# 1 Introduction

## 1.1 Motivation

“Golden Age for Gas”, phrase coined by the International Energy Agency (IEA) in 2011, perfectly describes the last few decades of unprecedented ongoing transformation and growth of the natural gas industry worldwide. During this period, natural gas has significantly increased its share in global energy supply mix. One of the main drivers behind such success of natural gas as an energy source is undoubtedly the expansion of the global LNG market. The share of LNG in international gas trade in 2021 accounted for more than 45% of natural gas trade worldwide, an increase of 10% in ten years, and, according to forecasts, it is expected to reach almost 60% share in 2040.

Probably the most important event that initiated the boom of global LNG trade was putting into operation the largest LNG liquefaction facility in Qatar twenty-five years ago. Qatar set the stage for surge in LNG trade and continues to be one of the most important LNG exporters, but other players and developments are also making a significant contribution to this trend.

The shale gas revolution in the first decade of this millennium enabled the world greatest energy consumer, USA, to change its status from a large natural gas importer to a large natural gas exporter. Shale gas bonanza, once it satisfied the domestic demand, stimulated companies to monetize the surplus abroad. This, together with the expansion of Panama Canal in 2016, which provides for a shorter trade route to the largest LNG importers located in Asia, led and still leads not only to the investment in new liquefaction capacities and LNG carriers, but to the new pricing and contract schemes too. The similar story happened at the other corner of the world, in Australia, where large gas discoveries and investment in export capacities allowed that country to overtake the longstanding LNG export champion Qatar few years ago. Russia, the world largest exporter of piped gas, has recently also significantly increased its LNG export volumes to become a top four LNG exporter thanks to the ability to utilize the Northern Sea Route which connects Atlantic Ocean and Pacific Ocean. Suddenly, thanks to the booming LNG trade, the traditional model of the global natural gas market, represented by its geographical division into Pacific and Atlantic Basin trade regions, became much more interconnected.

The natural gas abundance was and remains a necessary condition for global LNG trade boom, but without huge increase in demand, such development would not be possible. Numerous factors are fueling support in LNG demand: ever-lower entry barriers due to the technological progress leading more countries to import LNG, economic and population growth in emerging economies, concerns about air quality (coal-to-gas switch), increased flexibility and liquidity thanks to the possibility to sign shorter-term contracts and buy and sell LNG cargoes on spot market.

All of the trends mentioned above can indicate the emergence of a new, global, much more competitive gas market, in which market participants can cash in on potential price arbitrage among regions, ultimately leading to a more or less convergent world gas prices.

## 1.2 Research question

The core objective of this thesis is to try to find out if there is a price convergence of the worldwide wholesale price of gas due to increasing global trade in LNG. Furthermore, the linear optimization model developed in the course of this thesis is also used to investigate the potential gas price movements in the future. Different sensitivity analysis are also conducted to examine the conditions under which gas prices converge/diverge. In addition to the core objective, other factors that have or will have direct impact on LNG prices and environment, like the number of LNG carriers or greenhouse gas emissions caused by transportation of LNG, are analyzed too.

## 1.3 Applied methods

The linear optimization model is implemented in Python, using the optimization modeling language Pyomo. For the data manipulation and analysis the Python package pandas is used. The objective function minimizes the overall LNG import costs, while fulfilling the LNG demand of all importers. As a result of the optimization, the optimal distribution of LNG flows from a set of exporters to a set of importers is determined and then used to calculate the prices at each importer.

As input parameters, model uses monthly or yearly LNG import volumes, LNG export capacities and LNG break-even prices. Additionally, geographical, technical and economic data necessary for calculating the LNG transportation costs are used as input too.

Finally, the model is solved with the open-source optimizer GLPK.

## 1.4 Outline of thesis

Following the short introduction to the topic, Chapter 2 provides an overview of the state of the art of different gas pricing and contract schemes, literature review and own contribution. Methodology and the mathematical formulation of the optimization model are presented in Chapter 3. Chapter 4 presents the results of a base model and LNG Outlook. The effects of different input parameter variations, such as higher/lower LNG demand, decrease of LNG supply, higher/lower shipping costs, are shown in Chapter 5. In the final chapter, the results of the work are discussed and the conclusions are made.

# 2 State of the art and progress beyond

At the beginning of this chapter, in section 2.1, an overview of different types of wholesale gas price formation mechanisms is given. The current state-of-the-art of research on price convergence of wholesale gas prices is presented in section 2.2. The own contribution in section 2.3 concludes this chapter.

## 2.1 Main types of wholesale gas price formation mechanisms

Unlike other commodities, transportation of natural gas over long distances is quite difficult, and thus costly, especially when it has to be cooled down to LNG to become suitable for maritime transport. For this reason, historically, both pipeline and LNG import projects could be commercially viable only if natural gas was price competitive at the place of consumption vis-à-vis other energy sources like oil or coal (at certain markets there is such competition even between LNG and pipeline gas). Since oil and coal markets were established long before the beginning of en gros production and consumption of natural gas, natural gas producers were forced to set the price of natural gas energy equivalent on a local/regional market in such a way that it had to be lower than that of competing fuels, a principle known in European gas business by a German word *Anlegbarkeit*. Over the time, natural gas markets evolved differently in different parts of the world and thus the wholesale gas price formation mechanisms as well. Although International Gas Union (IGU) defines eight different types of price formation mechanisms (reference to “Wholesale Gas Price Survey”), only the most important ones will be reviewed.

### 2.1.1 Oil-linked pricing

After the 1973 oil shock, Japan decided to reduce its dependence on oil for power generation by substituting it with LNG. The sellers had to guarantee that LNG price will be at a discount to the current oil prices and will not exceed certain upper bound (price cap). On the other hand, Japanese consumers accepted to bear the volume risk by signing long-term take-or-pay contracts, thus guaranteeing a revenue stream which enabled banks to provide the tens of billions of dollars in financing needed to develop gas fields, pipelines, liquefaction facilities and build LNG carriers to deliver the LNG and also guaranteed minimum LNG price that shielded the seller in case of very low oil prices. These pricing terms were translated into the so called S-curve concept - a price formula that linked oil and gas prices (Figure 1), which is used for more than half of total LNG imports worldwide, mainly in Asia and southern Europe.

The typical formula for determining the price of LNG, used in most of the Asia LNG contracts, can be expressed by:

$$P_{LNG} = \alpha * P_{crude} + \beta$$

, where:

α: crude linkage slope

$P_{crude}$: price of crude oil (for example Japanese customs-cleared (JCC), Brent, …)

β: constant, usually reflects fixed costs like shipping costs

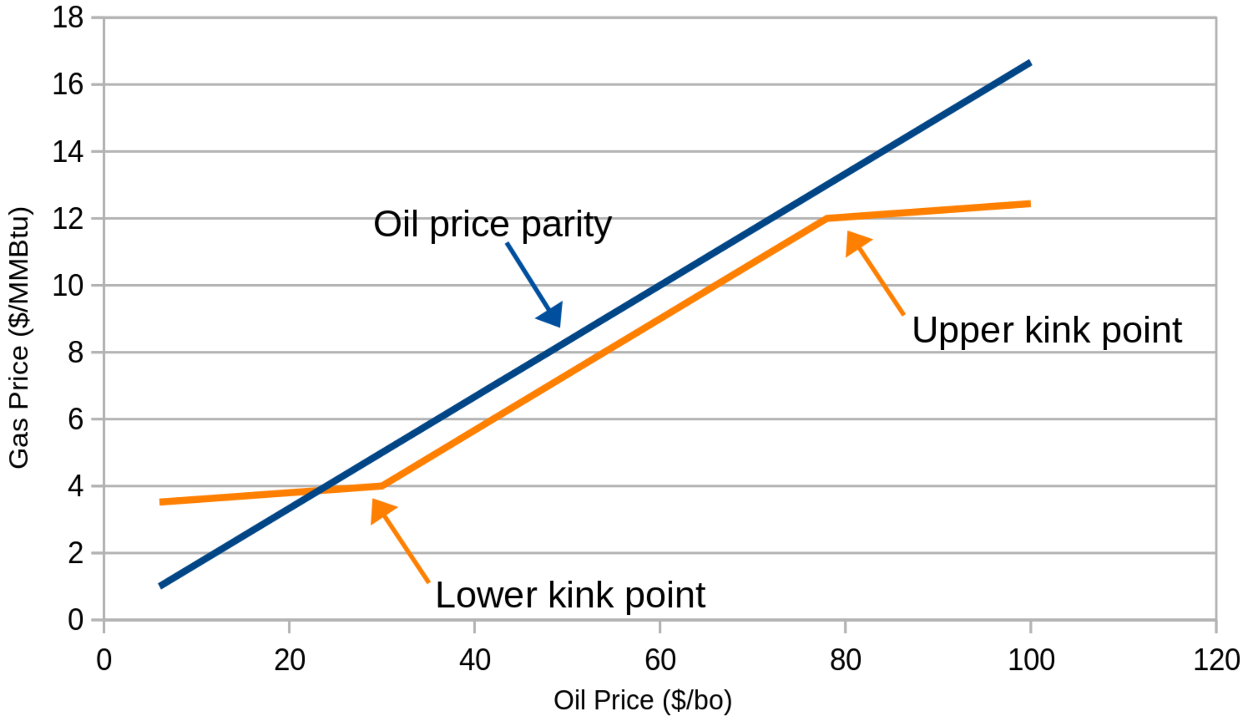


*Figure 1: S-curve linking oil and LNG price*

As can be seen on Figure 1, S-curve is a stepped pricing mechanism, with each step having its own slope determined in process of negotiation. The slope of about 17% indicates that price of LNG is equal to that of oil on an energy equivalent basis. With oil prices below lower kink point or above the upper kink point the slope flattens out (can even be horizontal → cap and floor), thus protecting the seller or buyer from negative impacts of to low or to high oil prices respectively. In periods of oversupplied markets, LNG buyers have better bargaining position and the slope between the kink points tends to be lower than in periods of undersupply. On the other side, sellers demand higher slopes for short-term contracts than for the long-term ones.

