns the gas. The shipper in turn often has a gas sales agreement, which is a separate contract between the shipper who owns the gas and the clients who buys the gas. The tariffs vary widely from a range of $0.5/MMBTU/1000 km at the lower end to over $2.5/MMBTU/1000 km for the most expensive pipeline routes. Once the gas has entered the importing country, there is a different price mechanism for the local distribution with much shorter contracts (Hafner & Luciani, 2022).

The capacity of a pipeline depends on the diameter. For example, a 56 inch pipeline has a capacity of 30 bcm/year, a 36 inch has a capacity of 10 bcm/year. Once the pipeline is build it is not possible to increase the capacity beyond what it was designed for, thus if increased capacity is needed, then a new larger pipeline is needed (Hafner & Luciani, 2022).

1.2.3 Liquefied natural gas

The production of liquefied natural gas takes place by cooling natural gas down to -162 °C. This reduces its volume by approximately 600 times and is done with the aim of transporting natural gas in a more flexible manner, as distinct from pipelines that have a fixed route by definition. International trading of LNG takes place through LNG carriers that are specially designed for transporting LNG (Hafner & Luciani, 2022).

Global LNG trade has grown from less than 50 bcm/year in the 1970s to over 500 bcm in 2020, representing over 10% of global gas consumption and over 50% of international trade of the gas. It is common in LNG trade that bcm (billion cubic meters) measures the amount of gas that LNG will provide when converted back to gaseous form (Shively, 2022).

The LNG value chain consists of three main components:

1. The condensing terminal where the gas is purified and cooled down to -162 °C. The energy required to cool natural gas down to this temperature corresponds to 10% of its initial energy content.
2. Transport via LNG carriers.
3. A regasification terminal: including storage tanks, vaporizers, LNG unloading arms, odor and measurement stations and dispatch to the transmission system of the importing country.

Similar to long-distance pipelines, the LNG value chain is characterized by high initial costs and relatively low operating costs. Especially the construction of the liquefaction terminal is expensive and have become even more expensive to build due to the increased demand for engineering and construction of such facilities when many different projects have been going on at the same time throughout the world (Hafner & Luciani, 2022).

Over half of all LNG carriers are built recently and have an average age of less than 10 years, which is a result of the increased demand for LNG over the last decade. LNG that is traded internationally between countries is transported via large carriers with a special cargo containment system that maintains a temperature of -162°C (Hafner & Luciani, 2022).

In a typical LNG carrier with a cargo capacity of 160,000 m^3, the transportation cost will be $0.04 per MMBTU and 1000km, which is significantly cheaper compared to pipelines where the unit transportation cost ranges between $0.5 and $2.5 per MMBTU and 1000 km.
As seen in figure 1, an LNG carrier is only effective against pipeline transport when it comes to long distances since it has a long-term rent of $80,000/day and also incurs a liquefaction cost of about $2.4/MMBTU and regasification fee of $0.4/MMBTU. As with pipeline transportation, the operator of the LNG carriers are separated from the gas owners (Hafner & Luciani, 2022).

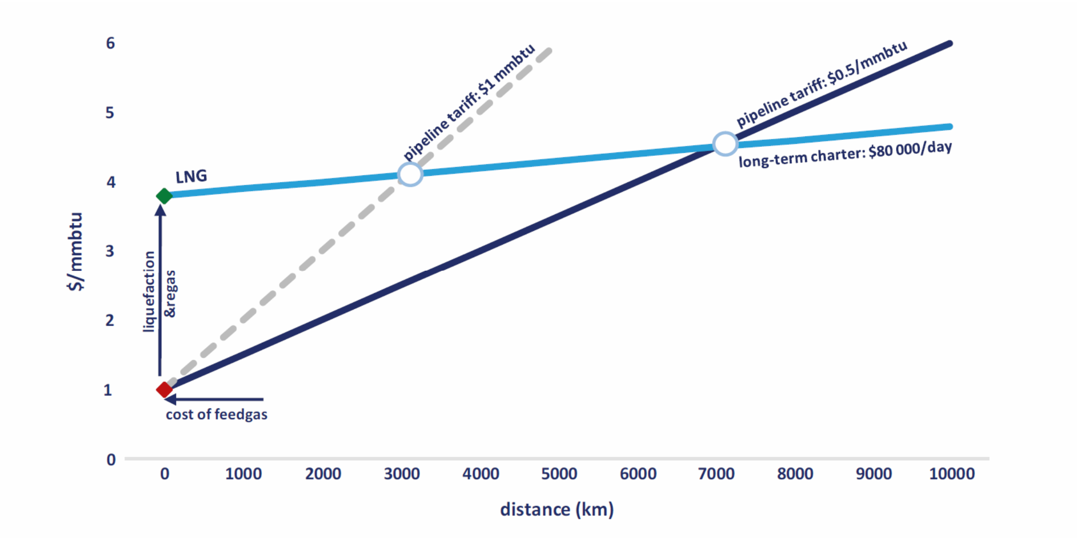

Figure 1: Comparing transportation costs between LNG and pipeline (Source: Hafner & Luciani, 2022)

1.2.4 Trading and price discovery in the natural gas market

There are three major ways of pricing gas: gas-to-gas competition, oil-indexation and bilateral monopoly. Notably some gas used has no price at all, it is given away for free to consumers, and if not used by consumers, it would be flared (Hafner & Luciani, 2022). Flaring means that gas, most often when it is a biproduct in oil extraction, is just burned directly at site without being used for anything. Annually 144 bcm are flared, which corresponds to the energy needs for half of Africa (Worldbank, n.d.).

Gas-to-gas pricing means that gas has a normal market price. This is most common in Europe. Oil-indexation means that the price of gas is decided in a contract and tied to the price of a basket of oil products. The contracts are very long, for example 20 years. In Asia, long oil-indexation contracts are common (Hafner & Luciani, 2022). Another example of long contract is the German-Qatar contract of LNG-shipping reported in media in November 2022 (Ekot, 2022) which has a contract period of 15 years. The reason for the long contracts and oil index is, as explained by Hafner and Lucianii (2022), that it protects against price manipulation and provides the stability needed to do the large initial investment.

Bilateral monopoly means that the governments of two countries negotiate a fair price. For example, the gas between Qatar and Oman is traded that way (Hafner & Luciani, 2022).

Domestic prices, for example in Africa and in Russia are often regulated below cost. Overall, 30% of the gas consumed is subject to price regulations (IGU, 2022). Also, the international trading of gas has in some cases a political importance contributing to rapprochement, and the pricing reflects other values than just the gas. As an example, Japan sought to secure their energy supply after the 1973 oil crises. Japan favoured imports of gas from Indonesia and Malaysia, which were countries that Japan had occupied during the second world war, over imports of oil from the Middle East (Hafner & Luciani, 2022).

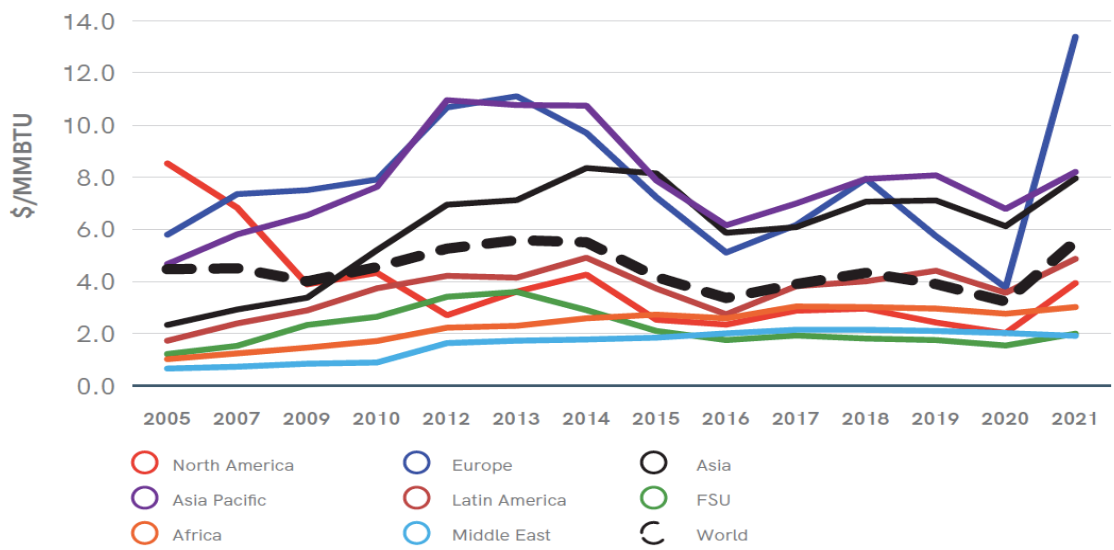

Figure 2: Wholesale price levels from 2005-2021 by region (FSU=Former Soviet Union). (Source: IGU, 2022)

It is important to realize, as seen in figure 2, that the price of natural gas is different in different parts of the world. Figure 2 also shows that the prices in different parts of the world do not always move in the same direction (IGU, 2022). In North America the price of natural gas fell drastically in 2005 to 2012 and during that time America started to extract large volumes of shell gas using a controversial method called fracking. With prices as low as $2/MMBTU, America went from an importer of gas to an exporter (The Economist, 2012). Despite the technical difficulties related to shipping of natural gas, international trade becomes interesting when the price differences are so large (The Economist, 2012).

LNG shipping capacity, liquefaction and regasification terminals are a prerequisite for long distance trade of natural gas. Figure 3 shows a world map where liquefaction (orange, red) and regasification terminals (blue, green) are marked. Note that Canada who is a major gas producer completely lacks liquefaction terminals.

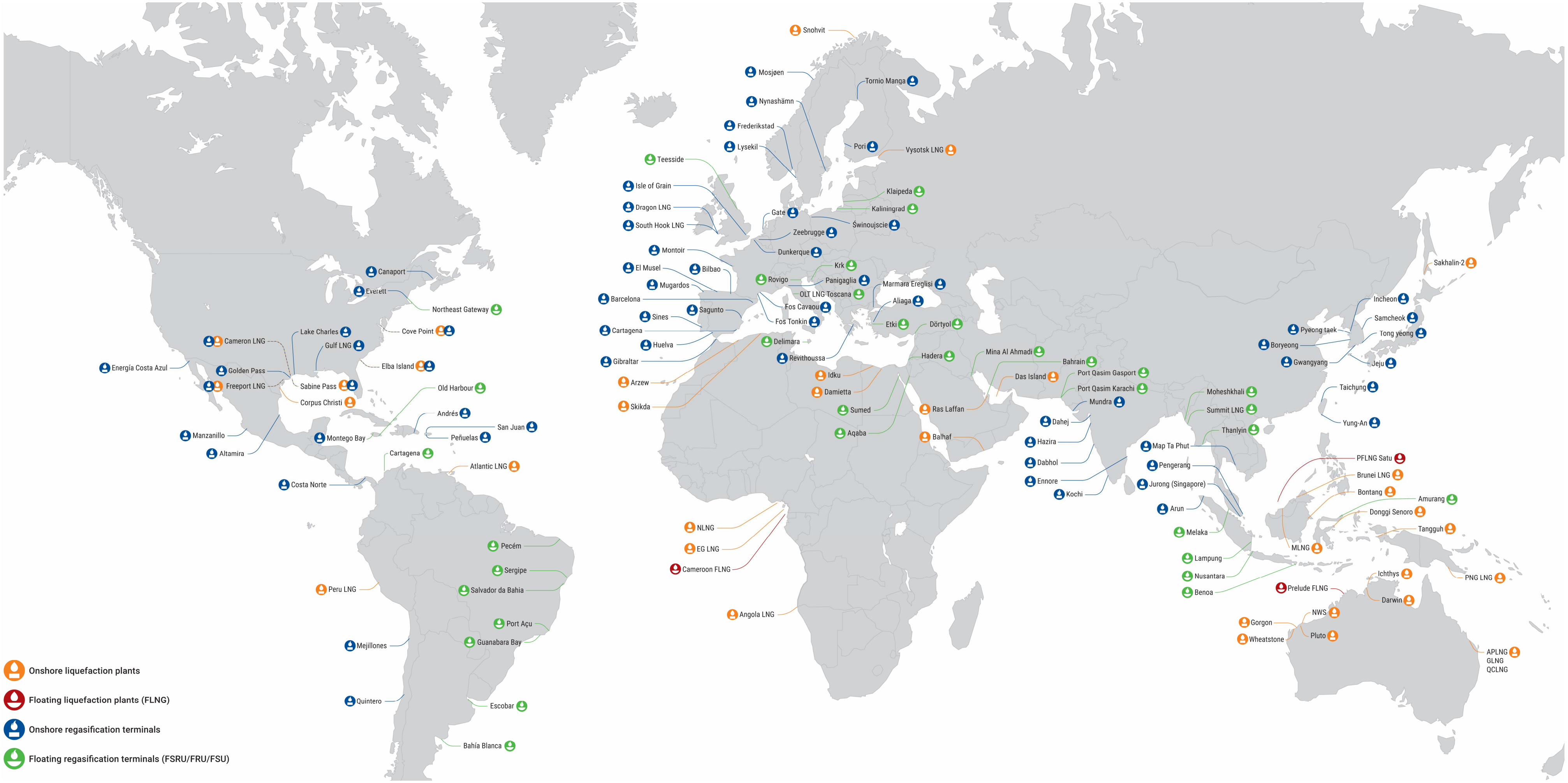

Figure 3: World map over liquefaction (orange, red) and regasification terminals (blue, green). (Source: GIIGNL, 2022)

2 Literature Review

2.1 Integration of natural gas markets

A central question in the economic literature on natural gas has been the degree of integration between the gas markets over the world. The methodologies used to do so vary from simple statistical empirical works that only use price data to more complex models that include both price and non-price data, such as transaction cost, trade flows, arbitrage opportunities and capacity constraints. A few articles use the spatial price equilibrium theory (Dukhanina & Massol, 2018).

Before going into the description of the different methodologies used, let us first define what is meant by a "market". Cournot (1838) is defining the market as "[...] a whole territory in which parties are in such free intercourse with one another that prices of the same goods are levelled out easily and promptly [...]". Marshall (1890) expanded that definition to allow for price differences if transportation costs are considered. This leads to the work of Samuelson (1952) and Takayama and Judge (1964) which explains that the price at market A plus the transportation cost between market A and market B, will equal the price at market B, but only under the condition that the transportation cost is less than the price spread. If the transportation cost is larger than the price spread, then there will be no trade and the price will be determined separately on the two different markets.

In a literature review of 55 articles Dukhanina and Massol (2018) identified seven different categories of statistical methods used in the literature for measuring the degree of market integration in the markets for natural gas. For example, correlation-based studies mean that price movements between integrated but geographically separated markets should be similar, thus the degree of integration can be measured using simple correlation analysis. If the time series are non-stationary, first difference can be used to avoid spurious results. Another example is cointegration test which means that two non-stationary price series are cointegrated if they have a stationary linear combination.

Many other examples mentioned in the literature review by Dukhanina and Massol (2018), all fall into the category of different time-series based statistical approaches to measure integration between markets. From these models it can be deduced that the majority of the empirical methods estimate the relationship between the prices over time, and that a large aspect of the models is that they focus on the time series properties of the prices. Furthermore, it can be seen that only a few of these models take into account the role of transport and arbitrage costs. Dukhanina and Massol (2018) argues that this is problematic because in the gas industry, transportation costs consist of a value of approximately 50% of the total costs, which means that these aspects cannot be ignored when forming natural gas prices.

2.2 Factors driving global LNG trade

Zhang et al. (2017) investigated factors that drive international LNG trade. Their method of choice was the gravity model and the definition they used of the gravity model was that the one-way trade volume between two countries is proportional to the size of each country's respective economy and is inversely proportional to the distance between them. Zhang et al. (2017) described the basic form of the gravity model with the following equation:

$$T_{ij} = \frac{A(M_i M_j)}{D_{ij} U_{ij}}$$

where T_{ij} represents the shipped volume from country i to country j, M_i is the GDP of the importing country, M_j is the GDP of the exporting country, D_{ij} is the distance between the two countries and U_{ij} is various other factors that promote or hinder trade between the two nations. To be able to run a regression analysis they used a logarithmic linear form of the gravity model which included eleven factors:

$$\ln(T) = \beta_0 + \beta_1 \ln(GDP_{im}) + \beta_2 \ln(GDP_{ex}) \beta_3 \ln(P_{ex}) \beta_4 \ln(GDP_{im}) + \beta_5 \ln(CNG_{im}) + \beta_6 \ln(P) + \\ \beta_7 \ln(Ra) + \beta_8 \ln(D) + \beta_9 \ln(L) \beta_{10} \ln(Ri) + \beta_{11} \ln(R \,\&\, D) + \varepsilon$$

GDP_{im}	GDP of import country
GDP_{ex}	GDP of export country
P_{ex}	Natural gas production of export country
P_{im}	Natural gas production of import country
CNG_{im}	Pipeline gas import volume of import country
P	Natural gas import price of import country
R&D	Ratio of research and development investment to GDP
Ra	Proportion of gas in primary energy consumption of import country
D	Distance
L	Common language

Ri	Political risk index

Table 1: The definition of the parameters in the gravity model of Zhang et al.

Zhang et al. (2017) ran two regressions, one on the global market and one on the Asian market. The global trade from 2004 to 2015 was analyzed and included data from 26 major LNG-exporting countries and 29 importing countries. Except for R&D all parameters were found to be significant in the global market. In the Asian market, on the other hand, all parameters were significant except for GDP_{ex}, CNG_{im} and Ri. The conclusions Zhang et al. (2017) drew from their study were that LNG trade, compared to general merchandise trade, are more affected by the importers GDP. Furthermore, pipeline gas is a substitute of LNG. In Asia, with small possibilities to replace LNG with pipeline gas, the volumes imported are more sensitive to price changes than the global average. This is due to the lack of barging power for the LNG importers in Asia. Zhang et al. (2017) also argue that Asia are not benefitting from the new cheap gas from North America due to the long contracts they have with their current gas providers. They also argue that there is still a long way to go before there is a true integrated world market for natural gas, but that the arbitrage possibilities between regional prices will be reduced due to the development of LNG trade.

2.3 Elasticities of supply and demand in the natural gas market

Supply and demand curves are fundamental input data into the SPE model (Takayama & Judge, 1964). The supply and demand curves are shaped by the price elasticities (Perloff, 2017).

Krichene (2002) reported 0,8 as elasticity of supply for natural gas. Boeters and Bollen (2012) say that "The empirical estimates of fuel supply elasticities exist in a wide range. Our reading of the literature is that values of one for oil and gas and four for coal are reasonable.”. In a more recent article by Mason and Roberts (2018) the elasticity of supply for natural gas was studied in Wyoming and they reported a value of 1.2 in the long run. One important point made by Mason and Roberts (2018) is that once a well has been opened, the production from that well is determined by the geological characteristics of it, and the production is almost completely unresponsive to price changes. The way gas producers react to price changes is instead by drilling rates and by choosing to drill at locations with less productive wells when price is high, according to Mason and Roberts (2018).

In table 2 estimates of price elasticity of demand for households or for industry from 21 different studies are presented. As seen in table 2 the values for demand elasticity also vary in the literature.

Author	**Year**	**Country/region**	**Demand elasticity household**	**Remark/note**
Alberini et al	2020	Ukraine	-0,16	
Alberini et al	2011	USA	-0,6	
Andersen et al	2011	OECD	-0,1 to -0,6	
Asche et al	2008	Europe	-0,1	
Balestra and Nerlove	1966	USA	-0,6	
Berkhout	2004	Netherlands	-0,2	
Berndt and Watkins	1977	Canada	-0,7	
Brenton	1997	Avg. income countries	-0,9	
Burke & Yang	2016	44 countries	-1,25	
Csereklyei	2020	Europe	-0,53	-0,75 to -1 for industry
Dagher	2012	USA	-0,2	
Dilaver et al	2014	Europe	-0,2	
Gautam and Paudel	2018	USA	-0,14	For industry -0,28
Krichene	2002	World	-1,1	
Li et al	2022	USA	n/a	For industry -0,13
Lin et al	1987	USA	-1,2	
Maddala et al	1997	USA	-0,2 to -1,4	
Payne	2011	USA	-0,3	
Tatlı	2018	OECD	-0.146	
Yoo et al	2009	Korea	-0,2	
Yu et al	2014	Kina	-1,4	

Table 2: Demand elasticity reported in various studies.

Huntingtona et al. (2019) did a review of demand elasticities for energy related commodities like oil, electricity, gasoline and gas, both in long and short run. They point out that various studies have used different methodologies which can lead to different estimates of elasticities. Huntingtona et al. (2019) argues that to get to a reasonable value, judgment is important to avoid misleading values.

When reading table 2 it is worth noting that no one studied the elasticity of different parts of the world in the same study. There seems to be a weak tendency that the more elastic values are reported from studies of the North American markets.

Hartley and Medlock (2005) presented an algorithm for calculating long run demand elasticity that depends on the proportion of gas in the energy mix and GDP. They used that algorithm in a model for world gas trade.

2.4 Models of the natural gas market

Lochran (2021) describes that the European indigenous supply of natural gas has been declining, which has lead to an increased dependency of imports, which in turn has lead to security concerns. Therefore, many mathematical models have been made to model disturbances in gas imports with the purpose of providing a deeper insight into the risks and assist in investment strategies to manage that risk. Lochran (2021) reviews 22 such models in his article. In the article also a completely new model called Gas Network Optimization Model for Europe (GNOME) is presented.

Lochran (2021) categorizes the existing models by seven attributes; problem type, geographical scope, temporal scope, network infrastructure, gas demand, gas production and producer behaviour and finally infrastructure investments. Given this thorough description made by Lochran (2021) especially the following is worth to point out;

- Models often use optimization of cost or welfare, using linear or nonlinear programming. Lochran (2021) mentions 9 such models that uses that theoretical framework to find an optimal solution of trade and production that satisfies the demand. Some models try to include market power in the model by using game theory.
- Lochran (2021) argues that for a European model, all countries in Europe as well as gas exporters to Europe should be included.
- Models can predict the future with different time horizons and granularity. The longest model predicts the gas market in 2050. The most granular predict gas market per hour.
- Gas network structure is important to account for in a model, according to Lochran (2021), and points out that for example the pipelines in Ukraine used to transport gas from Russia to Poland. But after 2014 Crimean crisis Ukraine instead imported gas from Poland through the same pipelines.
- Aggregating LNG imports by country can be misleading. Some models therefore model the capacity at each LNG terminal and also account for the exact distance to model transportation costs.
- Models can include demand as an endogenous variable that depends on e.g., population and GDP in the model, demand can be determined by a linear demand function, or it can be an exogenous variable.

- Gas production levels are by a majority of the studied models an endogenous variable.
- Half of the models have investments in gas infrastructure as an endogenous variable in the model.

From an evaluation perspective Lochran (2021) argues that all the existing models have shortcomings. Lochran (2021) criticizes the aggregation of LNG and pipeline capacity, lack of reversed flows in pipelines, seasonal variation not being accounted for, not including investments, and not including all relevant countries in the models. Only two models, the TIGER (Lochner et al., 2007) and WM-GGM (Haftendorn, 2016) can in an adequate way reflect the European gas market, according to Lochran (2021). Those two models are privately owned and not available to the general public. Therefore Lochran (2021) created a new model called GNOME. GNOME optimizes by minimizing cost and is a model based on the so called transhipment problem (Orden, 1956) which is a mathematical framework for finding optimum linked paths over a series of points. The model optimizes production, imports, transportation, storage, and investments in pipelines and regasification. All in all, the model includes 25 equations. Notably, the GNOME model by Lochran (2021) does not include countries in Asia but is limited to Europe, Ukraine and Turkey. African and American producers are included in the model, but only as supplier and not with a demand market of their own. The model also makes many different assumptions, among those are the supply curves which were based on the work by Rystad Energy (2019) which is not an academic source, but material provided by a Norwegian energy analysis and consulting company.

Lochran (2021) used the model to simulate two scenarios, one with Nordstream 2 and one with more restricted capacity of pipeline shipping from Russia to Europe. No scenario included restricted trade due to economical sanctions. The results from the model include many different aspects of the future gas market in Europe, including utilization of pipelines, storage capacity, international trade etc. One prediction by the model is that the demand for natural gas in Europe is going to decline from 508 bcm/year in 2025 to 456 bcm/year in 2040 (approximately from 18 to 16 million BBTU/year). The model predicts that the building of Nordstream 2 was unnecessary, the capacity it was supposed to provide were not needed according to the GNOME model predictions. One final note about the GNOME model is that

Lochran (2021) provides the inputs, results and the source code in GAMS completely open and free online on a webpage.

3. Theoretical framework

3.1 The Spatial Price Equilibrium model

The Spatial Price Equilibrium (SPE) was first described by Samuelson (1952) and later reworked by Takayama and Judge in 1964. Notably Takayama and Judge also solved a simple example SPE model with three markets, three suppliers and a single commodity using the IBM 7094 which was a computer that was programmed using machine code instructions on push cards. The program took 12 seconds to complete.

Figure 4: IBM 7094 computer at Columbia University Computer Center in 1965. (Source: Columbia University Archive)

In the original article by Takayama and Judge (1964) the SPE model is generalized to work for a spatial price equilibrium with more than one product. Since this thesis is only concerned with one single product - natural gas - we instead chose a simplified version of the SPE used by Kalvelagen (2003). The only difference is that this version of the SPE is only defined for one single product traded.

According to Kalvelagen (2003), assume that there are linear demand and supply curves.

$$d_j = \alpha_j + \beta_j p_j$$
$$s_i = \gamma_i + \delta_i \pi_i$$

with $\beta_j < 0, \delta_i > 0$.

The indices i and j are used to denote supply and demand regions. p and π are demand and supply prices. Inverse formulations of the demand and supply equations are as follow:

$$p_j = \zeta_j + \eta_j d_j$$
$$\pi_i = \theta_i + \lambda_i s_i$$

with $\zeta_j, \theta_i, \lambda_i > 0$ and $\eta_j < 0$. ζ_j and η_j are the intercept and slope of the demand functions. θ_i and λ_i are the intercept and slope of the supply functions.

In addition, there are constraints on supply and demand quantities with respect to transportation quantities $x_{ij} \geq 0$:

$$\sum_{i=1}^{n} x_{ij} \geq d_j$$

$$\sum_{i=1}^{n} x_{ij} \leq s_i$$

Kalvelagen (2003) assume further that unit transportation costs are denoted by $c_{ij} \geq 0$. To clarify the explanation by Kalvelagen (2003), the transportation cost c_{ij} is allowed to be different for each pair of supplier and market.

The objective is to maximize the global sum of producers and consumers surplus after deduction of the transportation costs. The objective was called net social payoff by Samuelson (1952) but in our thesis we refer to it as welfare. The welfare is defined by:

$$\max \sum_{j=1}^{n} \int_{0}^{d_j} d_j(\phi_j) d\phi_j - \sum_{i=1}^{n} \int_{0}^{s_i} \pi_j(\rho_i) d\rho_i - \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij}$$

Then Kalvelagen (2003) integrates the inverse demand and the inverse supply function to get the following quadratic objective function:

$$\max \sum_{j=1}^{n} \left(\zeta_j d_j + \frac{1}{2} \eta_j d_j^2 \right) - \sum_{i=1}^{n} \left(\theta_i s_i + \frac{1}{2} \lambda_i s_i^2 \right) - \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij}$$

Maximize the objective function in order to solve the general spatial price equilibrium. This can be done by means of a mathematical method called linear programming (Takayama & Judge, 1964).

The objective function can be explained in an intuitive way using a graphical approach, as seen in figure 5[1].

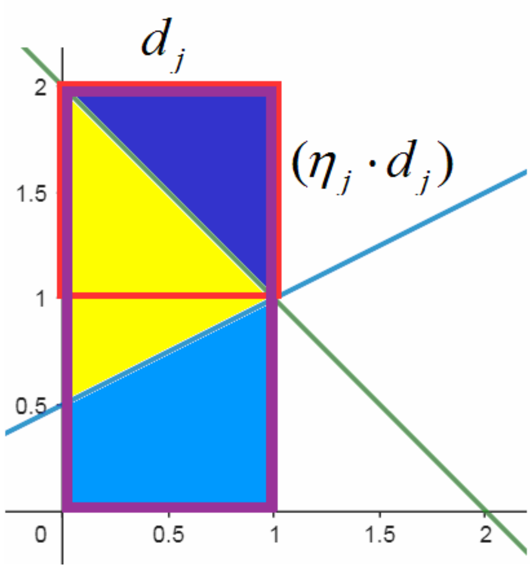

Figure 5: Supply and demand with only one supplier and one market. Colours and areas represent terms in the objective function of the SPE model.

Assume a single market with an inverse demand function p=2-x illustrated in green in figure 5, and a single producer with a supply function p=0.5+0.5x illustrated in blue in figure 5. Then the first term $\zeta_j d_j$ in the objective function would be 2 multiplied by 1 and correspond to the purple area. The second term $\frac{1}{2}\eta_j d_j^2$ corresponds to the dark blue area.

The reason why $\frac{1}{2}\eta_j d_j^2$ is the dark blue area is seen if we expand $\eta_j d_j^2$ to $(\eta_j \cdot d_j) \cdot d_j$ where $(\eta_j \cdot d_j)$ is the length of the vertical side of the red rectangle and d_j is the other side of the same rectangle. Remember that the slope of the demand function η_j is a negative number, thus we can divide the red rectangle in half to subtract that blue part from purple part which is not included in the welfare.

[1] Johansson, T. (2022). Department of Economics at the Swedish University of Agricultural Science. Personal message.

In a similar way we can then graphically illustrate the second term $\theta_i s_i + \frac{1}{2}\lambda_i s_i^2$ related to the supply function in light blue colour which we also subtract from the purple rectangle. That leaves us with the welfare in yellow. It is now possible to subtract the welfare lost in the transportation cost $c_{ij}x_{ij}$, which is the last term in objective function, and which is not represented in the graph.

4 Methodology, data and scenarios

4.1 Methodology and data

We implemented the SPE model in GAMS, General Algebraic Modeling System, which is software that is designed to formulate complex optimization problems.

The inputs to our model are demand and supply curves and transportation costs. Demand and supply curves are in turn determined by elasticities, quantities and prices, while transportation costs depend on transportation method and distance. We also included a set of restrictions, in addition to the restrictions that are included in the SPE theory itself. These restrictions are on maximum production capacity and also in some scenarios a restriction on world LNG shipping capacity. However, we did not include a restriction on pipeline capacity.

Our model included all countries in the world with an export or import greater than 10 000 terajoules (≈9.5 million MMBTU) of natural gas, except for a few countries in central Asia and Switzerland that were excluded due to geographical implications that were difficult to manage in the model. All data used in our model are from the year 2019. The choice of year was based on that we wanted a recent year, but not affected by impact of Covid-19 on international trade.