### 2.1.2 Gas-on-gas pricing

A growing number of major natural gas markets in the world have adopted (USA, UK and north-western Europe) or have been migrating to the gas-on-gas pricing mechanism. Gas prices at these markets, characterized by extensive pipeline networks, gas storage systems and interconnectors, are set by the interplay of regional gas supply and demand. Trading of both current and future contracts takes place at gas hubs and instead of oil-indexation, gas prices at gas hubs are used as a reference in the gas price formulas. More than two thirds of domestically produced natural gas and pipeline imports (combined about 90% of total world consumption) has gas-on-gas pricing mechanism. In stark contrast, only one third of the world LNG imports has pricing mechanism based on gas hub prices.

US LNG exporters adopted exactly this kind of pricing mechanism in their sale and purchase agreements (SPAs), setting their export price against the U.S. Henry Hub, thus rising the influence of this gas hub price on global gas prices. The typical price would be 115% of Henry Hub price plus a fixed liquefaction fee plus shipping cost, though price formulas using other indices like the Asian JKM or Dutch TTF have also been used recently, reflecting the growing competition among LNG export projects.

### 2.1.3 Regulated markets

The most numerous gas markets in the world are those with regulated gas prices. Those markets are usually relatively immature and controlled by the government through the national oil and gas company. The price at these markets can be set to cover the "cost of service" or can intentionally be fixed below the average cost of production and transportation as a kind of state subvention to the population. In period of extreme energy crisis even the government of a country with well established gas market can intervene and for example cap the price of gas for the production of electricity.

## 2.2 Current research on price convergence of wholesale gas prices

Although oil and natural gas share many characteristics, the differences between them when it comes to selling and pricing are more than obvious. Of course, the most important one is that natural gas prices tend to be different in different parts of the world. The recent fast-paced development of natural gas industry in general and that of LNG in particular led some to boldly proclaim "the establishment of a global market for natural gas" (a 2017 headline from WSJ), but the question of market integration (both intracontinental and intercontinental) and consequently of price convergence got into the spotlight of academic research much earlier.

Early empirical research tried to find out if there is evidence of price convergence and market integration on intracontinental and intra-country level. The results indicated significant increase of price convergence in natural gas spot markets since the deregulation in the mid 1980s in North America (King and Cuc, 1996) and an indication of the cointegration of German natural gas import prices Asche, Osmundsen and Tveterås, 2000). On the other hand, there were no signs of price convergence between different Continental European markets (Neumann et al., 2006). This has changed in the more recent studies motivated by the introduction of European Gas Directives (the last one was introduced in 2009), which have found strong evidence of market integration and convergence of European natural gas prices (Renou-Maissant, 2012; Chiappini et al., Bastianin et al., 2018; 2019; Broadstock et al., 2020) that can be traced back to the establishment and maturity of Gas Hubs and sufficient interconnection among national gas systems.

The growing number of natural gas liquefaction facilities and import terminals around the world motivated the research on intercontinental price convergence. The underlying hypothesis presumed that the price integration should be a natural consequence of an increased LNG trade, since LNG trade could serve as a price-leveling arbitrage instrument (Neumann, 2008). This hypothesis additionally gained in relevance in the recent years, due to the fast increasing export of LNG mainly from Australia and USA. Most of the research results associated with this hypothesis confirm the evidence of the long-term cointegration and price convergence, yet the possible reasons for such outcome vary. One explanation is that rather than supply-demand dynamics, the oil-linked pricing mechanisms stand behind the integration, particularly between European and Asian regions (Eliston, 2009; Li et al., 2014). Another one is that the rising exports of US LNG since 2016 with its more flexible terms and fewer destination clauses as well as shift from long-term to short-term and spot-based transactions has strengthened the degree of co-movement between global benchmark prices for natural gas (Lalenti, 2021).

However, not all recent studies found the evidence of global price convergence. Although the last analysis done by IGU shows that there was a continuous convergence of natural gas prices since 2005, this trend stalled or came to an end in 2015 (Wholesale Gas Price Survey 2021 Edition IGU). Loureiroa et la. (2022) shows that there is no natural gas price convergence, with the exception of Europe and rejects the hypothesis that increased LNG trade acts as a price-leveling arbitrage mechanism.

## 2.3 Own contribution

Unlike the literature presented above, which uses different econometric, statistical and control theory methods applied in time series analysis, this work utilizes linear optimization modeling to detect the possible natural gas price convergence and market integration. Furthermore, it explores the potential gas price(s) movements in the future as well as different scenarios which would lead to the “one price”.

An additional contribution of this thesis is the analysis of the technical and environmental constraints associated with the LNG industry and their impact on natural gas prices.

# 3 Model

The model comprises the ten largest LNG exporters and the twelve largest LNG importers in the world in year 2019. These are represented as geographical nodes. In order to cover smaller LNG exporters and importers as well, five additional export and import nodes respectively are appended. These nodes aggregate export capacities or imported volumes of countries from the same geographical region. Therefore, the total number of export nodes is fifteen and the total number of import nodes is seventeen. In the majority of cases, for the exact geographical position of each node the longitude and latitude of the largest liquefaction facility or of the largest LNG import terminal are taken. Furthermore, each export node is characterized by its installed liquefaction capacity and its LNG break-even price, whereas each import node has its imported volume of LNG as a unique feature (Appendix 1). Finally, between each export and import node there is a shipping route that directly connects them. Since all of these shipping routes have different lengths, the costs that arise from transporting LNG from an exporter to an importer are also unequal.

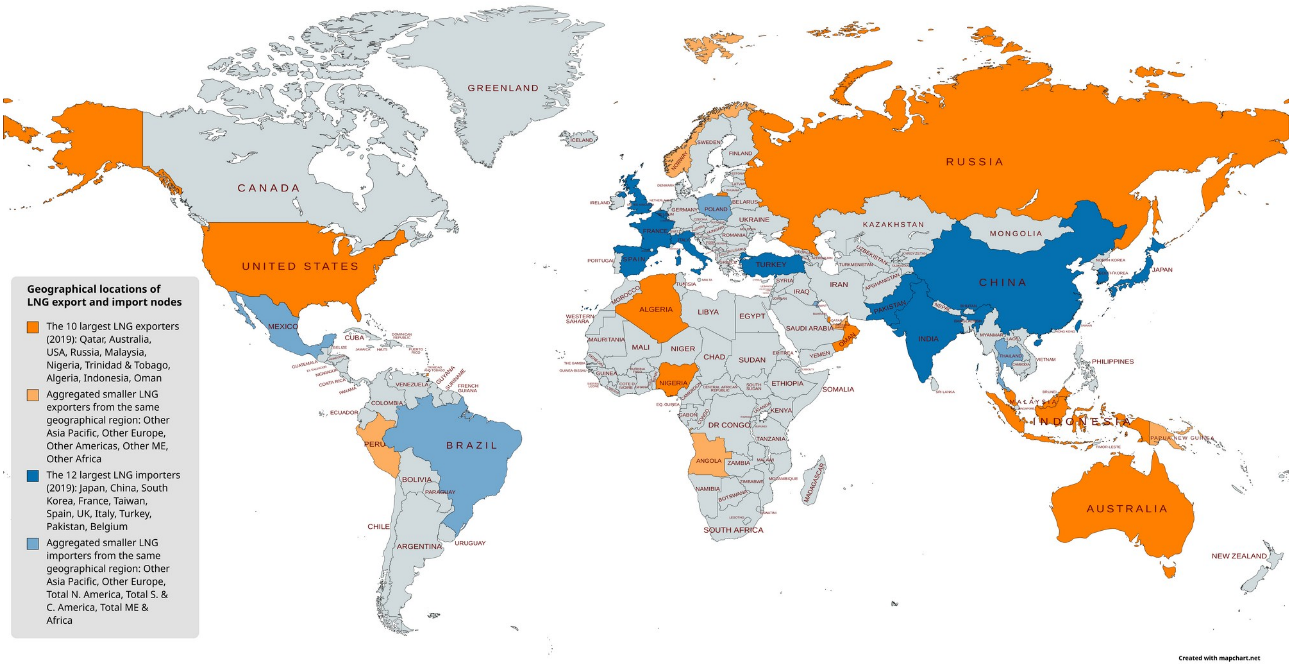


*Figure 2: Geographical locations of LNG export and import nodes*

The following equations ((1) - (5)) represent the mathematical description of the global LNG trade model:

**Objective function**:

- $$minimize: Cost = \sum_{e \in Exporters} \sum_{i \in Importers} DESPrice[e,i] \, v[e,i] \quad (1)$$

**Constraints**:

- $$DESPrice[e,i] = LNGbreakevenprice[e] + Transportcosts[e,i] \quad (2)$$
- $$\sum_{e \in Exporters} v[e,i] \leq ExportCapacity[e], \forall \, e \in Exporters \quad (3)$$
- $$\sum_{i \in Importers} v[e,i] = Import[i], \forall \, i \in Importers \quad (4)$$

- $\sum_{e \in Exporters} v[e,i] \leq \frac{1}{3} Import[i], \forall i \in Importers$ (5)

**Variables**:

v: volume of shipped LNG from exporter to importer

**Parameters**:

DES_Price: Delivery ex ship price – price of delivered mmBtu of LNG at the destination port, the seller carries the obligation and costs of transportation

LNGbreakevenprice: Price of LNG (the cost of feed gas + CAPEX on liquefaction facilities + royalties and taxes)

Transportcosts: All transport related costs (maybe put Transportcosts equation as constraint and add more parameters? )

Export_Capacity: Total liquefaction capacity for export

Import: Total LNG imports

e: Export node

i: Import node

**Sets**:

Exporters: Set of all export nodes

Importers: Set of all import nodes

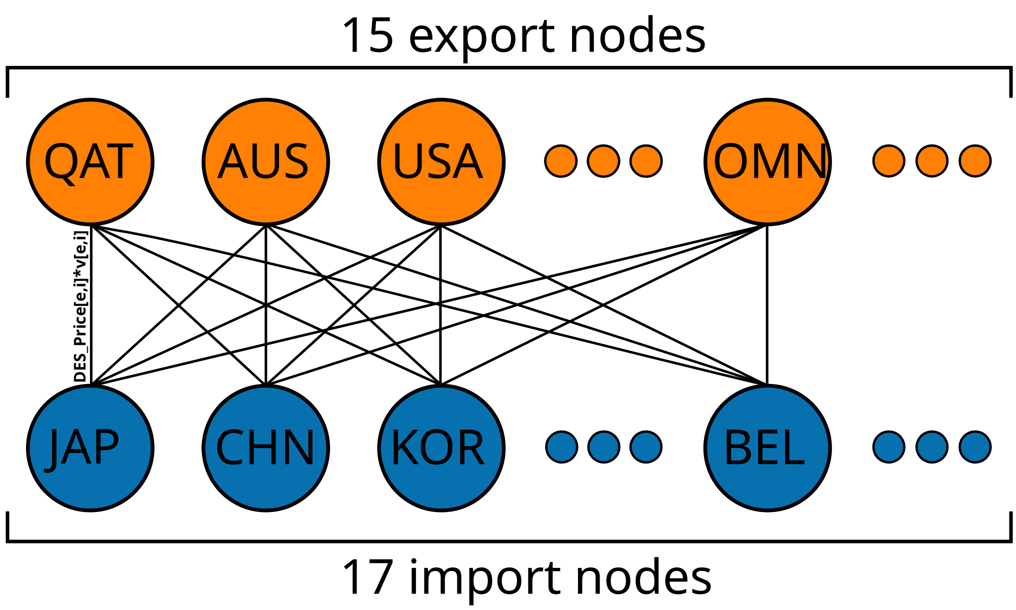


*Figure 3: Links connecting export and import nodes*

The aim of the model is to calculate the optimal distribution of a commodity (LNG) from a set of exporters to a set of importers in such a way that the overall costs are minimal (1) while satisfying different constraints at the same time. The LNG spot market is modeled by links connecting a set of nodes representing exporters to a set of nodes representing importers (Figure 2). For each link there is a parameter *DES_Price[e,i]* denoting the delivery ex ship price per MMBtu of the transported LNG over the link connecting exporter *e* and importer *i*. This parameter is calculated as a sum of LNG break-even price in particular export node *e* and transport costs specific for each export-import link [*e*,*i*] (2). A non-negative decision variable *v[e,i]* represents the volume of shipped LNG over the link. All shipments from an exporting node can not exceed the liquefaction capacity of that exporting node (3). Demand at each import node must be satisfied (4). Since importers try to diversify their LNG supplier portfolios in order to increase the energy security, each importing node receives LNG from at least 3 different exporters (5). The model is implemented in the Python-based optimization modeling language Pyomo and solved with the open-source optimizer glpk. The modeling results (the optimal distribution of LNG flows) are then used to determine the prices at import nodes. Since LNG imports data used for modeling have a monthly time resolution, the prices are calculated as volume weighted average DES prices. Taking into account the merit order effect and the fact that the price of LNG is generally higher than that of the pipeline gas at the importing markets (regasification costs and system entry costs are neglected due to the lack of data and for simplicity's sake), it can be considered that LNG is a price setter at import nodes. In this way, regardless of LNG share in gas mix (compared to the domestic production and pipeline gas imports) and under assumption of perfectly competitive spot markets, the comparison of wholesale gas prices at different nodes is possible.

# 4 Results

Results of the modeling which will give the answer on the main question of this thesis, namely whether there is a price convergence of wholesale gas prices on world market(s) or not, are presented in this chapter. In addition to the calculated weighted average DES prices at importing nodes in 2019, other factors useful for understanding the fundamentals of LNG markets (reduced costs and shadow prices, number of necessary LNG carriers) and their environmental impact (transportation emissions) are given. Furthermore, the modeling results for LNG outlook untill 2040 are presented.

## 4.1 Global LNG market in 2019

### 4.1.1 LNG flows among importers and exporters and weighted average DES prices

Considering the two most important parameters impacting the competitiveness of an LNG project/exporter, namely the break-even price of LNG (feedgas + liquefaction cost) and the proximity to the buyer, as well as the objective function of the model (minimal summarized import costs), the determined LNG flows (Figure 4) confirm the clear perspective of the geographical division of the world LNG market into three main regions (valid both for importers and exporters): the Atlantic Basin, Pacific Basin and Middle East. Furthermore, the “natural” destination markets for certain LNG exporters become obvious too.

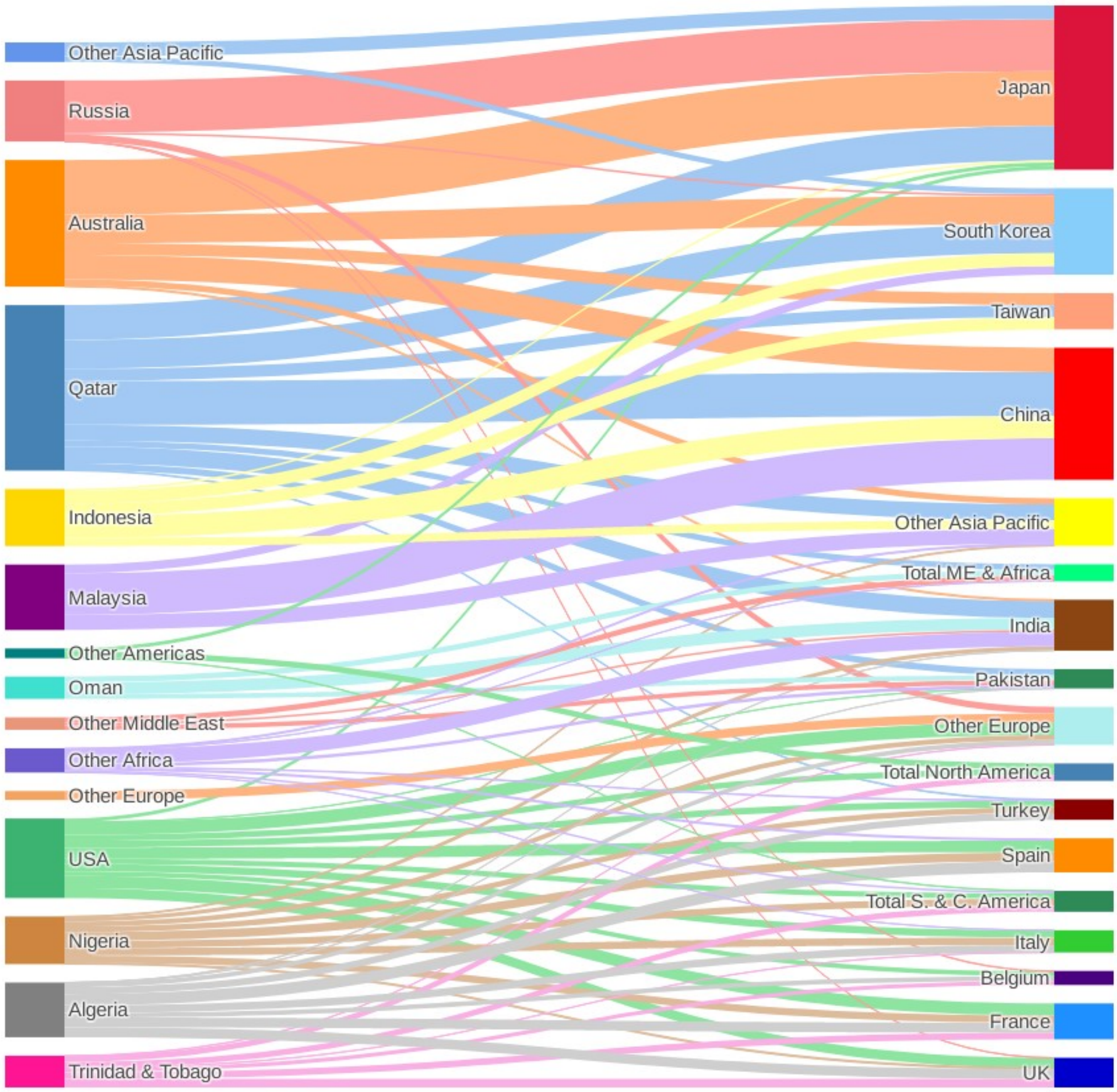


*Figure 4: LNG flows (2019)*

The results show that the biggest world LNG importers like Japan, China, South Korea, which are located in Northeast Asia, are to a large extent supplied by exporters from the Pacific Basin (Australia, Indonesia and Malaysia). On the other hand, demand in European countries, which are the largest LNG importers in the Atlantic Basin and in which LNG competes with pipeline gas on the spot market, is predominantly satisfied by LNG shipments from Atlantic Basin, mainly by USA, Algeria and Nigeria. Despite the fact that energy abundant countries from Middle East (Qatar was the largest LNG exporter in 2019) have the lowest break-even prices and such geographical position that enables them great flexibility regarding the potential export destination markets, almost all of their export volumes end up satisfying the ever-growing energy demand in Asian countries.

Since presenting the monthly DES prices for all 17 importing nodes on one figure would be too confusing, in order to show the more or less obvious LNG market(s) trends only the prices for purposely chosen importers are shown (Figure 5). It is evident that there is a certain spread between prices in Asian and European countries. This discrepancy is especially obvious during the summer months in which the price difference can reach even more than 2 \$/mmBtu (price in Asia Pacific more then 25% higher), since the magnitude of price fluctuations during these months is larger in European import nodes than in Asian ones. On the other hand, the alternating price ups and downs are more frequent at Asian importers. As a consequence of the heating season in the northern hemisphere and additionally the lack of storage capacity in Asian countries (particularly in China[1]), the demand in winter months is significantly higher. This is reflected in higher prices, but also in higher number of LNG carriers necessary for the transport (Figure 6) and higher overall costs for imported LNG (Figure 7).