For elasticity of supply, we use 1.0 for all suppliers, as suggested by Boeters and Bollen (2012). For elasticity of demand, our interpretation of the values reported in the literature, as described in table 2, is that the more inelastic estimates tend to be from countries with less substitutes to natural gas and also the countries with higher prices. Therefore, we have used a demand elasticity formula ε_{demand}=-1.6+0.15×price. This results in elasticities of demand ranging from -0.1 to -1.5. The most inelastic demand is in Asia, in particular in Japan, and more elastic in the oil and gas producing countries. Due to the uncertainty related to the demand elasticity we also ran a type of sensitivity analysis using -0.2 and -1.1 as demand elasticity equally for the whole world. As Huntingtona et al. (2019) pointed out, to get to a reasonable value for elasticity of demand, judgment is important to avoid misleading values. Based on that, we consider the approach with the demand elasticity formula to be the more reasonable input values of demand elasticity to the model.

Also needed to calculate the intercept and slope is the price and the quantity produced or consumed. We used price data from IGU Wholesale Gas Price Survey (2020) and quantity is read from the IEA World Natural gas statistics database (2022). Note that the prices represents wholesale price. The price to the consumer can be higher.

In order to calculate the supply and demand functions we used the following reasoning. Assuming a linear demand function $Q = a - bP$, the price elasticity of demand is defined as (Perloff, 2017)

$$\varepsilon = \frac{\delta Q}{\delta P}\frac{P}{Q} = -b\frac{P}{Q}$$

Rearranging terms gives:

$$b = -\frac{\varepsilon Q}{P}$$

and that is how the slope was calculated. Then the inverse demand function is:

$$P = \frac{a}{b} - \frac{1}{b}Q$$

Rearranging terms gives:

$$\frac{a}{b} = P + \frac{1}{b}Q$$

and that is how the intercept was calculated. The supply curve and the corresponding equations are as follows.

Supply curve:

$$Q = a + bP$$

Calculate the slope:

$$b = \frac{\in Q}{P}$$

Inverse demand:

$$P = -\frac{a}{b} + \frac{1}{b}Q$$

Intercept:

$$\frac{a}{b} = \frac{1}{b}Q - P$$

Using the equations above combined with data for price, quantity and estimates of elasticity, we calculate the intercept and slope of every country in the model. This results in a separate supply and demand function for each country in the model.

The transportation cost between each destination is measured in $/MMBTU. Dollars per million British terminal unit is what that the gas industry often uses to express prices of natural gas. It can be converted into metric unit; 1 Btu ≈ 1055.056 joule, but this varies slightly between different definitions (Thompson & Taylor, 2008). Also volume conversion differs between natural gas from different sources. We use 1 million cubic meter gas [MCM] = 35.31073446 BBTU (billion British terminal unit). Note that there is confusion in the gas industry about units. In the gas industry M sometimes denotes 1000000 as in Mega in the unit prefix in metric systems, sometimes it denotes M in the Roman number system where M equals 1000 (Chen, 2022). So a value given in MCM can be either a million cubic meters or it can be thousand cubic meters. One has to be aware of this when interpreting values in the gas industry to avoid mistakes.

The transportation cost is calculated using the estimates of transportation cost provided by Hafner & Luciani (2022) like this for LNG:

cost = ((distance in km/ 1000) * 0,04 in $/MMBTU/1000km)

+ $2.4 liquefaction + $0.4 regasification

and for pipeline:

cost = distance in km / 1000 * 1,5 $/MMBTU/1000km.

Normally a fee for feed gas (gas to drive the pumps that creates the pressure differences that drives the gas forward in the pipes) should be added to the cost, but we considered that the feed gas cost is already included in the price listed and ignores it in the cost calculation.

The source data for the distance is coming from the CERDI-seadistance database (Bertoli et al., 2016) and from CEPII GeoDist (Mayer & Zignago, 2011). This data of course does not exactly match the real world distance for every transportation route, but it is an approximation that we could use in the model.

In the real world there are cases where both LNG and pipeline transportation can be used between an exporter and an importer, but we cannot simulate that in our model, and we consider that a minor issue. In order to decide which transportation method that is used between a source and a market, a dummy variable was introduced that indicated if LNG or pipeline was used for each route. The decision on LNG or pipeline were made by us using the world map of LNG shipping routes and pipeline infrastructure provided by Natural Gas Information (2019).

An additional restriction in the model that we introduced was a maximum production capacity at each source. This is an assumption made by us that it is impossible to increase the production capacity with more than 20% in the short run to semi long run. This is not true for some countries in the past, as seen in IEA (2022). For example, Australia increased their production from 2016 to 2021 by 82%. There are also other examples of a five year period increase in production by 30 to 40%. However, for the top ten producers in the world and from the year 2010 to 2015 and from 2016 to 2021 the average five year increase was 20% according to IEA (2022). We also see that the largest increases did not happen in the most recent years. So, to our judgement, 20% is a reasonable value to choose as maximum production increase. The source of current production capacity is from the IEA statistics (IEA, 2022).

All data that we use were stored in our own SQL database. We read the data values from the database using a PERL-program that we have written, which enables us to generate a GAMS code automatically. If we did not generate the GAMS code using data from our SQL database, then the editing of the GAMS code would be a too tedious task as the full model includes over 5000 variables.

The model includes all countries in the world with more that 10 000 terajoules in export or import, except for the countries in central Asia, Belarus, Kazakhstan, Turkmenistan, Uzbekistan and Azerbaijan. Also, Switzerland was excluded. They were excluded because our model does not handle their geographical location well and their contribution to the world trade is of less importance, according to our judgment. In addition to that Papua New Guinea, who exported around 450 000 terajoules in 2019 (IEA, 2022), could not be included in a correct way due to missing information in the IEA Statistics database on indigenous quantity produced and consumed, and thus the resulting value of the demand and supply function will be zero.

The full listing of countries that were part of the model is seen in table 3.

Code	Country	Code	Country	Code	Country
AGO	Angola	GEO	Georgia	NLD	Netherlands
ARE	United Arab Emirates	GRC	Greece	NOR	Norway
ARG	Argentina	HKG	Hong Kong	OMN	Oman
AUS	Australia	HUN	Hungary	PAK	Pakistan
AUT	Austria	IDN	Indonesia	PER	Peru
BEL	Belgium	IND	India	PNG	Papua New Guinea
BGD	Bangladesh	IRL	Ireland	POL	Poland
BGR	Bulgaria	IRN	Iran	PRT	Portugal
BOL	Bolivia	IRQ	Iraq	QAT	Qatar
BRA	Brazil	ITA	Italy	RUS	Russia
BRN	Brunei	JOR	Jordan	SGP	Singapore
CAN	Canada	JPN	Japan	SVK	Slovakia
CHL	Chile	KOR	South Korea	THA	Thailand
CHN	China	KWT	Kuwait	TTO	Trinidad and Tobago
CZE	Czech Republic	LBY	Libya	TUN	Tunisia
DEU	Germany	LTU	Lithuania	TUR	Turkey
DZA	Algeria	MDA	Moldova	TWN	Taiwan
EGY	Egypt	MEX	Mexico	UKR	Ukraine
ESP	Spain	MMR	Myanmar	USA	United States
FRA	France	MYS	Malaysia	ZAF	South Africa
GBR	United Kingdom	NGA	Nigeria		

Table 3: Countries and county codes that are included in the model.

The GAMS model generated is too large to be covered by the free license and instead we used GAMS studio and sent our model to the NEOS server to solve, which is free for academic use (NEOS Server, 2022).

To write the GAMS code we used the book Applied Mathematical Programming Using Algebraic System by McCarl and Spreen (2002), which has online resources accompanying the book. From that source we pulled example GAMS code provided in the file SPATEQ.GMS and used as a starting point for our model of the spatial price equilibrium. The source code for a limited version of our GAMS program with detailed comments is listed in Appendix B. We also have a link in Appendix A to online resources which include full program code and various other details related to the computer programs used to implement the model.

4.2 Scenarios simulated in the SPE GAMS model

We used the SPE model implemented in GAMS to run four scenarios that vary along two dimensions. The first dimension is trade, the second is LNG shipping capacity. Trade and LNG shipping capacity can be either limited or unlimited.

- Trade
  - Unlimited: All countries included in the model are free to trade.
  - Limited: Turkey, Iran, Iraq, India, China are the only countries that trade with Russia. These countries (not including Russia) are free to trade with all other countries also. This is to simulate economical sanctions and various other complications to world trade of natural gas following the Russian invasion of Ukraine in 2022.
- Shipping capacity
  - Limited: The world LNG shipping capacity is limited to 500 bcm/year (≈18 million BBTU/year), which is equal to the current world felt capacity of LNG transportation (IEA, 2022). Note that bcm measures the amount of gas when LNG is regasified.
  - Unlimited: There is unlimited LNG shipping capacity.

The scenarios are clarified in table 4.

	Limited LNG	**Unlimited LNG**
Unlimited trade	In this scenario the shipping capacity is limited to 500 bcm/year. All countries participate in trade. This scenario is corresponding to the situation before the Russian invasion of Ukraine. We call this the *base scenario*.	In this scenario the shipping capacity is unlimited. All countries participate in trade. This simulates a future peaceful world. We call this the *future world peace scenario*.
Limited trade	In this scenario the shipping capacity is limited to 500 bcm/year. In this scenario Turkey, Iran, Iraq, India, China are the only countries that trade with Russia. This corresponds approximately to the current world situation in end of 2022 when Nordstream pipeline is not delivering any gas at all between Russia and Europe, and many countries have decreased trade with Russia. We call this the *invasion scenario*.	In this scenario the shipping capacity unlimited. In this scenario Turkey, Iran, Iraq, India, China are the only countries that trade with Russia. This simulates a future world where conflicts persist and LNG shipping capacity is increased to allow for other sources of gas supply. Similar to what seems to be the strategy of current policy. We call this the *increased LNG shipping scenario*.

Table 4: The four different scenarios simulated in the model vary along two dimensions.

The four scenarios were simulated and compared to each other, and to the real-world trade flows according to the statistics from International Energy Agency (IEA, 2019).

4.3 Interpreting results

The output from the GAMS implementation for the SPE is around 500 rows of data for each scenario. In addition to that, we also have the vast statistical data from the databases that needs to be considered. To interpret the results we built data visualization tools using Java programming and PERL programming.

4.4 Scaling

The slopes of the demand and supply curves are very flat with a magnitude up to 10^{-11}. The price is roughly between 1 and 10 dollars and the quantity of gas is a number that can be over a billion when measured in the unit MMBTU. Numbers with very different magnitude or very large numbers can cause a problem for the solver in GAMS that is known as scaling (McCarl, 2014). If we run the model with the values for the amount of gas measured in the unit MMBTU, GAMS will not be able to solve the model and reports an error message "An initial function value is too large" and suggests that one should either scale the variables or increase the allowable range. Changing the allowable range can be done using the Rtmaxv option. We have tested both methods; scaling or increasing Rtmaxv. For the test we used the eight country example listed in Appendix B and could see that they both produce the exact same result with the exception that the calculated amounts of gas produced, consumed and shipped differ by the scaling factor. The values for the demand and supply prices are identical between the two methods. However, the Rtmaxv option is set in an option file and we were unable to find a way to utilize an option file when solving the full model with all countries on the NEOS-server. Therefore we used the scaling method, which is anyway what is recommended as the preferred method in the Conopt manual (Drud, n.d.). In practice it means that the quantities that were fed into the algorithm that calculates supply and demand functions were scaled down by a factor 1000 from MMBTU (million British thermal units) to BBTU (billion British thermal units). This makes the slopes steeper and the result from that is that the GAMS solver were able to handle the numbers in the calculations without any errors, and that the output of amount of natural gas from the model is not in MMBTU but in BBTU.

5. Results

This section is divided into five subsections.

-5.1 First the general results from the real world statistics and from all scenarios simulated in the main model are presented. The results from the main model were obtained by using the demand elasticity formula as input for demand elasticity.

-5.2 Sensitivity analysis where the main results are compared to values resulting from the alternate inputs -0.2 and -1.1 as demand elasticity.

-5.3 The SPE model base scenario results compared to real world trade.

-5.4 Simulation of limited trade following the Russian invasion of Ukraine in the invasion scenario.

-5.5 Simulation of limited trade with Russia with unlimited LNG shipping in the increased LNG shipping capacity scenario.

5.1 Visualisation of the results in tables and figures.

In this section the results from the main model that used the demand elasticity formula, and from the real world is presented in tables and figures.

Scenario	Max LNG trade	LNG trade	Pipeline trade	Total trade	Indigenous produced and consumed	Total production	Total consumption	Of which total European consumption
Real world	17 655 000	16 357 910	19 054 496	35 412 406	N/A	130 309 049	128 778 279	16 640 946
Base	17 655 367	17 655 367	20 609 624	38 264 992	87 720 675	125 985 667	125 985 667	17 952 465
Invasion	17 655 367	17 655 367	12 055 531	29 710 898	94 387 340	124 098 239	124 098 239	13 988 639
Increased LNG	N/A	29 362 248	9 094 528	38 456 776	85 309 662	123 766 438	123 766 438	17 561 111
Future peace	N/A	26 029 524	15 600 257	41 629 780	82 742 537	124 372 317	124 372 317	18 783 924

Table 5: Trade, consumption and production for the real world and the scenarios (BBTU/year).

In table 5 it is worth noting that the base scenario produces a result that is close to the values in the real world. The total produced and consumed gas in the four different scenarios is similar to each other. The LNG shipping is increased when the max restriction on LNG shipping is removed. This indicates that there are arbitrage possibilities. The difference in the total production and consumption in the real world differs slightly due to that there are countries excluded from the model that trade with countries included in the model. Since this difference is small, it indicates that it did not matter much that they were excluded. In all scenarios indigenous produced and consumed gas dominates heavily over traded gas, roughly 75% of total gas consumed.

Country	Base	Invasion	Increased LNG	Future peace	Max prod	Real world prod
AGO	129 770	143 990	173 950	145 220	288 140	240 117
ARE	1 523 600	1 639 700	1 921 200	1 686 100	2 334 600	1 945 500
ARG	1 678 400	1 704 000	1 678 400	1 678 400	1 886 100	1 571 750
AUS	2 077 200	2 077 200	2 077 200	2 077 200	6 144 900	5 120 750
AUT	29 054	39 361	34 468	30 024	39 361	32 801
BEL	143	165	140	130	165	138
BGD	886 450	1 035 700	793 840	746 900	1 175 200	979 333
BGR	977	1 493	1 111	1 009	1 647	1 372
BOL	330 590	463 340	298 740	265 770	687 260	572 717
BRA	686 220	828 020	625 550	581 680	1 129 300	941 083
BRN	114 710	114 710	114 710	114 710	430 430	358 692
CAN	7 925 800	7 967 000	7 967 000	7 967 000	7 967 000	6 639 167
CHL	64 674	64 674	64 674	64 674	64 674	53 895
CHN	4 537 800	5 103 200	3 558 700	3 799 200	7 465 000	6 220 833
CZE	7 454	8 856	8 226	7 628	8 856	7 380
DEU	144 940	225 870	175 920	149 800	254 060	211 717
DZA	3 812 000	3 812 000	3 812 000	3 812 000	3 812 000	3 176 667
EGY	2 348 400	2 348 400	2 348 400	2 254 500	2 918 200	2 431 833
ESP	3 923	4 697	3 710	3 469	5 678	4 732
FRA	556	677	515	481	677	564
GBR	1 416 700	1 663 800	1 362 400	1 262 800	1 663 800	1 386 500
GEO	408	408	408	408	408	340
GRC	269	355	264	249	377	314
HKG	0	0	0	0	0	0
HUN	39 547	65 297	48 642	40 915	72 712	60 593
IDN	1 700 800	1 851 000	1 664 900	1 664 900	2 821 400	2 351 167
IND	1 011 400	1 227 100	882 770	848 090	1 282 100	1 068 417
IRL	90 797	112 160	84 419	78 230	112 160	93 467
IRN	8 819 400	8 005 800	9 687 900	8 819 400	9 858 500	8 215 417
IRQ	403 170	379 600	428 330	403 170	472 880	394 067
ITA	172 960	203 390	164 350	154 560	203 390	169 492
JOR	4 244	4 244	4 244	4 078	5 216	4 347
JPN	50 204	60 679	45 722	42 031	104 310	86 925
KOR	4 854	5 888	4 413	4 059	10 148	8 457
KWT	784 050	784 050	760 520	713 540	828 390	690 325
LBY	380 900	380 900	380 900	380 900	601 260	501 050
LTU	0	0	0	0	0	0
MDA	2	3	2	2	3	2
MEX	1 354 100	1 354 100	1 354 100	1 354 100	1 354 100	1 128 417

MMR	186 040	186 040	221 930	191 630	755 030	629 192
MYS	2 163 700	2 320 100	2 087 900	1 952 200	3 085 900	2 571 583
NGA	925 140	925 140	1 010 400	925 140	1 956 800	1 630 667
NLD	1 160 500	1 415 700	1 201 400	1 053 600	1 415 700	1 179 750
NOR	2 187 900	3 271 600	2 376 400	1 908 000	5 043 800	4 203 167
OMN	1 092 200	1 154 100	1 206 100	1 178 900	1 724 800	1 437 333
PAK	1 267 600	1 267 600	1 216 200	1 141 700	1 359 600	1 133 000
PER	349 910	349 910	349 910	349 910	569 040	474 200
PNG	0	0	0	0	0	0
POL	151 470	239 480	202 020	155 720	239 480	199 567
PRT	0	0	0	0	0	0
QAT	7 102 100	7 102 100	7 102 100	7 102 100	7 102 100	5 918 417
RUS	31 940 000	26 642 000	29 018 000	32 461 000	32 461 000	27 050 833
SGP	0	0	0	0	0	0
SVK	3 086	4 989	3 717	3 190	5 254	4 378
THA	873 360	1 052 100	783 560	738 040	1 306 300	1 088 583
TTO	893 550	893 550	1 062 600	893 550	1 547 300	1 289 417
TUN	93 282	93 282	91 294	85 812	93 282	77 735
TUR	10 396	13 302	10 316	10 396	20 085	16 738
TWN	2 930	3 523	2 632	2 481	7 086	5 905
UKR	326 870	763 360	568 450	342 880	854 660	712 217
USA	32 669 000	32 669 000	32 669 000	32 669 000	40 769 000	33 974 167
ZAF	49 986	49 986	49 986	49 986	49 986	41 655

Table 6: Production in the different scenarios, max production limit and real world production per country (BBTU/year). Production at max limit marked in yellow.

In table 6 it is worth noting that many countries, even exporters, are not producing on their maximum capacity. The scenario with most countries producing on the max limit is in the invasion scenario. The countries producing on max are the countries that supply Europe with gas, indicating that there is a large shortage in Europe due to the limited trade in that scenario.

The following maps in figure 6 to figure 10 show the world trade flows in the real world and in the four different scenarios. Figure 11 to figure 14 show total exports and total imports by country. Figure 15 and 16 show wholesale price differences between scenarios. Finally figure 17 shows the demand elasticities in different parts of the world according to the demand elasticity formula.

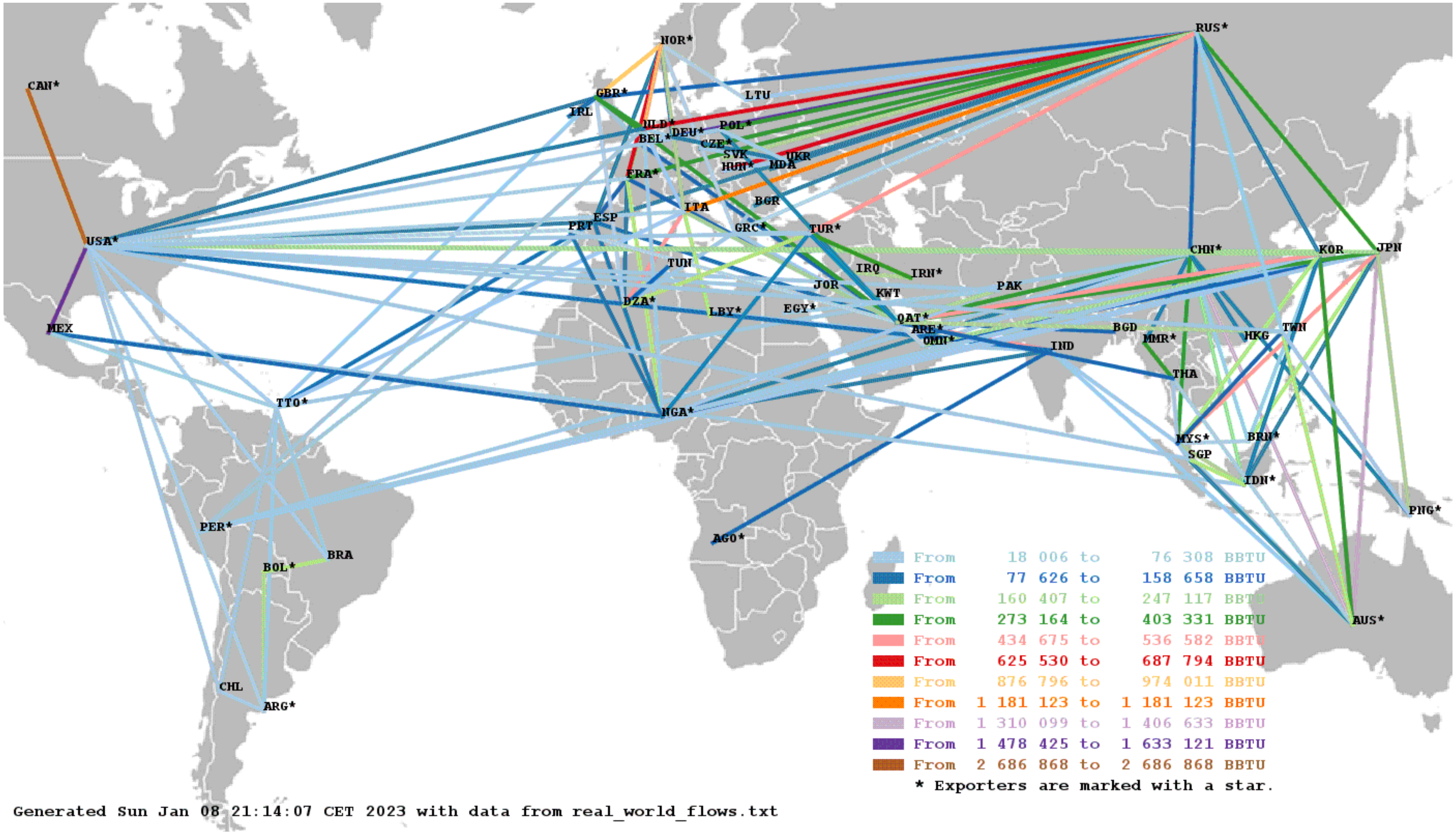

Figure 6: Real world trade flows show many more countries involved in international trade compared to the simulations.

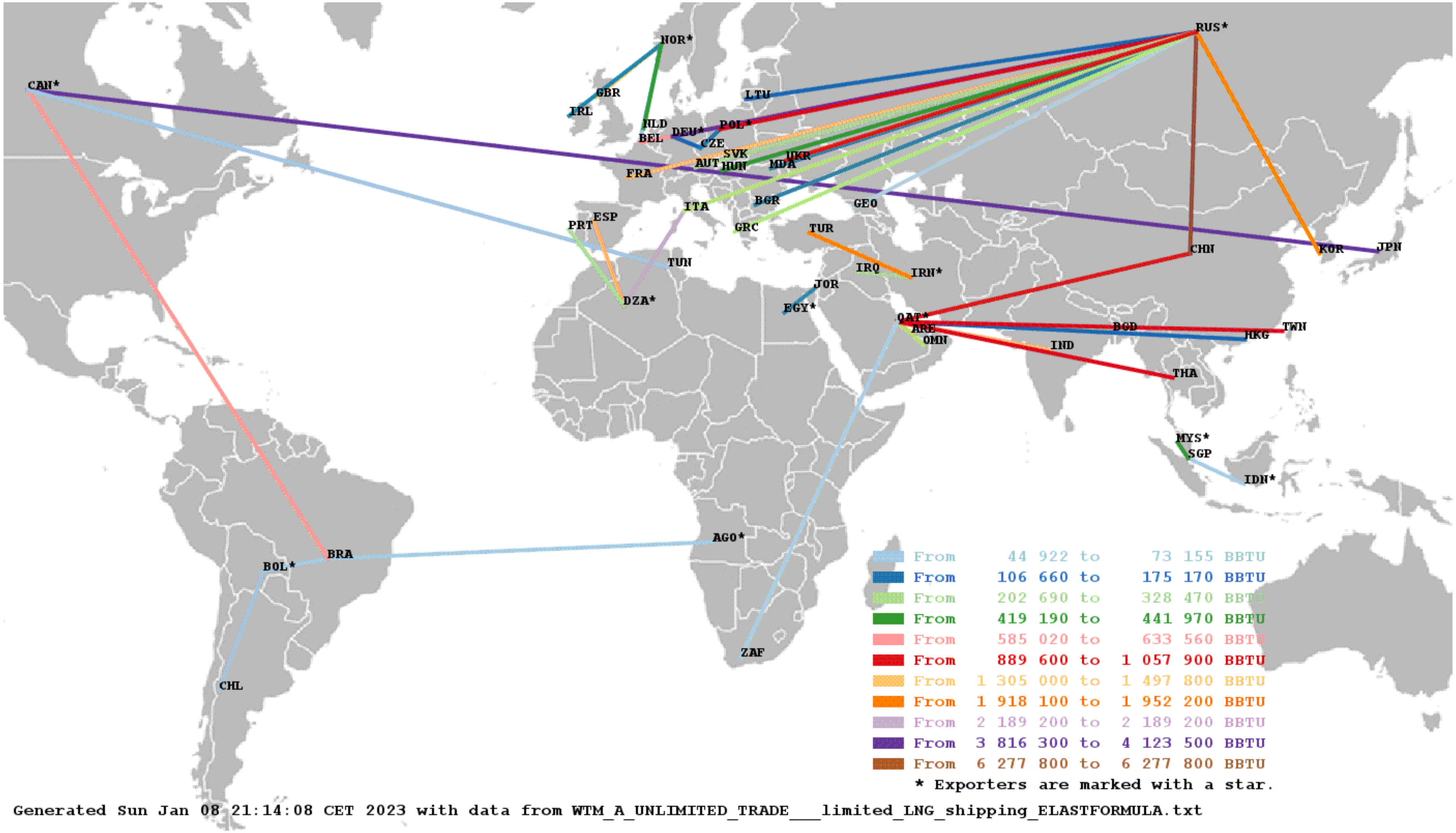

Figure 7: Base scenario. Unlimited trade and limited LNG shipping capacity. This is the base scenario corresponding to the situation before Russian invasion of Ukraine.

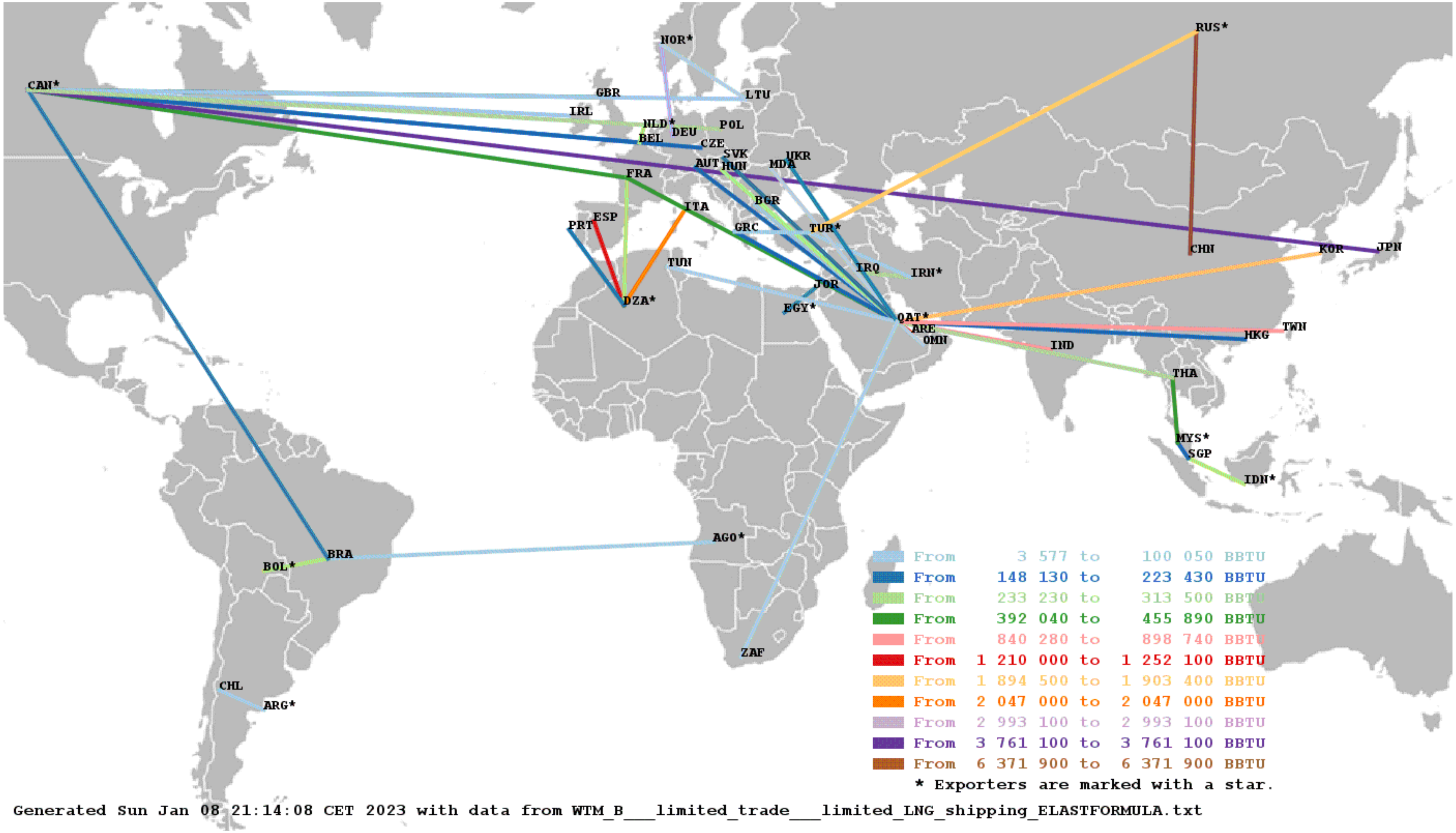

Figure 8: Invasion scenario. Limited trade and limited LNG shipping capacity. This is the scenario simulating sanctions and other complications to international trade following the Russian invasion of Ukraine.