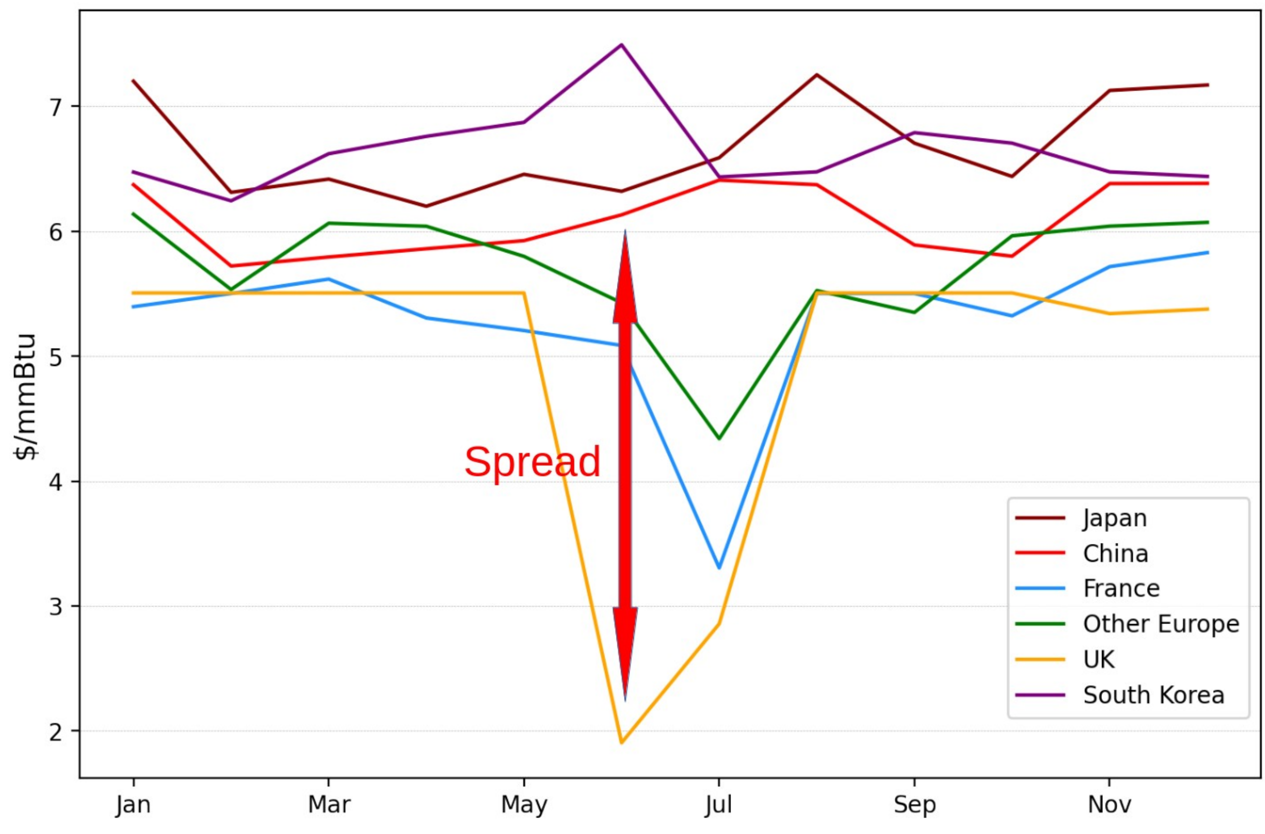


*Figure 5: Monthly weighted average DES-Prices*

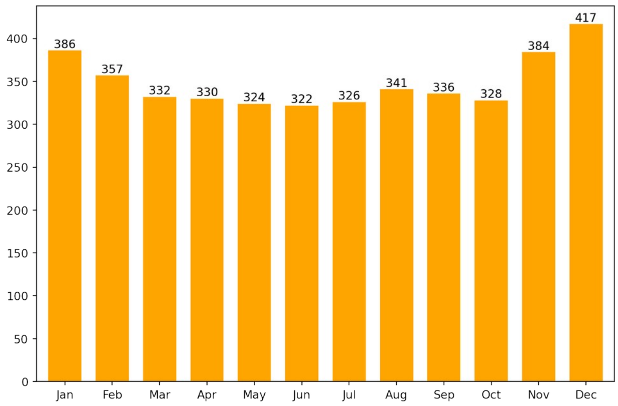


*Figure 6: Number of LNG carriers (2019)*

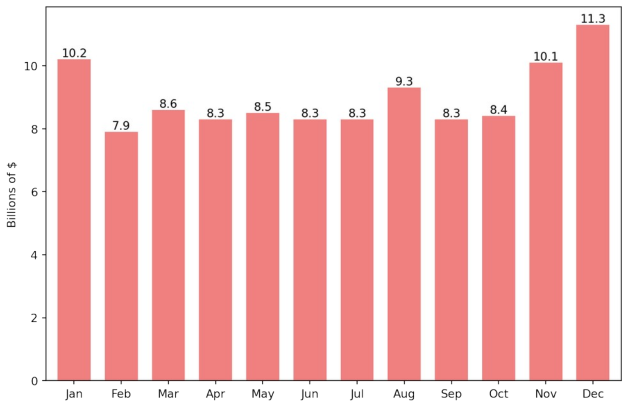


*Figure 7: Monthly costs of imported LNG (2019)*

### 4.1.2 Country specific dual variables

#### 4.1.2.1 Dual variables (shadow prices) of export nodes (liquefaction capacity constraint)

Dual variables of export nodes are shown on Figure 8. These marginal values are telling us how much the total costs (summarized for all importing nodes) will be decreased for each MMBtu increase in the available supply from each exporter, or, in other words, how the increase in export capacity from exporter *e* and therefore the change in liquefaction capacity constraint (equation 3) influences the overall cost.

What catches one's eye right away is that all export nodes, depending on the value of this indicator, can be divided into three groups (in ascending order):

- 1. Group: Nodes with no or minimal overall cost decreasing potential: Australia, Other Asia Pacific, USA and Other Americas
- 2. Group: Nodes with medium overall cost decreasing potential: Trinidad & Tobago, Indonesia, Malaysia, Other Africa, Other Europe, Nigeria and Russia
- 3. Group: Nodes with high overall cost decreasing potential: Oman, Qatar, Algeria, Other Middle East

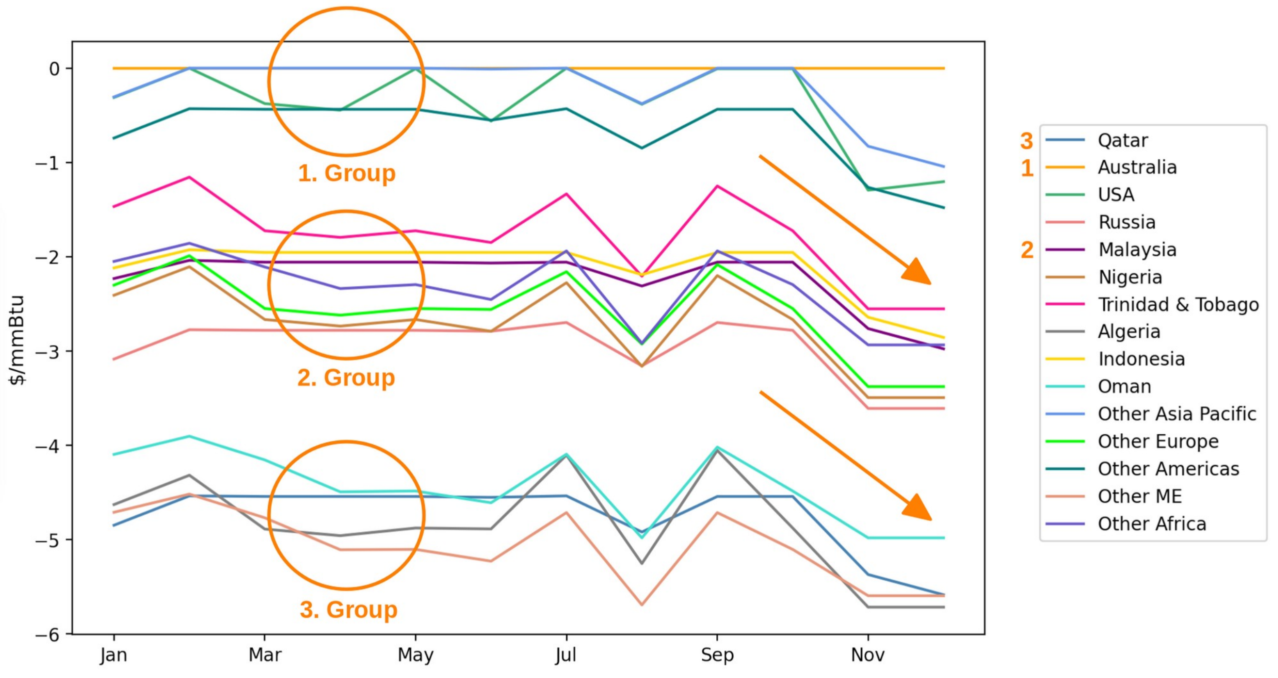


*Figure 8: Dual variables of export nodes (2019)*

Australia's zero dual variable during the whole year and those of Other Asia Pacific and USA in several months are an indicator that the LNG facilities in these export nodes from the 1. Group are not operating at full capacity, since DES prices of those nodes are the least competitive. This rules out any further/significant overall cost reductions by increasing the available supply in export nodes from the this group.

Facilities in export nodes from the 2. and 3. Group are operating at nameplate capacity all the time, since their dual variables are non zero in each month. Marginal values of these nodes suggest that the total costs would be reduced by a certain value for each additional mmBtu of supply. Exporters from these two groups are more resilient to dipping prices, especially those from the 3. Group.

Higher dual variables of the nodes in these two groups can also be interpreted in a way that, in case that the total demand remains unchanged, any increase in export capacity volume in one of these nodes would squeeze out the same export capacity volume from a node with a zero dual variable from the spot market. This means that the additional export capacity at any node from the 2. Group (e.g. Malaysia) or from the 3. Group (e.g. Qatar) would remove the equal export capacity from Australia (1. Group) from the spot market. Bearing this in mind, signing long-term contracts serves as a shield for exporters from such market development(s) too and could be the cause for the possible further stagnation of spot and short-term market share in total trade LNG trade.

Another insight possible to get from the figure with dual variables of export nodes (Figure 8) is the typical seasonality of the gas market. Indicated by the orange arrows, increased shadow prices in winter months in all nodes, with the exception of Australia, are pointing out to the significantly increased demand in import nodes in this period.

### 4.2.2 Dual variables (shadow prices) of import nodes (import volumes constraint)

Looking at the monthly importer dual variables (Figure 9), the same seasonal trends already observed at previous charts are easily spotted again: the blue arrows mark the steepest ascent of importers shadow prices which occurs in winter.

This diagram offers also a more refined picture for understanding the demand fluctuations in certain import nodes during the year and their influence on overall import costs, since importers dual variables indicate how much the total costs of all import nodes will increase if there is an additional mmBtu of demand at any of them. It is important to emphasize at this place that increasing demand in one import node results in diverting of shipments to other import nodes as well. This means that the net effect of this set off “chain reaction” can only be measured through a proper investigation of shipments in all import nodes.

Unlike three groups of exporters with similar range of dual variables, there is a clear geographical division of importers in two world regions according to the value of their respective importers dual variables (to avoid unnecessary noise in the graph, dual variables of few importing nodes were omitted):

- 1. Region (Asia-Pacific Basin): Higher shadow prices: Japan, China, South Korea, Taiwan, Other Asia Pacific
- 2. Region (Atlantic Basin): Lower shadow prices: France, Spain, Other Europe, UK, Italy, Turkey, Belgium, Total S.& C. America

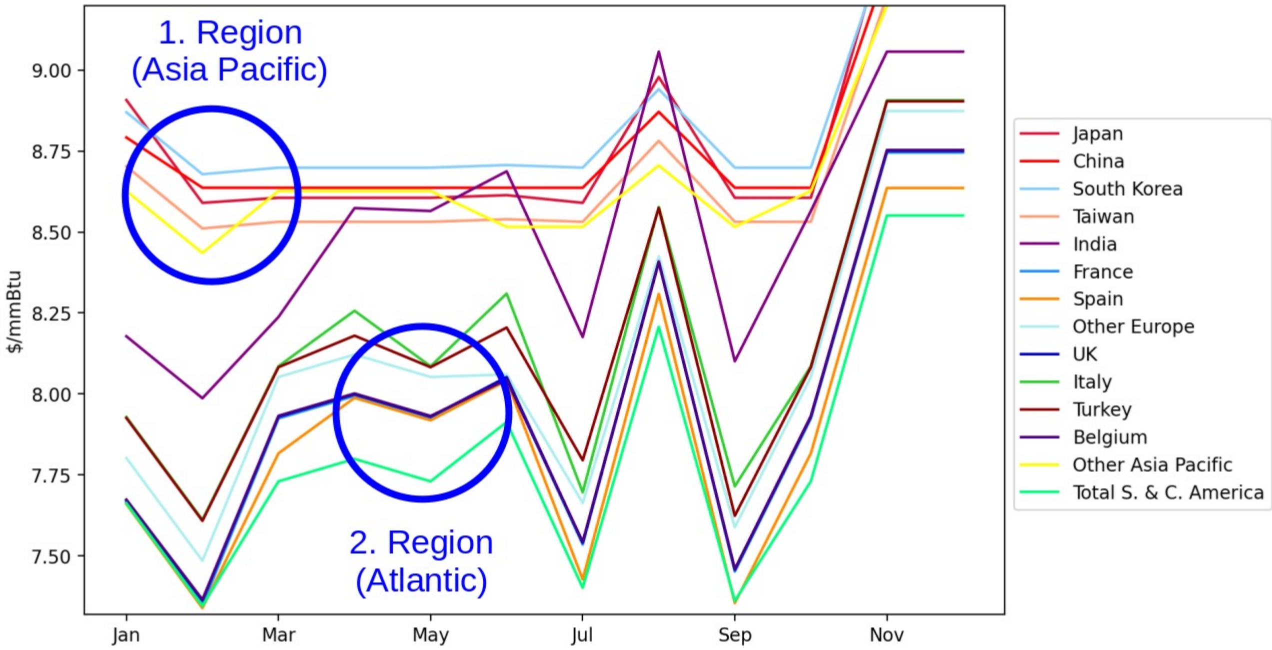


*Figure 9: Dual variables of import nodes (2019)*

All nodes from the 1. Region are situated in Asia-Pacific Basin, all nodes from the 2. Region in Atlantic Basin. This is the consequence of closeness of importers from each of these two geographical regions to the exporters with the least/most competitive LNG prices or lowest/highest exporters dual variables: proximity of importers from the 1. Region (Asia-Pacific Basin) to the exporters from the 1. Group and lower half of the 2. Group; proximity of importers from the 2. Region (Atlantic Basin) to the exporters of the higher half of the 2. Group and the 3. Group.

### 4.1.3 LNG transportation carbon emissions

In the light of the recent COP26 goal of securing global net zero by mid-century[(2)], endorsing of gas and nuclear as “green” transition energies by European Commission[(3)] and publication of an EU Methane Strategy and Regulation[(4)], the carbon-dioxide and methane emissions caused only by combustion of boil-off gas and bunker fuel in LNG carriers are shown in Table 1 and Table 2, respectively.

The sum of monthly $CO_2$ emissions caused by seaborne LNG deliveries amounts to 60.73 megatonnes in 2019 or 0.185% of global $CO_2$ emissions in that year[(5)]. To put it in another context, the price for offsetting average monthly $CO_2$ emissions caused by transportation of LNG would be ~€150 millions calculated with the average price of carbon emission futures of 25€/t in 2019[(6)]. This directly translates into an average additional cost of $0.09 for every mmBtu delivered, or about 1,5% of average DES price.

The calculations for offsetting the $CH_4$ emissions can not be conducted, since EU will not conclude the first phase of gathering sufficient data on emissions necessary to develop its methane standard and pricing mechanism until the end of 2025[(7)].

*Table 1: Country Specific CO2 Emissions*

| | Total CO2 Emissions (megatonnes) | Average CO2 Emissions (t/mmBtu) | Emissions Offsetting Price (€/mmBtu) |
|---|---|---|---|
| Japan | 16.36 | 0.00431 | |
| China | 9.68 | 0.00317 | |
| South Korea | 7.75 | 0.00387 | |
| India | 3.3 | 0.00278 | |
| Taiwan | 2.53 | 0.00308 | |
| Pakistan | 0.69 | 0.00164 | |
| France | 2.68 | 0.00325 | 0.081 |
| Spain | 2.21 | 0.00280 | 0.070 |
| UK | 2.1 | 0.00325 | 0.081 |
| Italy | 1.92 | 0.00396 | 0.099 |
| Turkey | 1.75 | 0.00377 | 0.094 |
| Belgium | 0.98 | 0.00377 | 0.094 |
| Other Asia Pacific | 2.88 | 0.00387 | |
| Other Europe | 2.69 | 0.00320 | 0.080 |
| Total North America | 1.4 | 0.00451 | |
| Total S. & C. America | 1.61 | 0.00342 | |
| Total ME & Africa | 0.19 | 0.00056 | |

| | Total CH4 Emissions (tonnes) | Average CH4 Emissions (t/mmBtu) |
|---|---|---|
| Japan | 10412.68 | 0.000002742 |
| China | 6124.15 | 0.000002006 |
| South Korea | 4925.26 | 0.000002461 |
| India | 2079.4 | 0.000001756 |
| Taiwan | 1595.68 | 0.000001944 |
| Pakistan | 428.88 | 0.000001010 |
| France | 1693.35 | 0.000002054 |
| Spain | 1391.78 | 0.000001765 |
| UK | 1329.6 | 0.000002052 |
| Italy | 1221.33 | 0.000002513 |
| Turkey | 1112.47 | 0.000002396 |
| Belgium | 617.36 | 0.000002382 |
| Other Asia Pacific | 1813.46 | 0.000002434 |
| Other Europe | 1701.95 | 0.000002020 |
| Total North America | 885.9 | 0.000002861 |
| Total S. & C. America | 1022.15 | 0.000002167 |
| Total ME & Africa | 106.4 | 0.000000311 |

## 4.2 Development of global LNG markets until 2040

The steady growth of global LNG trade continues. Even the unprecedented volatility caused by imposed lockdowns around the world since the outbreak of the COVID-19 pandemic could not reverse this trend. One of the reasons for the resilience and flexibility of global LNG market is the ever growing number of countries joining the LNG importing club. These are not only located in traditional importing regions of the world but also in developing African coastal states and South and Central America. The Floating Storage and Regasification Units (FSRU) with their lower CAPEX (50-60% of an onshore terminal), relocation option which is absent in land-based facilities, “LNG to Power” possibility (FSRU and a power plant are integrated into one vessel) and probably the most important, the much shorter time to come online, provide especially in emerging economies quicker route to gas market(8)(9).

### 4.2.1 Weighted average DES prices

The DES prices development till 2040 is shown on Figure 10. The significantly higher importing prices as well as price differences among the importing nodes in 2030 and 2040 are not only caused by significantly increased share of suppliers with higher break-even prices (USA, Other Americas, ...), but also their geographical position and consequently higher transportation costs to Asian importers, which will account for about three quarters of LNG demand increase in this period(10). Direct repercussions of those assumptions are reflected in more than doubled number of LNG carriers (Figure 11) and overall import costs (Figure 12), although the cumulative inflation rate of 2% per year taken into account also contributed to a large extent to such prices and total costs development.