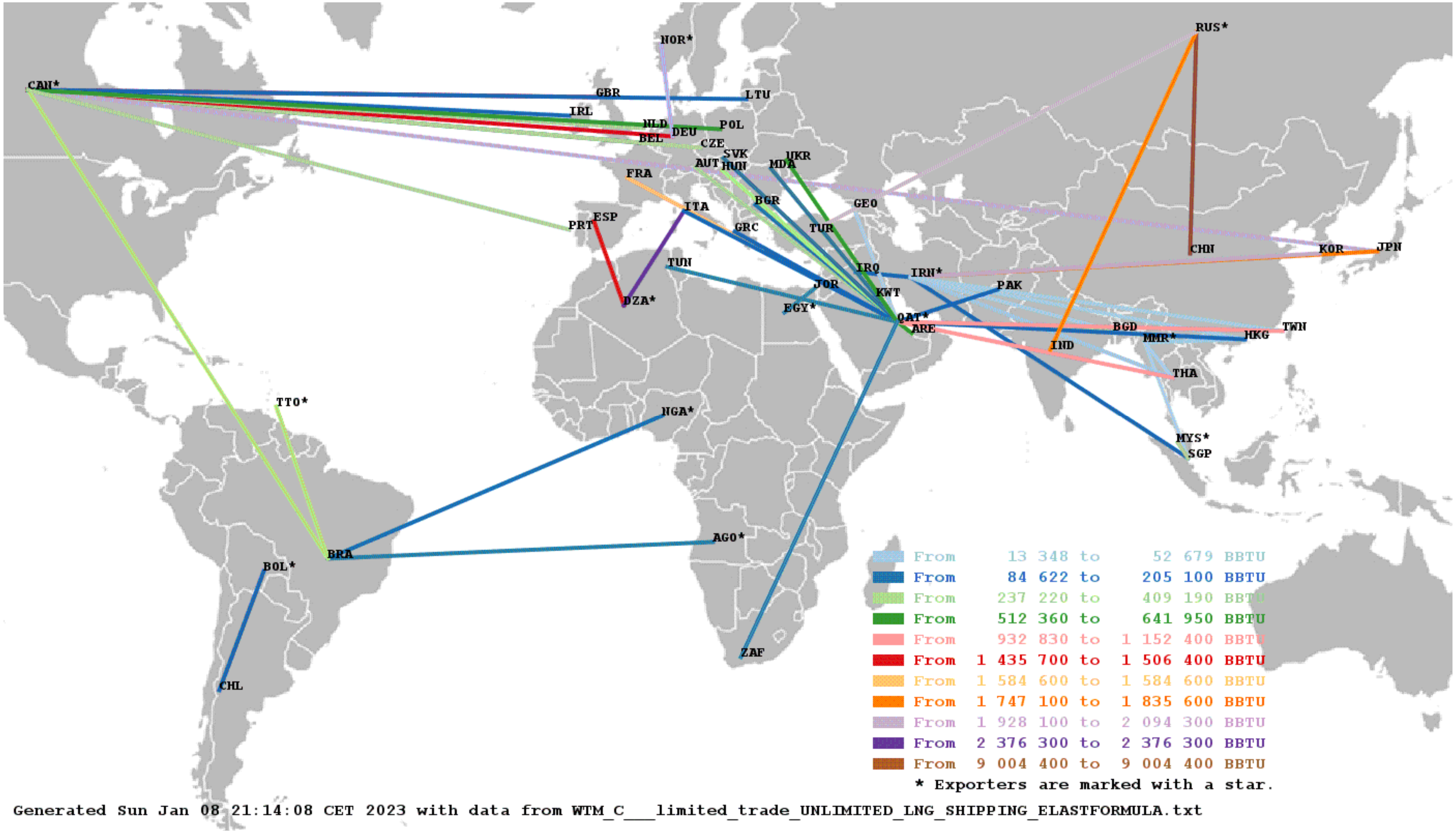

Figure 9: Increased LNG shipping capacity scenario. Limited trade and unlimited LNG shipping capacity.

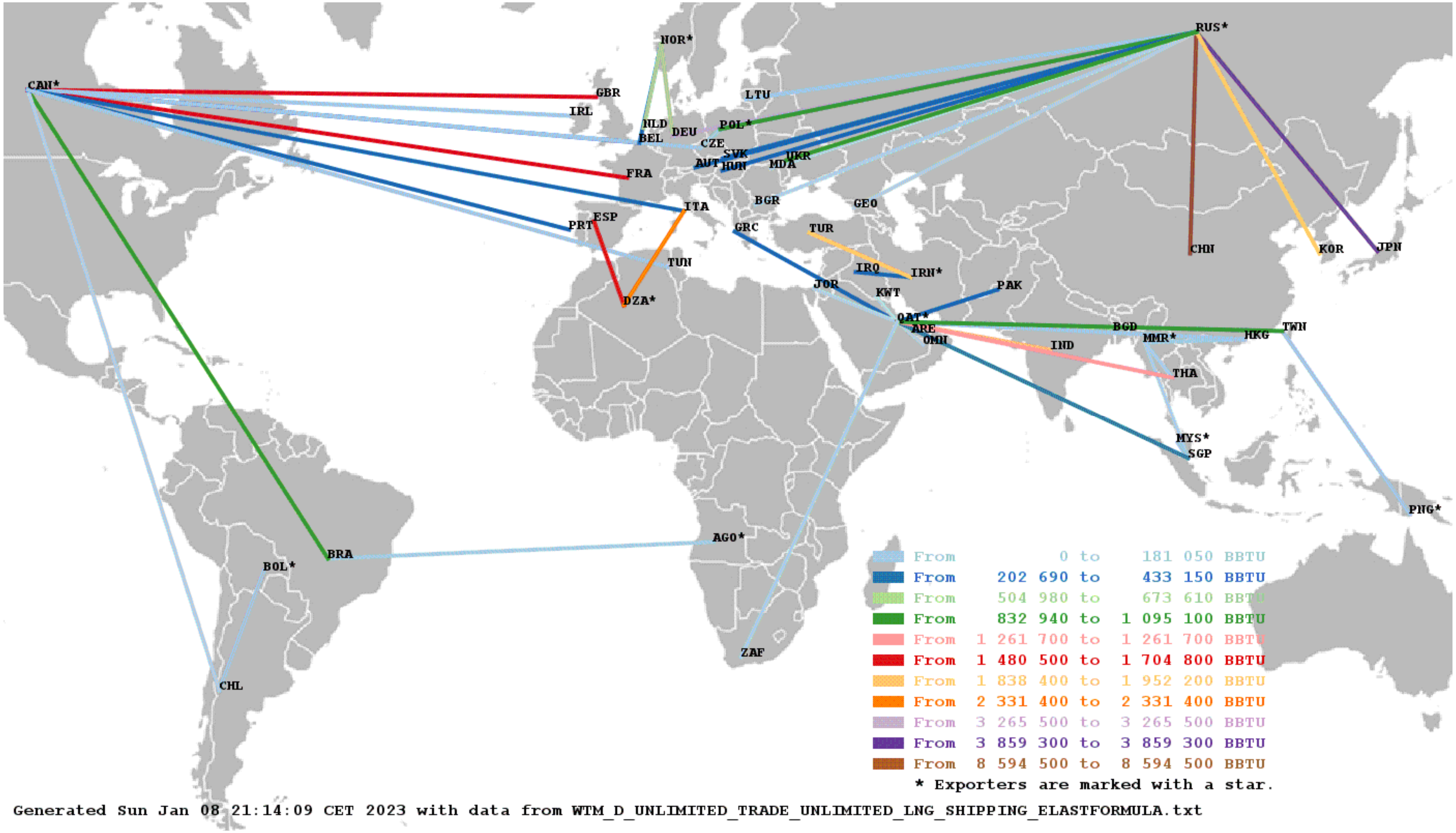

Figure 10: Future world peace scenario. Unlimited trade and unlimited LNG shipping capacity.

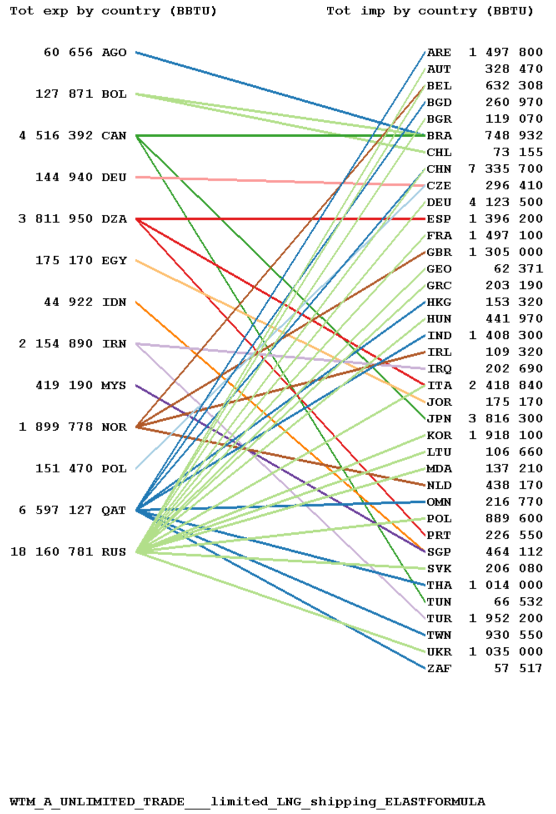

Figure 11: World trade flows in base scenario.

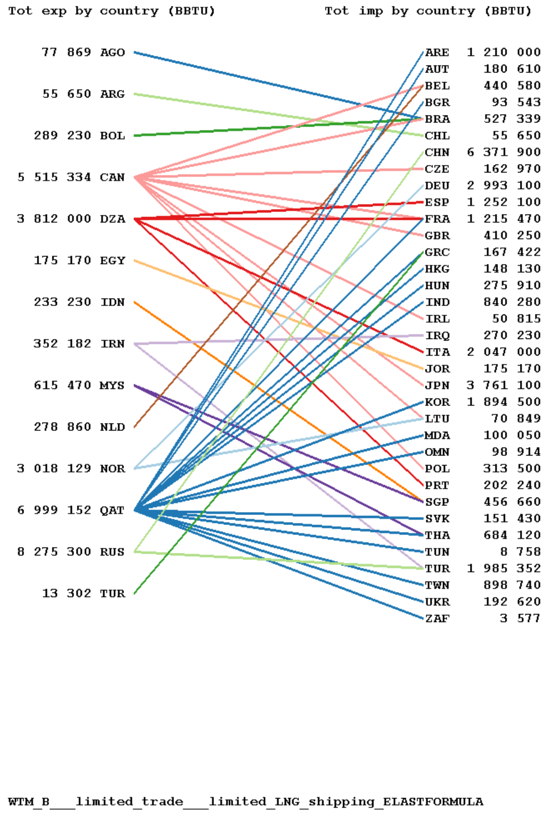

Figure 12: World trade flows in invasion scenario.

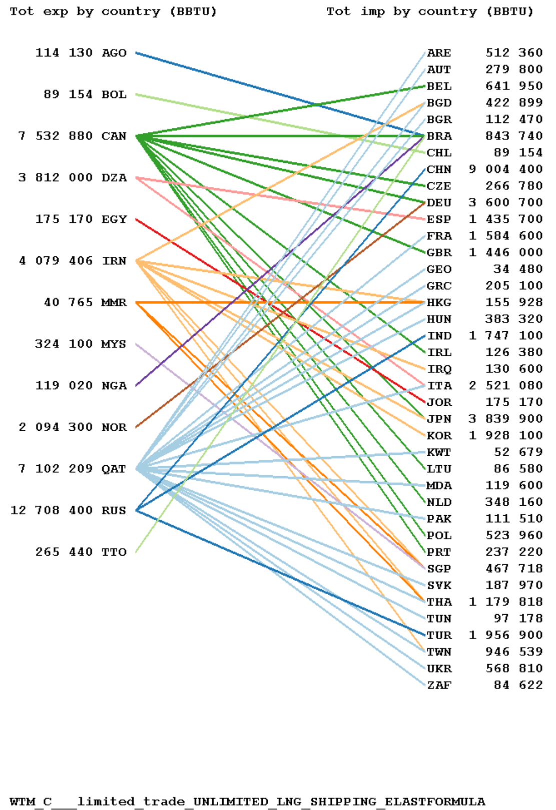

Figure 13: World trade flows in increased LNG capacity.

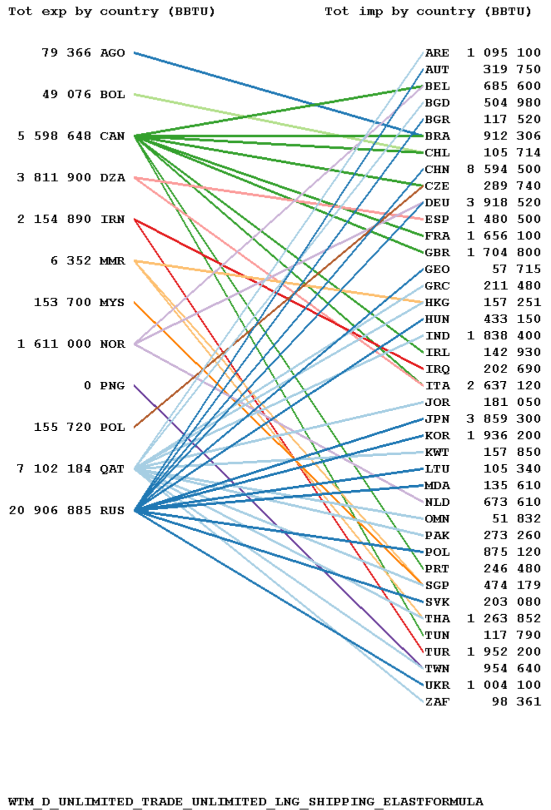

Figure 14: World trade flows in future world peace scenario.

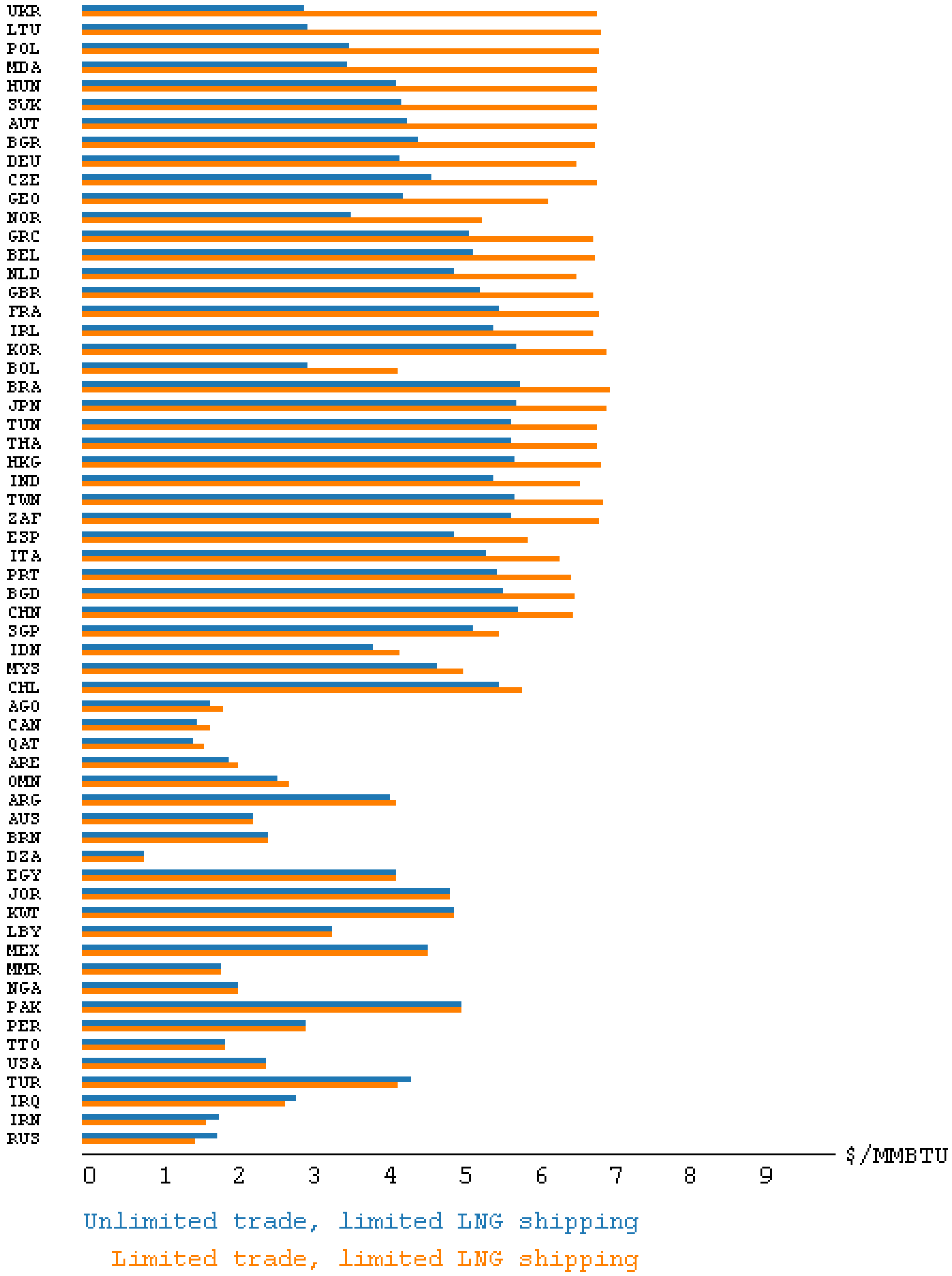

Figure 15: Wholesale prices per country in base scenario (blue) and invasion scenario (orange) sorted by price difference.

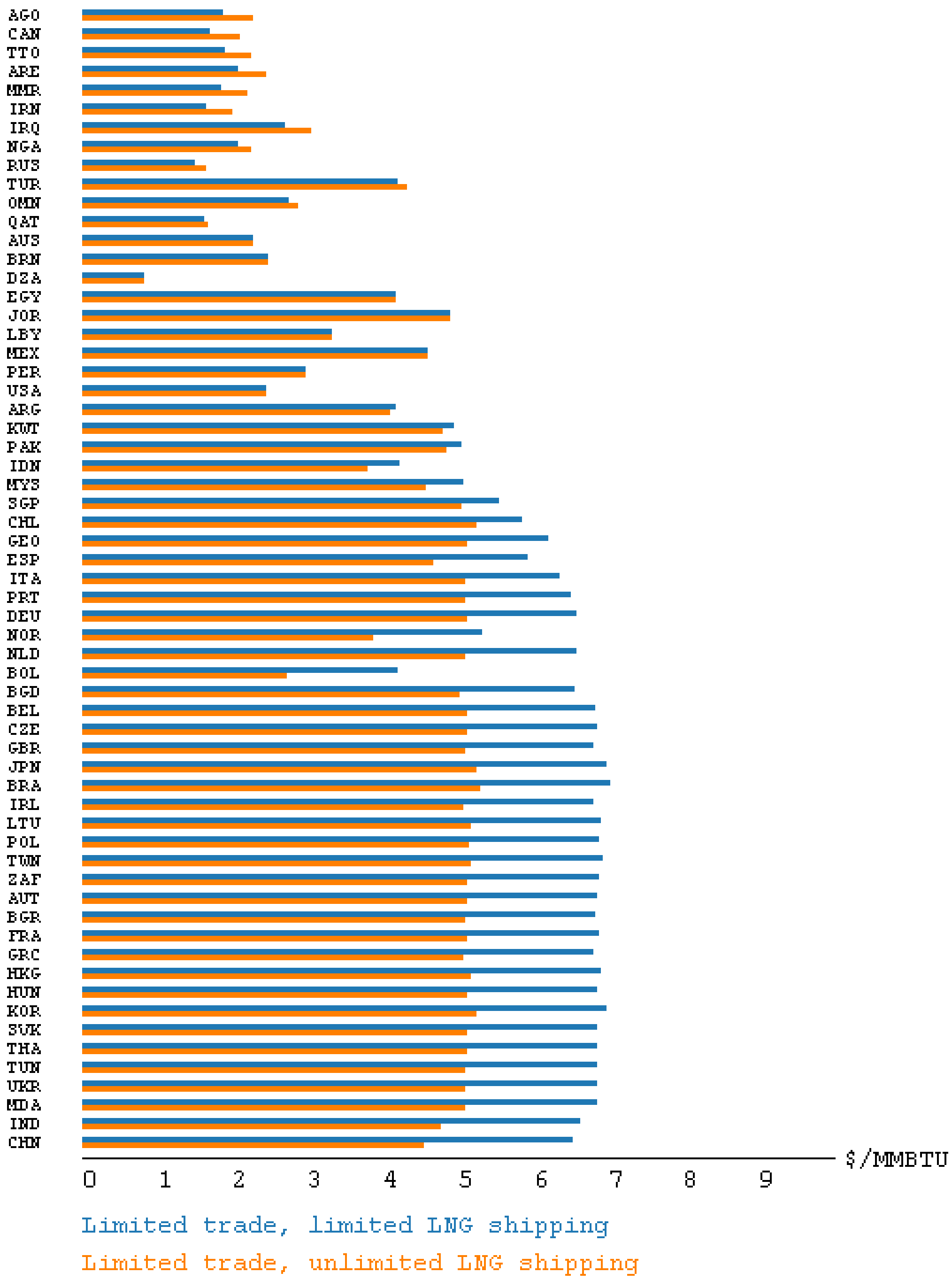

Figure 16: Prices per country in invasion (blue) and increased LNG shipping capacity (orange) scenario sorted by price difference.

Figure 17: Demand elasticity in different parts of the world according to the demand elasticity formula.

The output from the model is very extensive. Appendix A provides a link to even more detailed results online where prices, transportation costs, production and consumption in all scenarios and in all elasticity variations from the sensitivity analysis are published. In the online material one can for example note that in the base scenario Egypt exports natural gas to Jordan. They do not trade with other countries. According to the tables in the detailed result file
WTM_A_UNLIMITED_TRADE___limited_LNG_shipping_ELASTFORMULA.html
the transportation cost between Egypt and Jordan is 0.74 $/MMBTU. The demand price in Jordan is 4.88 $/MMBTU and in Egypt 4.14. According to the SPE theory the price spread between the two markets should equal the transportation cost. Since 4.88-4.14 equals 0.74 this verifies that the model matches the theory.

In the online material in the same file we can also see supply and demand prices, total production value and total consumption value for both the model and in the real world. For example in Germany the total consumption value is 21 billion dollar. According to the model it is 17. Or in Canada the production is worth 8 billion dollar in reality, but in the model it is 12. These values indicate arbitrage possibilities.

Also see appendix A and follow the link to see the results from the test of the scaling method verses the increased Rtmaxv method to verify that they produce equal results.

5.2 Sensitivity analysis

See Appendix A for the link to the detailed results from the sensitivity analysis which is presented online. The main difference between the main results and the sensitivity analysis in the base scenario is that in the -0.2 and -1.1 demand elasticity variations the number of exporting countries is different from the formula version. In formula version there are 13 exporting countries, in -1.1 version there is one more and in -0.2 version there is three more than in -1.1 version. Also for number of importing countries there are small differences between the versions.

Elasticity	**Consumption**	**Base**	**Invasion**	**Increased LNG**	**World peace**
formula	Total consumption	125 985 667	124 098 239	123 766 438	124 372 317
formula	Of which European	17 952 465	13 988 639	17 561 111	18 783 924
-0,2	Total consumption	126 717 212	125 600 215	126 614 776	126 443 145
-0,2	Of which European	16 815 372	15 530 173	16 670 642	17 006 314
-1,1	Total consumption	129 112 832	125 663 479	127 714 064	126 999 238
-1,1	Of which European	18 484 549	12 275 219	17 175 015	18 922 191

Table 7: Base scenario consumption (BBTU) for different levels of demand elasticity.

As seen in table 7 the consumption does not vary much between the different levels of demand elasticity. For example in the base scenario total consumption varies between 126.0 to 129.1 million BBTU in the formula and the -1.1 version respectively. The largest differences are found in the European consumption level in the invasion scenario, where the spread is from 15.5 to 12.3 million BBTU between the two extremes. In all versions we see that increased LNG returns the consumption levels approximately back to normal.

Further we can tell from the detailed results presented online that in the -1.1 version some more countries produce on max level and in -0.2 version then a few more also do so. But the difference is small.

5.3 The SPE model results compared to real world trade

Figure 6 shows the trade flows in the real world. Figure 7 shows the trade flows according to our model. The model maximizes the welfare, and since the trade flow shows that results from the model are different from the real world this also indicates that the world market for natural gas is not efficient. For example, in the real world it is USA who is the larger exporter compared to Canada even though the gas is cheaper in Canada and the countries that import from USA would benefit from importing from Canada instead. This is one of many examples of the arbitrage possibilities in the world market for natural gas.

Comparing the real trade flows as described in table 5 with the total volumes in the base scenario, we see that the results are very similar, both with regards to total production and consumption, and traded volumes.

5.4 Simulation with limited trade following the Russian invasion of Ukraine

In this section we compare the model's results from the base and invasion scenario. In figure 15 we see that the prices in Europe increase drastically when the trade with Russia is limited as a consequence of the Russian invasion in Ukraine during 2022. At the same time, Japan is affected by the increased demand for Canadian gas in Europe with higher prices in Japan too, but not as much. In South America there are no price changes at all, indicating that the world market is only partially integrated. It is worth noting that China which is the largest importer of natural gas in the real world, and also in our model, is one of the countries still importing from Russia in the simulated scenarios. Most Russian gas is exported to China in the invasion scenario.

In figure 11 and 12 we can follow the changed trading volumes and directions. Russia goes from 18 million BBTU to 8 million BBTU in exports due to the sanctions simulated in that scenario. That is a significant loss. At the same time, Norway and Canada increases their export. From figure 7 and 8 we see how Russia shifts from pipeline export to Europe to LNG export to China.

For Europe there is a drastic reduction in gas consumption, as seen in table 5. From figure 15 we can see that also the price is changed. In the European countries there is a significant change in price, e.g., Germany from roughly 4 in base scenario to roughly 7 in the invasion scenario, almost a doubling of the price. In Asia the change is much less, and in South America the price does not change at all in for example Trinidad and Tobago.

In Russia, as seen in the online material, the total production value in the base scenario is $57 billion and in the invasion scenario it is $40 billion. This is a 30% decrease in income from the gas production in Russia, according to the model.

5.5 Simulation of increased LNG shipping capacity

Figure 11 to 13 and table 4 tells us that in the short run, in the invasion scenario, there is a reduction in the consumption in Europe. In all scenarios the level of exports from Canada and from Qatar are about the same. When keeping the limited trade in the long run and simulating that the worlds LNG shipping capacity becomes unlimited, then we see that new countries start to import, and volumes traded increase.

Comparing the price in Germany (DEU) we see in figure 15 how the price first increases drastically when trade with Russia is limited due to the invasion of Ukraine. Then in figure 16 it is seen that the price in Germany is reduced when LNG shipping capacity is increased and almost reaches the same level as from the beginning. There is a similar outcome for the other European countries. So, in the long run and according to the model, the limited trade will not matter very much in terms of level of gas consumed, traded and produced - neither for Europe nor for Russia - if the LNG capacity is increased. What the model predicts when trade is limited and LNG shipping capacity is increased is just a shift in trade flows, but the actual production and consumption remains approximately the same as from the beginning. However, since the price changes at the same time as the trade flows, then the resulting total value of production is a more important change. In Russia, as seen in the online material, the total production value in the scenarios base, invasion, increased LNG and peace are 57, 40, 47 and 59 billion dollars respectively. This can be compared to the total cost of consumption in Germany, which are 17, 21, 19 and 17 billion dollars respectively in the simulated scenarios, which is a more limited spread compared to the value of production in Russia.

If world peace again, then Russia can increase their production to even more than it was in the base scenario and take markets shares from Canada, as seen in figure 14. Qatar is almost on the same export level in every scenario.

6. Discussion and conclusions

The first research question that we posed was if it is possible to describe the world natural gas trade flows prior to 2022 using the SPE model. We would say the answer is yes, and for two reasons. Firstly, in the base scenario, our model produces results that are close to the real world. The total volumes traded, total production, total consumption, ratio between production that is consumed indigenous to production that is exported are all close to what is being observed in the real world. What differs though is which countries that contributes most to the export. Also it is seen that the model in the invasion scenario reflects similar changes that actually took place during 2022 in the real world. For example the model predicted higher prices in Europe. When increased LNG imports become available in the increased LNG scenario, then Europe uses that, according to the model. This is also what we can observe in the real world that Europe has tried to do.

Secondly, we see from the literature that there are many models that are built up in a similar way. So, as it turned out, trying to model the world market for natural gas based on the same or similar theoretical framework was not a new idea. When comparing our model's results to the GNOME-model, we see that both models predict similar levels of consumption in the base scenario for Europe, even though our model is much less complicated.

The model gives some meaningful input to whether the world natural gas market is efficient or not. For example, in Asia the model shows that the long run contracts used is not the best solution for Japan, from a strict economical point of view. On the other hand, the long term contracts represent other values related to e.g. political stability and was arguably also needed to facilitate the initial investments in shipping capacity. This deviation from efficiency could perhaps partially be explained by the factors "common language" and "political risk" used in the model by Zhang et al. (2017) which are two factors that are completely ignored by the SPE-model.

It is worth noticing that Canada would benefit from exporting to other countries than USA, according to the model. In reality Canada exported 76 092 MCM (million cubic meter) to USA and USA exported 25 551 MCM to Canada in 2019. In the real world, USA is a large exporter to many different countries, but the price is higher in USA compared to Canada, and the countries importing from USA could import natural gas cheaper from Canada instead.

The explanation of this result is most likely that Canada in the real world lacks infrastructure for exporting LNG, as was seen in figure 2. Maybe this can also explain the price difference between USA and Canada if there is upwards pressure on the price in USA caused by the USA export.

The reasoning behind the choice of supply elasticities is that in the short run production will not differ much, for example due to gas not being the primary production but instead a biproduct in oil extraction. But in the long run, at least some production will be affected by a price change. On the other hand, supply is limited, resources will become exhausted. We try to balance this when choosing elasticities, but this is a weak point in the model and would require more research to increase the precision of the model. Likewise, the elasticity of demand is also a weak point in the model due to the large variation in the estimates reported in the literature. These estimates are also done in the past and might not reflect current consumer's behaviour. On the other hand, the sensitivity analysis did not show that the results are heavily affected by the demand elasticities, at least not in the intervals that we tried.