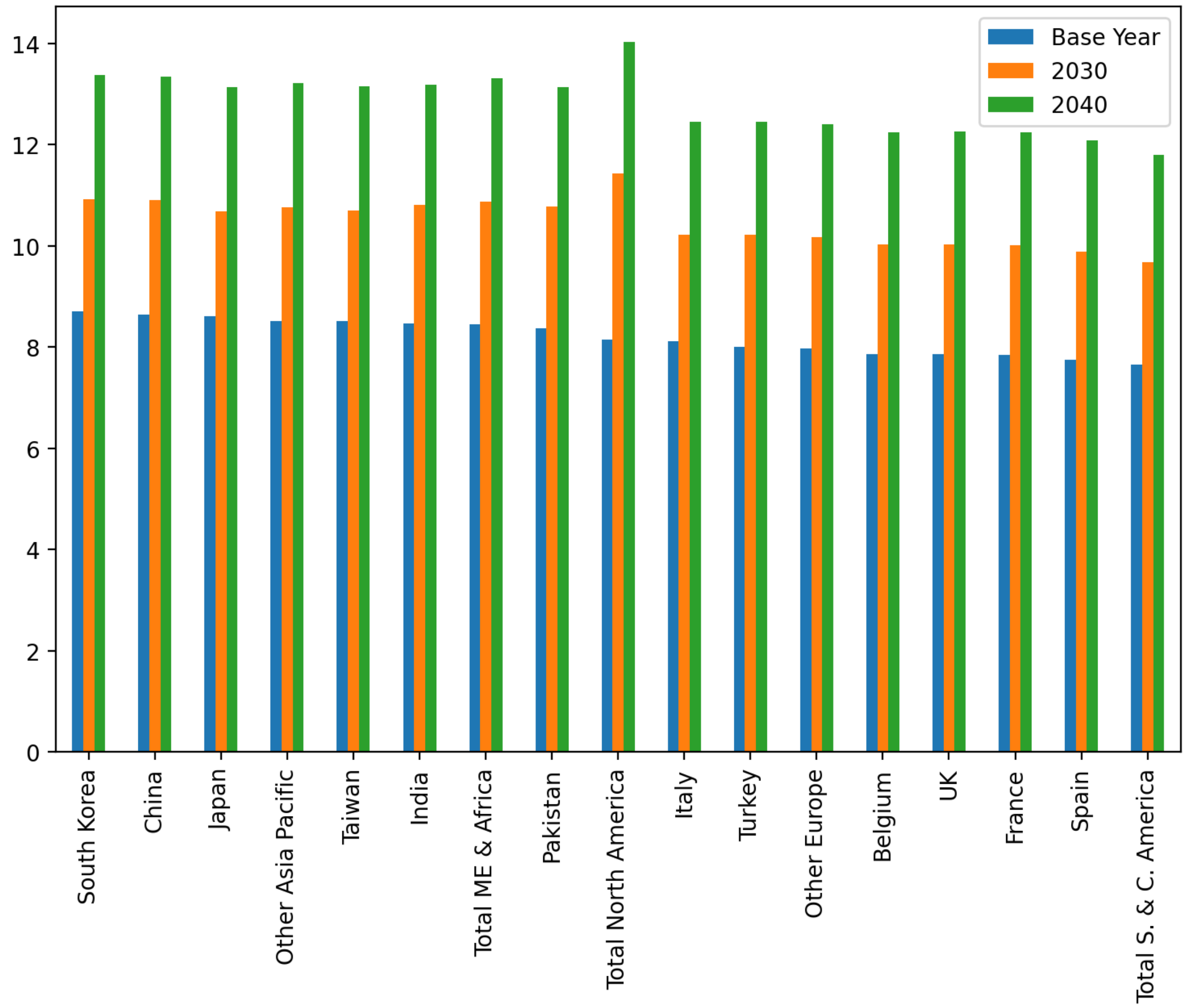


*Figure 10: DES prices untill 2040*

Prices in the base year are sorted in descending order. This enables us to see more easily that the same geographical price pattern will remain valid and even become more apparent in the future. The importers from Asia and Americas will still have to pay more than their counterparts from Europe. The influence of changing LNG exporters landscape is particularly evident in cases of India and Pakistan: the prices in these two countries in base year are very low as a result of their proximity to Middle Eastern exporters, but predicted surge in their imports will have to be satisfied by shipments of more expensive LNG from much more distant exporters.

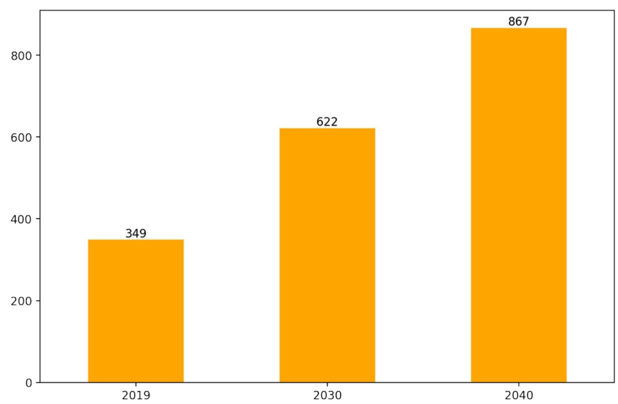


*Figure 11: Number of LNG carriers until 2040*

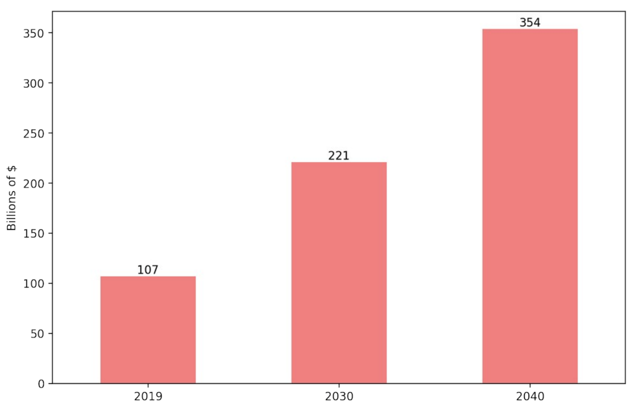


*Figure 12: Total import costs until 2040*

### 4.2.2 Dual variables

Development of importers dual variables shown on Figure 13 does not reveal any future change in geographical division of already in baseline defined two importing regions: Asian countries plus Total North America with their higher marginal values, which correlate to their proximity to the exporters with higher break-even prices and much higher dependence on the largest LNG exporter (USA) and hence higher transport costs in the years to come.

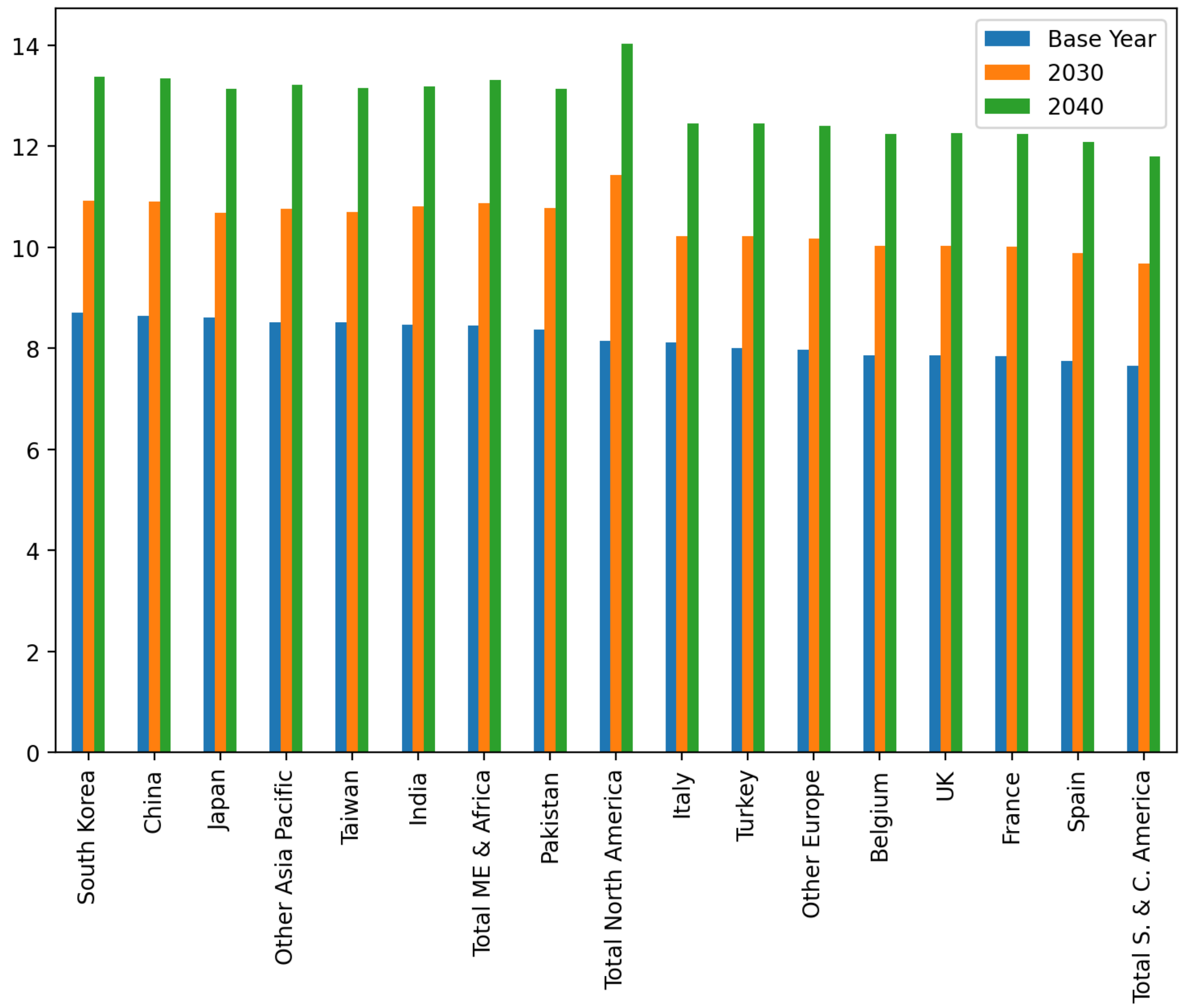


*Figure 13: Importers dual variables until 2040*

Looking at the exporters dual variables until 2040 (Figure 14) the same division of exporting nodes in aforementioned three groups is evident. The only important difference, indicated by zero shadow prices in 2030 and 2040, is that USA as exporter with the largest LNG liquefaction capacity replaces Australia as a marginal supplier. Shadow prices of exporters from the 2. and 3. Group are even higher then in base year, whereas those of the 1. Group remain very low.

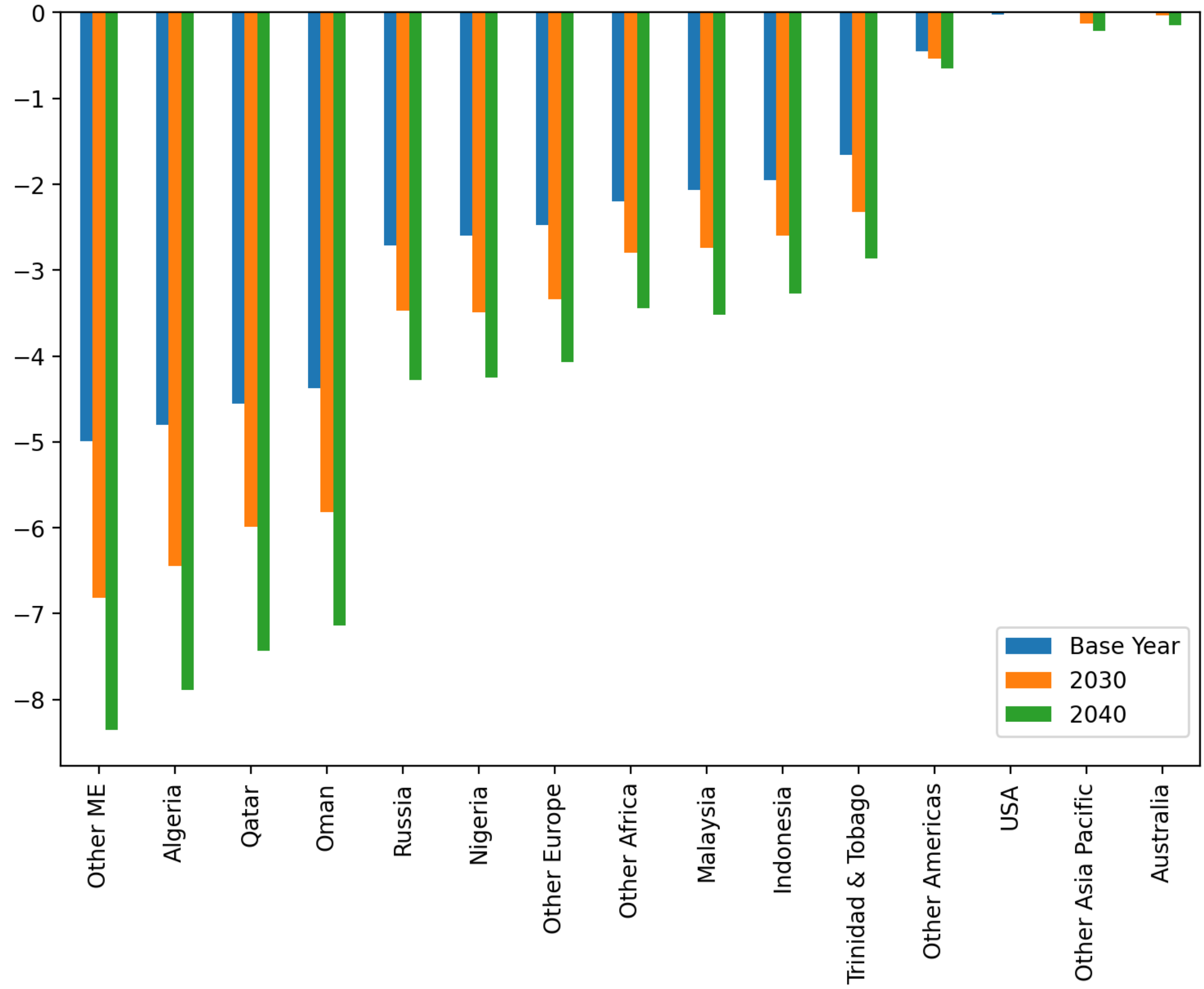


*Figure 14: Exporters dual variables until 2040*

### 4.2.3 Development of LNG transportation emissions until 2040

Direct effects of anticipated doubling of LNG demand and additionally by now several times mentioned increase in average transport distances are perhaps the most obvious and worrisome in clear nonlinear increase of $CO_2$ and $CH_4$ emissions displayed on Figures 15 and 16, respectively. Calculating with the average price of 85€/t for carbon emissions futures and exchange rate of $1.1 for €1 in the first quarter of 2022[(11)], the costs for offsetting only $CO_2$ emissions in 2040 would reach staggering $14.7 billions or about 0.4$/mmBtu or 4% of average DES price ($CO_2$ certificates price was not adjusted for inflation of 2% per year).

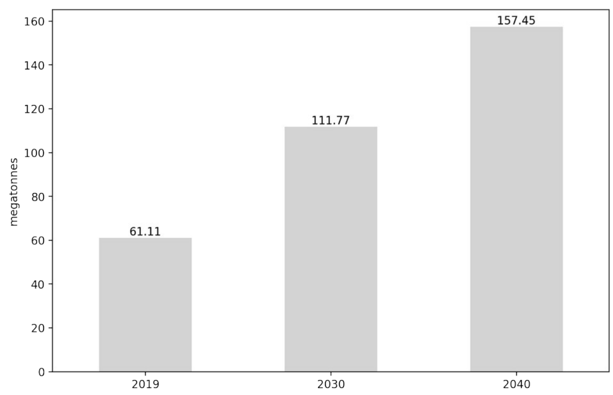


*Figure 15: $CO_2$ emissions until 2040*

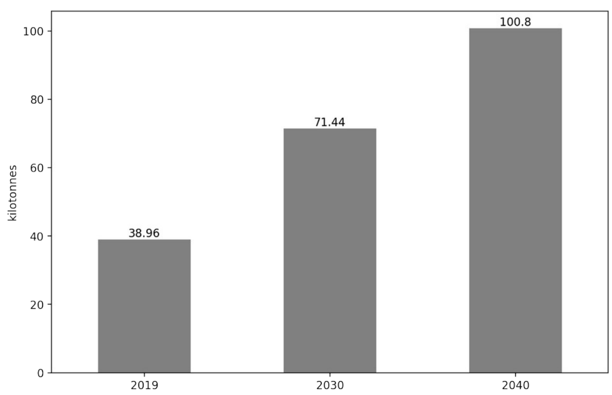


*Figure 16: $CH_4$ emissions until 2040*

# 5 Sensitivity analysis

## 5.1 Increasing diversification of LNG suppliers number per country-specific LNG demand

Energy security is becoming increasingly important nowadays. One of the possible measures that one country can take to enhance it, is the diversification of its LNG suppliers. Therefore, this sensitivity analysis simultaneously increases the minimal number of different LNG suppliers (export nodes) for each import node from three up to five.