Our second research question was how the European gas market would react to limitations of trade with Russia. The model predicts that Europe can replace the gas from Russia with LNG from Canada. Canada is currently according to contemporary newspaper articles unwilling to do so though, and currently Germany is having discussions with Mexico which has large reserves of shell gas (Cutler, 2022). So, there are options available for Europe, in the long run. As of December 17 2022 Germany's first LNG terminal became operational with a capacity of one million BBTU and which was built in only 4 months (Energinyheter, 2022). According to recent newspaper articles, Europe has also increased imports of LNG from Russia during 2022 (Natural Gas Intelligence, 2022), which also raises questions regarding the European energy security strategy.

Comparing the trade flows for Russia and for Europe in base scenario to increased LNG capacity, we see that the traded volumes do not change much. Russia exports approximately the same and Europe imports approximately the same as before. The only thing that differs is that the gas from Russia has new consuming countries, and Europe buys its gas from other sources, for example Canada and Norway, according to the model. The whole idea with the limited trade as a result from sanctions is pointless, from a volume point of view, since no one is affected much in the long run. On the other hand the model predicts that the economical impact on total production value should be so large that it has tangible consequences for Russia. If the world could keep peace instead, the total welfare would benefit from that, especially Russia who would increase their export from 18 in base scenario to 21 million BBTU in the future peace scenario.

Our third research question was how world trade would be affected by a large build-up of LNG shipping capacity. Comparing the base scenario to the increased LNG capacity scenario we see that consumption levels and prices for Europe can be returned to pre-war levels if huge investments are done in LNG-shipping capacity. We are sceptical to investments in LNG-shipping capacity since we know that we must cut down usage of fossil fuel anyway for climate change reasons. That cut down of fossil fuel might be necessary to do before the end of economical and technical life length of the investments in LNG shipping are reached. We suggest that further research includes renewable energy in the model and analyse what is the best investment alternative, renewable energy or LNG capacity?

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Appendix A

Full source code and full results available at this internet webpage:
http://www.freefarm.se/ekonomi/uppsats/coderesults/

Appendix B

In appendix B a shortened version of the code used is listed, with comments on what the code does.

```
* Comments in GAMS start with a * in the beginning of the line.
* This is a demo file with 8 countries. The full model contains
* 62. Source code for the full models can be found online
* http://www.freefarm.se/ekonomi/uppsats/coderesults/

* This program is based on the work by Erwin Kalvelagen
* https://www.researchgate.net/publication/2558234_Spatial_Equilibrium_Models_with_GAMS


* In GAMS programming language "sets" are like arrays. There is one set for all
* producers (SOURCE) and another for all consumer markets (MARKETS).
* CURVE is an internal used set to keep track of all intercepts and slopes.

SETS
    SOURCE PRODUCER OF NATURAL GAS  /AUS, CAN, CHN, DEU, JPN, NOR, RUS, USA/
    MARKET DEMAND MARKETS   /AUS, CAN, CHN, DEU, JPN, NOR, RUS, USA/
    CURVE  CURVE PARAMETERS  /INTERCEPT, SLOPE/
;


* This is the supply curves for the producers declared in a table
TABLE
    SUPPLYEQPARAM(SOURCE,CURVE)  INVERSE SUPPLY CURVE FOR THE LNG PRODUCER
                    INTERCEPT           SLOPE
AUS                 0.00000             1.08813706232233e-006
CAN                 0.00000             1.89152554679001e-007
CHN                 0.00000             1.2725431749339e-006
DEU                 -0.00000            2.89987061391613e-005
JPN                 0.00000             0.000114394776038108
NOR                 -0.00000            1.61783444738705e-006
RUS                 -0.00000            5.57090057267375e-008
USA                 -0.00000            7.42005610368195e-008
;

* This is the demand curves for the consumers (markets) declared in a table
TABLE
    DEMANDEQPARAM(MARKET,CURVE)  INVERSE DEMAND CURVES FOR THE MARKETS
                    INTERCEPT           SLOPE
AUS                 13.53223            -5.42637460834384e-006
CAN                 2.15282             -1.91713065742621e-007
CHN                 27.22428            -1.80653506051826e-006
DEU                 14.91030            -2.59723193265575e-006
JPN                 109.38605           -2.68054449451116e-005
NOR                 18.13333            -5.06613871285075e-005
RUS                 2.66619             -6.43573687292794e-008
```

```
USA                 4.62171             -6.72705426830604e-008
;

* This is a table with all the shipping costs. The price already reflect the method of transportation
* and the distance. The unit is doller per MMBTU
TABLE
   COST(SOURCE,MARKET)   SHIPPING COST FROM EACH SOURCE TO EACH MARKET. DOLLAR PER MMBTU
                  AUS               CAN               CHN               DEU               JPN               NOR               RUS               USA
AUS               0.0000000         3.3560800         3.2112400         3.6778800         3.2079200         3.7118800         3.2686800         3.3122400
CAN               3.3560400         0.0000000         3.2250000         3.0320000         3.1607200         3.0292000         3.1201600         1.1055638
CHN               3.2112400         3.2250000         0.0000000         3.6194000         2.8644400         3.6424000         8.6925675         3.2243600
DEU               3.6778800         3.0320400         3.6194000         0.0000000         3.6717600         1.2570381         2.4212685         3.1995200
JPN               3.2079600         3.1607600         2.8644800         3.6718800         0.0000000         3.7058800         2.8854800         3.1601200
NOR               3.7120400         3.0292400         3.6425200         1.2570381         3.7059200         0.0000000         2.4746985         3.2026400
RUS               3.2687200         3.1202000         2.9120400         2.4212685         2.8854800         2.4746985         0.0000000         3.1491200
USA               3.3122400         1.1055638         3.2243600         3.1996400         3.1600800         3.2026800         3.1491200         0.0000000
;

* This table is used to calculate the max LNG shipping capacity
TABLE
    ISLNG(SOURCE,MARKET)   SHIPPING METHOD. 1 MEANS THE SHIPPING BETWEEN 2 COUNTRIES IS DONE BY LNG AND 0 IS PIPELINE
                  AUS               CAN               CHN               DEU               JPN               NOR               RUS               USA
AUS               0                 1                 1                 1                 1                 1                 1                 1
CAN               1                 0                 1                 1                 1                 1                 1                 0
CHN               1                 1                 0                 1                 1                 1                 0                 1
DEU               1                 1                 1                 0                 1                 0                 0                 1
JPN               1                 1                 1                 1                 0                 1                 1                 1
NOR               1                 1                 1                 0                 1                 0                 0                 1
RUS               1                 1                 1                 0                 1                 0                 0                 1
USA               1                 0                 1                 1                 1                 1                 1                 0
;


* We make an assumption that none of the producers are able to increase their production
* above 20% of current production. Unit BBTU per year.
PARAMETERS
    MAXIMUM_PRODUCTION_CAPACITY(SOURCE)   MAXIMUM PRODUCTION CAPACITY AT EACH SOURCE
    /

AUS                 6144789
CAN                 7966826
CHN                 7464845
DEU                 254056
JPN                 104312
NOR                 5043674
RUS                 32460367
USA                 40768601

/
;

* These are variables that is used in the equations. Some of them are part of the
* optimization (e.g. SUPPLY_Q), other are just for making calculations (e.g SUPPLY_P).
* Since they are POSITIVE VARIABLES they must be larger or equal to zero.
```

```
* This is in line with the theory and how SPE is defined.
POSITIVE VARIABLES
         SHIPMENTS(SOURCE,MARKET)   AMOUNT SHIPPED OVER A TRANSPORT ROUTE
         SUPPLY_Q(SOURCE)           QUANTITY PRODUCED AT EACH SOURCE
         DEMAND_Q(MARKET)           QUANTITY CONSUMED BY EACH MARKET
         SUPPLY_P(SOURCE)           PRICE FOR THE QUANTITY PRODUCED AT EACH SOURCE
         DEMAND_P(MARKET)           PRICE PAYED BY CONSUMERS AT EACH MARKET
         TOT_SHIP                   TOTAL QUANTITY SHIPPED
         TOT_PROD                   TOTAL QUANTITY PRODUCED
         TOT_CONS                   TOTAL QUANTITY CONSUMED
         TOT_DOME                   TOTAL QUANTITY PRODUCED AND DOMESTICALLY CONSUMED
         TOT_LNG                    TOTAL QUANTITY SHIPPED WITH LNG CARRIERS
         TOT_PIPE                   TOTAL QUANTITY SHIPPED IN PIPELINES
         LNG_MAX                    MAXIMUM LNG TRANSPORT CAPACITY
;

* This is the total welfare variable used in the objective function.
VARIABLES
         WELFARE TOTAL CONSUMERS AND PRODUCERS SURPLUS;

* Before used, all equations must be declared.
EQUATIONS
        SUPPLY_MAX_EQ(SOURCE)              SUPPLY MUST BE LESS THAN THE MAXIMUM CAPACITY AT EACH SOURCE
        SUPPLY_P_EQ(SOURCE)                SUPPLY FUNCTION
        DEMAND_P_EQ(MARKET)                DEMAND FUNTION
        SUPPLY_RESTRICTION(SOURCE)         SUPPLY FROM ALL SOURCES MUST SATISFY THE REQUIERD SHIPMENT VOLUMES
        DEMANDE_RESTRICTION(MARKET)        SUPPLY TO ALL MARKETS MUST SATISFY THE DEMAND
        MAXLNG                             MAX WORLD LNG SHIPPING CAPACITY IN BBTU
        OBJECTIVE                          TOTAL SURPLUS EQUATION WHICH IS THE OBJECTIVE FUNCTION TO MAXIMIZE.
        SUM_SHIPPMENTS                    TOTAL QUANTITY SHIPPED
        SUM_PRODUCTION                    TOTAL QUANTITY PRODUCED
        SUM_CONSUMTION                    TOTAL QUANTITY CONSUMED
        SUM_DOMESTIC_PROD_CONS            TOTAL QUANTITY PRODUCED AND DOMESTICALLY CONSUMED
        TOT_LNG_EQ                         EQ  TOTAL QUANTITY SHIPPED WITH LNG CARRIERS
        TOT_PIPE_EQ                        EQ  TOTAL QUANTITY SHIPPED IN PIPELINES
        LNG_MAX_EQ                         EQ  MAXIMUM LNG TRANSPORT CAPACITY
        NOTRADE_RUS_AUS                   TRADE BETWEEN RUS AND AUS IS ZERO
        NOTRADE_RUS_CAN                   TRADE BETWEEN RUS AND CAN IS ZERO
        NOTRADE_RUS_DEU                   TRADE BETWEEN RUS AND DEU IS ZERO
        NOTRADE_RUS_JPN                   TRADE BETWEEN RUS AND JPN IS ZERO
        NOTRADE_RUS_NOR                   TRADE BETWEEN RUS AND NOR IS ZERO
        NOTRADE_RUS_USA                   TRADE BETWEEN RUS AND USA IS ZERO

;

* Here comes the tricky part when the restrictions and other calculations are implemented.
SUPPLY_MAX_EQ(SOURCE)..       SUPPLY_Q(SOURCE) =L= MAXIMUM_PRODUCTION_CAPACITY(SOURCE);

DEMANDE_RESTRICTION(MARKET).. DEMAND_Q(MARKET) =L= SUM(SOURCE,SHIPMENTS(SOURCE,MARKET)) ;
```

```
SUPPLY_RESTRICTION(SOURCE)..  SUPPLY_Q(SOURCE) =G= SUM(MARKET,SHIPMENTS(SOURCE,MARKET)) ;

SUPPLY_P_EQ(SOURCE).. SUPPLY_P(SOURCE) =E= SUPPLYEQPARAM(SOURCE,"INTERCEPT")+SUPPLYEQPARAM(SOURCE,"SLOPE")*SUPPLY_Q(SOURCE);
DEMAND_P_EQ(MARKET).. DEMAND_P(MARKET) =E= DEMANDEQPARAM(MARKET,"INTERCEPT")+DEMANDEQPARAM(MARKET,"SLOPE")*DEMAND_Q(MARKET);
* Exclude shippments from self to self by the diag statement who returns 0 if SOURCE equals MARKET
* This is needed or else domestic consumtion of domestic production woudl register as a shipping.
SUM_SHIPPMENTS..         TOT_SHIP =E= SUM((SOURCE,MARKET), SHIPMENTS(SOURCE,MARKET) * (1-diag(SOURCE,MARKET)) );
SUM_DOMESTIC_PROD_CONS.. TOT_DOME =E= SUM((SOURCE,MARKET), SHIPMENTS(SOURCE,MARKET) * (diag(SOURCE,MARKET)) );
SUM_PRODUCTION..         TOT_PROD =E= SUM(SOURCE , SUPPLY_Q(SOURCE));
SUM_CONSUMTION..         TOT_CONS =E= SUM(MARKET , DEMAND_Q(MARKET));
TOT_LNG_EQ..              TOT_LNG =E= SUM((SOURCE,MARKET),SHIPMENTS(SOURCE,MARKET)*(ISLNG(SOURCE,MARKET)));
TOT_PIPE_EQ..            TOT_PIPE =E= SUM((SOURCE,MARKET),SHIPMENTS(SOURCE,MARKET)*(1-ISLNG(SOURCE,MARKET)) *(1-diag(SOURCE,MARKET)) );
 LNG_MAX_EQ..            LNG_MAX =E= 500*1000*35.31;


* Note that for all source=market isLNG is 0, so it does not affect the MAXLNG sum.
MAXLNG.. SUM((SOURCE,MARKET),SHIPMENTS(SOURCE,MARKET)*(ISLNG(SOURCE,MARKET))) =L= 500*1000*35.31;

* Here the shipments are locked to zero in the limited trade scenarios.
NOTRADE_RUS_AUS..     SHIPMENTS("RUS","AUS") =E= 0.0 ;
NOTRADE_RUS_CAN..     SHIPMENTS("RUS","CAN") =E= 0.0 ;
NOTRADE_RUS_DEU..     SHIPMENTS("RUS","DEU") =E= 0.0 ;
NOTRADE_RUS_JPN..     SHIPMENTS("RUS","JPN") =E= 0.0 ;
NOTRADE_RUS_NOR..     SHIPMENTS("RUS","NOR") =E= 0.0 ;
NOTRADE_RUS_USA..     SHIPMENTS("RUS","USA") =E= 0.0 ;

* Finally the objective functions. Not that it is a direct copy of equation 1 listed in the thesis.
OBJECTIVE..
WELFARE
=E=
SUM(MARKET,DEMANDEQPARAM(MARKET,"INTERCEPT")*DEMAND_Q(MARKET)+0.5*DEMANDEQPARAM(MARKET,"SLOPE")*SQR(DEMAND_Q(MARKET)))
- SUM(SOURCE,SUPPLYEQPARAM(SOURCE,"INTERCEPT")*SUPPLY_Q(SOURCE)+0.5*SUPPLYEQPARAM(SOURCE,"SLOPE")*SQR(SUPPLY_Q(SOURCE)))
- SUM((SOURCE,MARKET),SHIPMENTS(SOURCE,MARKET)*(COST(SOURCE,MARKET))) ;


* Instruct GAMS to solve...
MODEL OurModel /ALL/;

* ... using the NLP solver
SOLVE OurModel USING NLP MAXIMIZING WELFARE;

* Print out some calculated variables
OPTION DECIMALS=8
OPTION DISPWIDTH=20;
DISPLAY TOT_LNG.L     ;
DISPLAY TOT_PIPE.L    ;
DISPLAY TOT_SHIP.L    ;
DISPLAY LNG_MAX.L     ;
DISPLAY TOT_DOME.L    ;
```

```
DISPLAY TOT_PROD.L    ;
DISPLAY TOT_CONS.L    ;
* This produces a nice table. One of many smooth little tricks in GAMS.
DISPLAY SHIPMENTS.L    ;

**** list of country codes ****
* AUS  = Australia
* CAN  = Canada
* CHN  = People's Republic of China
* DEU  = Germany
* JPN  = Japan
* NOR  = Norway
* RUS  = Russia
* USA  = United States


******************************************************************************
* If you run this code, for example using GAMS studio, then the output should be like this:
* ---- EQU SUPPLY_MAX_EQ  SUPPLY MUST BE LESS THAN THE MAXIMUM CAPACITY AT EACH SOURCE
*
*            LOWER          LEVEL          UPPER         MARGINAL
*
* AUS        -INF      2077243.9569   6144789.0000         .
* CAN        -INF      7966826.0000   7966826.0000        0.2167
* CHN        -INF      3475123.8245   7464845.0000        EPS
* DEU        -INF       163993.9062    254056.0000        EPS
* JPN        -INF        42697.1516    104312.0000        EPS
* NOR        -INF      2162503.7091   5043674.0000         .
* RUS        -INF      2.7108815E+7   3.2460367E+7         .
* USA        -INF      3.2668933E+7   4.0768601E+7         .
*
* ---- EQU SUPPLY_P_EQ  SUPPLY FUNCTION
*
*            LOWER          LEVEL          UPPER         MARGINAL
*
* AUS          .              .              .            EPS
* CAN          .              .              .            EPS
* CHN          .              .              .            EPS
* DEU          .              .              .            EPS
* JPN          .              .              .            EPS
* NOR          .              .              .            EPS
* RUS          .              .              .            EPS
* USA          .              .              .            EPS
*
* ---- EQU DEMAND_P_EQ  DEMAND FUNTION
*
*            LOWER          LEVEL          UPPER         MARGINAL
*
* AUS        13.5322        13.5322        13.5322        EPS
```

```
* CAN        2.1528         2.1528         2.1528         EPS
* CHN       27.2243        27.2243        27.2243         EPS
* DEU       14.9103        14.9103        14.9103         EPS
* JPN      109.3860       109.3860       109.3860         EPS
* NOR       18.1333        18.1333        18.1333         EPS
* RUS        2.6662         2.6662         2.6662         EPS
* USA        4.6217         4.6217         4.6217         EPS
*
* ---- EQU SUPPLY_RESTRICTION  SUPPLY FROM ALL SOURCES MUST SATISFY THE REQUIERD SHIPMENT VOLUMES
*
*           LOWER          LEVEL          UPPER         MARGINAL
*
* AUS         .              .            +INF          -2.2603
* CAN         .              .            +INF          -1.7236
* CHN         .              .            +INF          -4.4222
* DEU         .              .            +INF          -4.7556
* JPN         .              .            +INF          -4.8843
* NOR         .              .            +INF          -3.4986
* RUS         .              .            +INF          -1.5102
* USA         .              .            +INF          -2.4241
*
* ---- EQU DEMANDE_RESTRICTION  SUPPLY TO ALL MARKETS MUST SATISFY THE DEMAND
*
*           LOWER          LEVEL          UPPER         MARGINAL
*
* AUS       -INF             .              .            2.2603
* CAN       -INF             .              .            1.7236
* CHN       -INF             .              .            4.4222
* DEU       -INF             .              .            4.7556
* JPN       -INF             .              .            4.8843
* NOR       -INF             .              .            3.4986
* RUS       -INF             .              .            1.5102
* USA       -INF             .              .            2.4241
*
*                            LOWER          LEVEL          UPPER         MARGINAL
*
* ---- EQU MAXLNG            -INF      1.4874865E+7   1.7655000E+7         EPS
* ---- EQU OBJECTIVE           .              .              .            1.0000
* ---- EQU SUM_SHIPP~          .              .              .             EPS
* ---- EQU SUM_PRODU~          .              .              .             EPS
* ---- EQU SUM_CONSU~          .              .              .             EPS
* ---- EQU SUM_DOMES~          .              .              .             EPS
* ---- EQU TOT_LNG_EQ          .              .              .             EPS
* ---- EQU TOT_PIPE_~          .              .              .             EPS
* ---- EQU LNG_MAX_EQ   1.7655000E+7   1.7655000E+7   1.7655000E+7         EPS
* ---- EQU NOTRADE_R~          .              .              .           -2.5186
* ---- EQU NOTRADE_R~          .              .              .           -2.9068
* ---- EQU NOTRADE_R~          .              .              .            0.8241
* ---- EQU NOTRADE_R~          .              .              .            0.4886
```

```
* ---- EQU NOTRADE_R~          .              .              .           -0.4863
* ---- EQU NOTRADE_R~          .              .              .           -2.2353
*
*   MAXLNG  MAX WORLD LNG SHIPPING CAPACITY IN BBTU
*   OBJECTIVE  TOTAL SURPLUS EQUATION WHICH IS THE OBJECTIVE FUNCTION TO MAXIMIZE.
*   SUM_SHIPPMENTS  TOTAL QUANTITY SHIPPED
*   SUM_PRODUCTION  TOTAL QUANTITY PRODUCED
*   SUM_CONSUMTION  TOTAL QUANTITY CONSUMED
*   SUM_DOMESTIC_PROD_CONS  TOTAL QUANTITY PRODUCED AND DOMESTICALLY CONSUMED
*   TOT_LNG_EQ  EQ  TOTAL QUANTITY SHIPPED WITH LNG CARRIERS
*   TOT_PIPE_EQ  EQ  TOTAL QUANTITY SHIPPED IN PIPELINES
*   LNG_MAX_EQ  EQ  MAXIMUM LNG TRANSPORT CAPACITY
*   NOTRADE_RUS_AUS  TRADE BETWEEN RUS AND AUS IS ZERO
*   NOTRADE_RUS_CAN  TRADE BETWEEN RUS AND CAN IS ZERO
*   NOTRADE_RUS_DEU  TRADE BETWEEN RUS AND DEU IS ZERO
*   NOTRADE_RUS_JPN  TRADE BETWEEN RUS AND JPN IS ZERO
*   NOTRADE_RUS_NOR  TRADE BETWEEN RUS AND NOR IS ZERO
*   NOTRADE_RUS_USA  TRADE BETWEEN RUS AND USA IS ZERO
*
* ---- VAR SHIPMENTS  AMOUNT SHIPPED OVER A TRANSPORT ROUTE
*
*              LOWER          LEVEL          UPPER         MARGINAL
*
* AUS.AUS          .       2077243.9569       +INF            .
* AUS.CAN          .             .            +INF          -3.8928
* AUS.CHN          .             .            +INF          -1.0493
* AUS.DEU          .             .            +INF          -1.1826
* AUS.JPN          .             .            +INF          -0.5839
* AUS.NOR          .             .            +INF          -2.4736
* AUS.RUS          .             .            +INF          -4.0188
* AUS.USA          .             .            +INF          -3.1485
* CAN.AUS          .             .            +INF          -2.8193
* CAN.CAN          .       2238808.8427       +INF            .
* CAN.CHN          .             .            +INF          -0.5264
* CAN.DEU          .       1872188.5011       +INF            .
* CAN.JPN          .       3855828.6562       +INF      6.661338E-15
* CAN.NOR          .             .            +INF          -1.2542
* CAN.RUS          .             .            +INF          -3.3336
* CAN.USA          .             .            +INF          -0.4051
* CHN.AUS          .             .            +INF          -5.3732
* CHN.CAN          .             .            +INF          -5.9236
* CHN.CHN          .       3475123.8245       +INF            .
* CHN.DEU          .             .            +INF          -3.2860
* CHN.JPN          .             .            +INF          -2.4024
* CHN.NOR          .             .            +INF          -4.5661
* CHN.RUS          .             .            +INF         -11.6046
* CHN.USA          .             .            +INF          -5.2226
* DEU.AUS          .             .            +INF          -6.1732
* DEU.CAN          .             .            +INF          -6.0640
```

```
* DEU.CHN          .              .           +INF           -3.9528
* DEU.DEU          .        163993.9062       +INF              .
* DEU.JPN          .              .           +INF           -3.5430
* DEU.NOR          .              .           +INF           -2.5141
* DEU.RUS          .              .           +INF           -5.6667
* DEU.USA          .              .           +INF           -5.5311
* JPN.AUS          .              .           +INF           -5.8320
* JPN.CAN          .              .           +INF           -6.3215
* JPN.CHN          .              .           +INF           -3.3266
* JPN.DEU          .              .           +INF           -3.8006
* JPN.JPN          .         42697.1516       +INF              .
* JPN.NOR          .              .           +INF           -5.0916
* JPN.RUS          .              .           +INF           -6.2596
* JPN.USA          .              .           +INF           -5.6204
* NOR.AUS          .              .           +INF           -4.9503
* NOR.CAN          .              .           +INF           -4.8042
* NOR.CHN          .              .           +INF           -2.7188
* NOR.DEU          .       1873629.7197       +INF             EPS
* NOR.JPN          .              .           +INF           -2.3202
* NOR.NOR          .        288873.9894       +INF              .
* NOR.RUS          .              .           +INF           -4.4631
* NOR.USA          .              .           +INF           -4.2772
* RUS.AUS          .              .           +INF              .
* RUS.CAN          .              .           +INF              .
* RUS.CHN          .       9146848.1445       +INF              .
* RUS.DEU          .              .           +INF              .
* RUS.JPN          .              .           +INF              .
* RUS.NOR          .              .           +INF              .
* RUS.RUS          .       1.7961966E+7       +INF              .
* RUS.USA          .              .           +INF              .
* USA.AUS          .              .           +INF           -3.4760
* USA.CAN          .              .           +INF           -1.8060
* USA.CHN          .              .           +INF           -1.2262
* USA.DEU          .              .           +INF           -0.8681
* USA.JPN          .              .           +INF           -0.6998
* USA.NOR          .              .           +INF           -2.1282
* USA.RUS          .              .           +INF           -4.0630
* USA.USA          .       3.2668933E+7       +INF              .
*
* ---- VAR SUPPLY_Q  QUANTITY PRODUCED AT EACH SOURCE
*
*           LOWER          LEVEL          UPPER         MARGINAL
*
* AUS         .       2077243.9569       +INF            EPS
* CAN         .       7966826.0000       +INF             .
* CHN         .       3475123.8245       +INF             .
* DEU         .        163993.9062       +INF             .
* JPN         .         42697.1516       +INF             .
* NOR         .       2162503.7091       +INF             .
```

```
* RUS          .       2.7108815E+7        +INF             .
* USA          .       3.2668933E+7        +INF             .
*
* ---- VAR DEMAND_Q  QUANTITY CONSUMED BY EACH MARKET
*
*           LOWER          LEVEL          UPPER         MARGINAL
*
* AUS          .       2077243.9569        +INF             .
* CAN          .       2238808.8427        +INF      -7.54952E-15
* CHN          .       1.2621972E+7        +INF             .
* DEU          .       3909812.1270        +INF             .
* JPN          .       3898525.8078        +INF             .
* NOR          .        288873.9894        +INF             .
* RUS          .       1.7961966E+7        +INF      -4.44089E-16
* USA          .       3.2668933E+7        +INF      -4.44089E-16
*
* ---- VAR SUPPLY_P  PRICE FOR THE QUANTITY PRODUCED AT EACH SOURCE
*
*           LOWER          LEVEL          UPPER         MARGINAL
*
* AUS          .             2.2603        +INF             .
* CAN          .             1.5069        +INF             .
* CHN          .             4.4222        +INF             .
* DEU          .             4.7556        +INF             .
* JPN          .             4.8843        +INF             .
* NOR          .             3.4986        +INF             .
* RUS          .             1.5102        +INF             .
* USA          .             2.4241        +INF             .
*
* ---- VAR DEMAND_P  PRICE PAYED BY CONSUMERS AT EACH MARKET
*
*           LOWER          LEVEL          UPPER         MARGINAL
*
* AUS          .             2.2603        +INF             .
* CAN          .             1.7236        +INF             .
* CHN          .             4.4222        +INF             .
* DEU          .             4.7556        +INF             .
* JPN          .             4.8843        +INF             .
* NOR          .             3.4986        +INF            EPS
* RUS          .             1.5102        +INF             .
* USA          .             2.4241        +INF             .
*
*                            LOWER          LEVEL          UPPER         MARGINAL
*
* ---- VAR TOT_SHIP            .       1.6748495E+7        +INF             .
* ---- VAR TOT_PROD            .       7.5666136E+7        +INF             .
* ---- VAR TOT_CONS            .       7.5666136E+7        +INF             .
* ---- VAR TOT_DOME            .       5.8917641E+7        +INF             .
* ---- VAR TOT_LNG             .       1.4874865E+7        +INF             .
```

```
* ---- VAR TOT_PIPE            .        1873629.7197        +INF             .
* ---- VAR LNG_MAX             .        1.7655000E+7        +INF             .
* ---- VAR WELFARE           -INF       5.1014013E+8        +INF             .
*
*   TOT_SHIP  TOTAL QUANTITY SHIPPED
*   TOT_PROD  TOTAL QUANTITY PRODUCED
*   TOT_CONS  TOTAL QUANTITY CONSUMED
*   TOT_DOME  TOTAL QUANTITY PRODUCED AND DOMESTICALLY CONSUMED
*   TOT_LNG  TOTAL QUANTITY SHIPPED WITH LNG CARRIERS
*   TOT_PIPE  TOTAL QUANTITY SHIPPED IN PIPELINES
*   LNG_MAX  MAXIMUM LNG TRANSPORT CAPACITY
*   WELFARE  TOTAL CONSUMERS AND PRODUCERS SURPLUS
*
*
* **** REPORT SUMMARY :        0     NONOPT
*                              0 INFEASIBLE
*                              0  UNBOUNDED
*                              0     ERRORS
* GAMS 41.1.0  1682d454 Oct 28, 2022          WEX-WEI x86 64bit/MS Windows - 12/19/22 11:59:50 Page 7
* G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
* E x e c u t i o n
*
*
* ----    192 VARIABLE TOT_LNG.L             =      14874865.30180837  TOTAL QUANTITY SHIPPED WITH LNG CARRIERS
*
* ----    193 VARIABLE TOT_PIPE.L            =       1873629.71970824  TOTAL QUANTITY SHIPPED IN PIPELINES
*
* ----    194 VARIABLE TOT_SHIP.L            =      16748495.02151660  TOTAL QUANTITY SHIPPED
*
* ----    195 VARIABLE LNG_MAX.L             =      17655000.00000000  MAXIMUM LNG TRANSPORT CAPACITY
*
* ----    196 VARIABLE TOT_DOME.L            =      58917641.01351972  TOTAL QUANTITY PRODUCED AND DOMESTICALLY CONSUMED
*
* ----    197 VARIABLE TOT_PROD.L            =      75666136.03503746  TOTAL QUANTITY PRODUCED
*
* ----    198 VARIABLE TOT_CONS.L            =      75666136.03503670  TOTAL QUANTITY CONSUMED
*
* ----    200 VARIABLE SHIPMENTS.L  AMOUNT SHIPPED OVER A TRANSPORT ROUTE
*
*                    AUS                 CAN                 CHN                 DEU                 JPN                 NOR                 RUS                 USA
*
* AUS   2077243.95689297
* CAN                       2238808.84272404                         1872188.50110823    3855828.65616773
* CHN                                           3475123.82454761
* DEU                                                                 163993.90615319
* JPN                                                                                      42697.15158604
* NOR                                                                1873629.71970824                         288873.98937040
* RUS                                           9146848.14453240                                                                 17961966.40487941
* USA                                                                                                                                                32668932.93736607
*
```