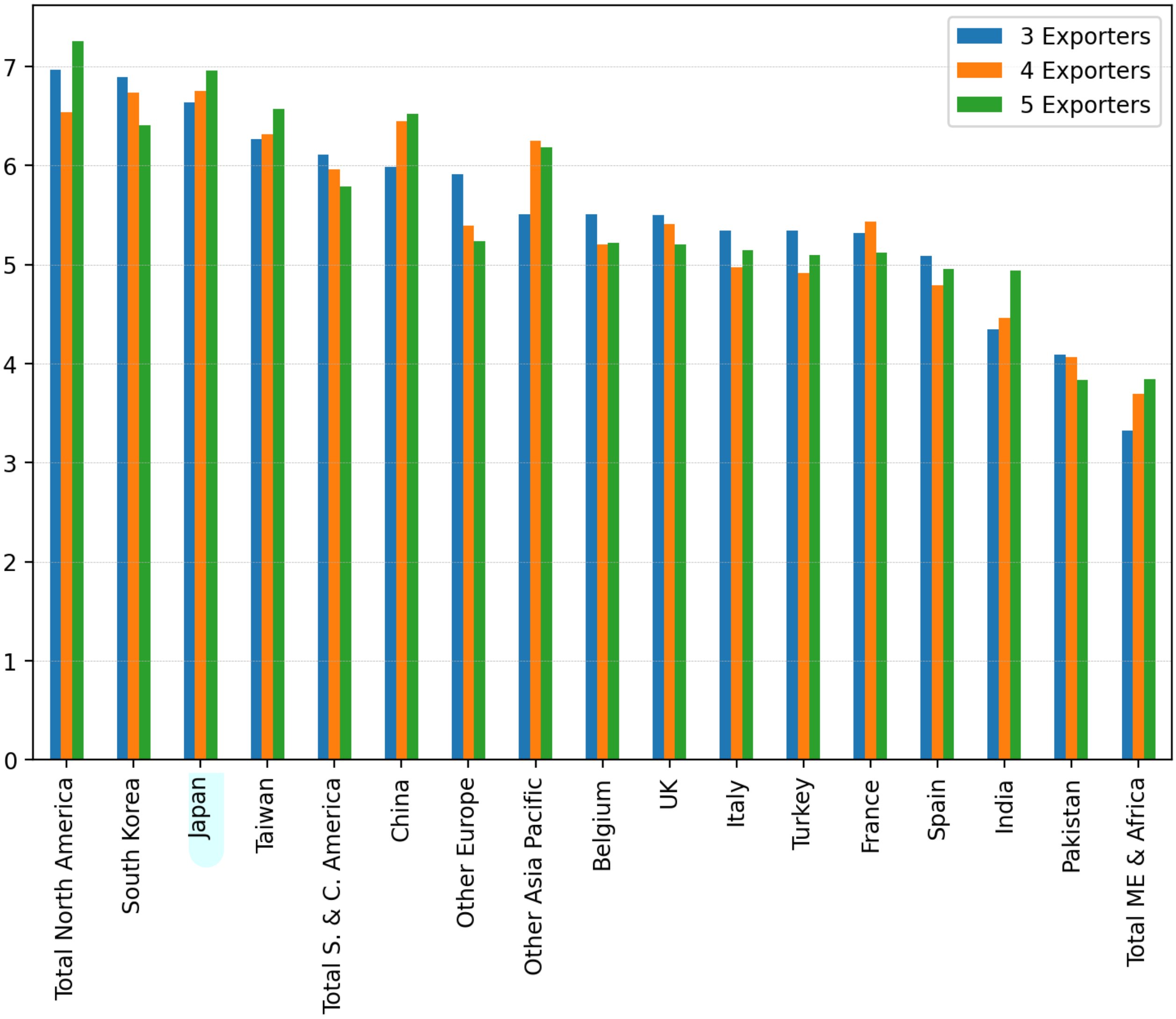


*Figure 17: DES prices depending on minimal number of different LNG suppliers*

The counterintuitive decrease of DES prices at European nodes and increase at Asian ones, with the exception of South Korea and Pakistan, is explicable by looking once again on LNG flows in base model shown on Figure 4: since the objective function of the model is to determine the lowest overall import costs, almost 100% of LNG flows from most competitive Middle Eastern exporters are headed towards biggest world importers which are located in Asia. The increased minimal number of suppliers causes that parts of these flows are diverted to European importers because of their proximity, hence lower DES prices in these nodes and higher in Asian ones. Larger absolute increase of importers dual variables in Asian nodes than in European ones (Figure 18) as well as Qatar's lower dual variables than in base model (Figure 19) reaffirm this interpretation.

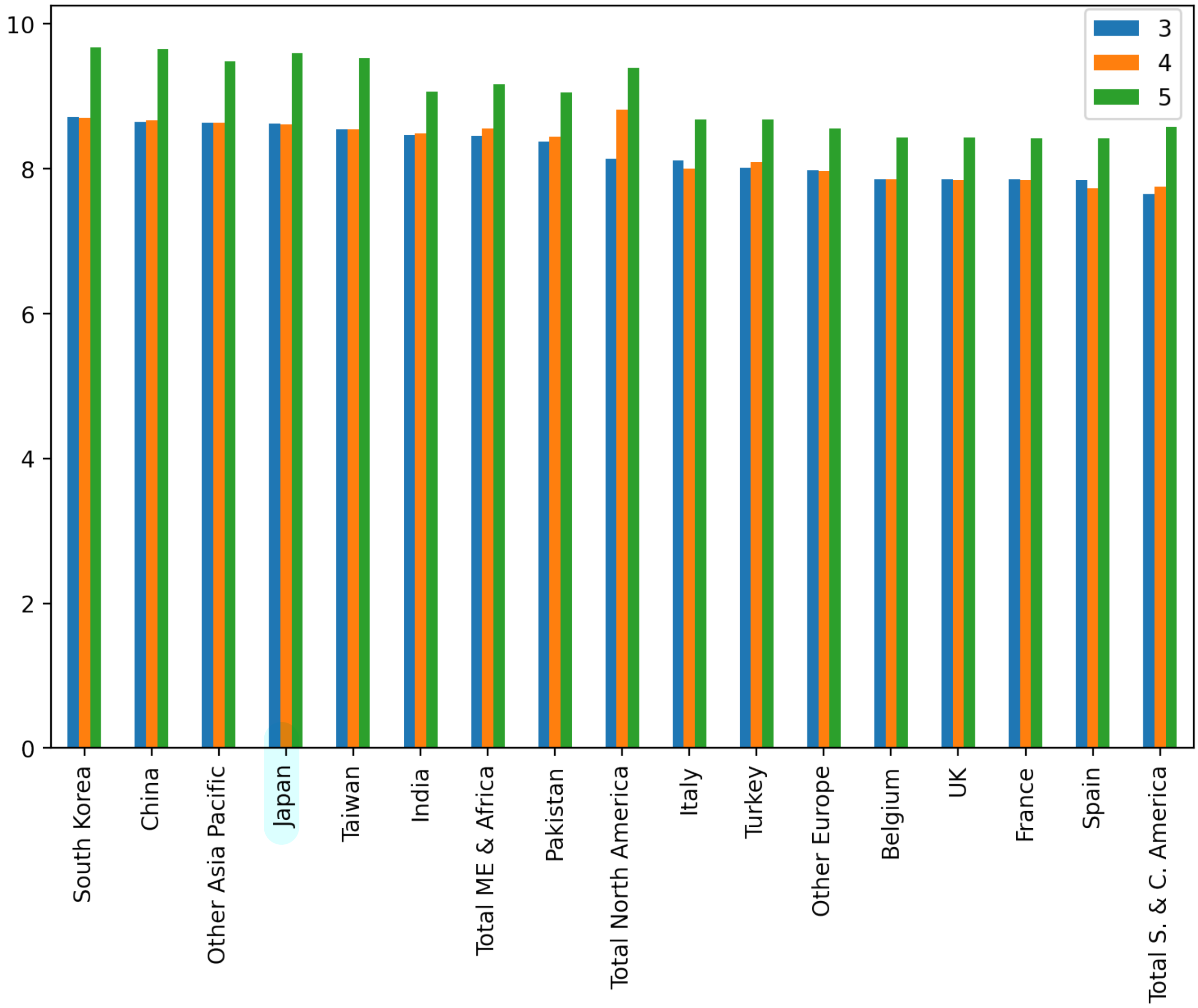


*Figure 18: Importers dual variables depending on minimal number of different LNG suppliers*

Another piece of information that can be derived from Figure 19 is that the biggest relative increase in dual variables have exporters from the 3. Group, followed by those from the 2. Group, indicating their enhanced competitiveness in a more diversified market.

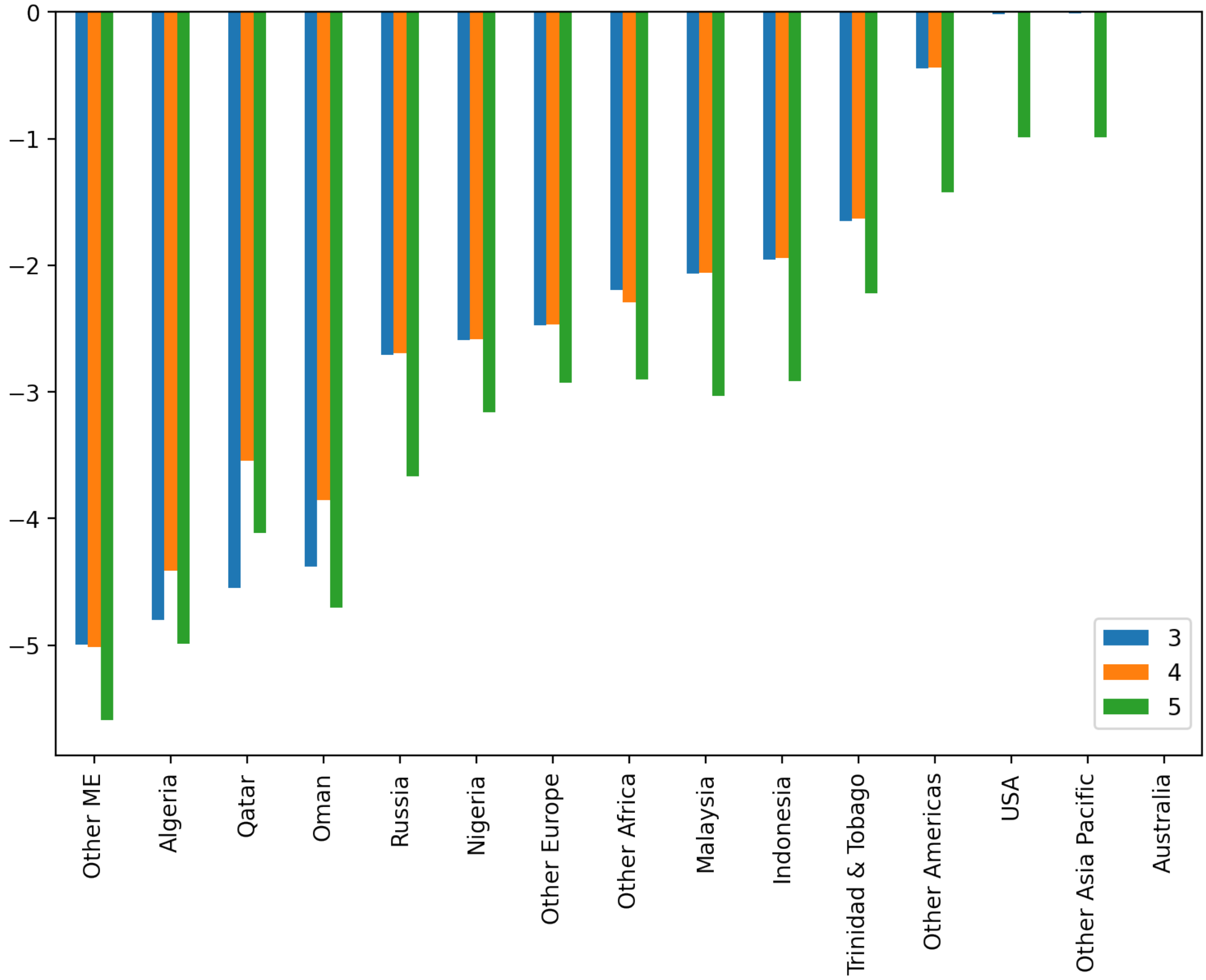


*Figure 19: Exporters dual variables depending on minimal number of different LNG suppliers*

Diversification of importing routes is inseparably linked with increased transportation challenges and consequently higher costs: both the minimal number of LNG tankers and the total import costs increase (Figures 20 and 21). In addition, the GHG emissions (Figures 22 and 23) also rise and the costs for their offsetting would add additional burden to the DES prices.

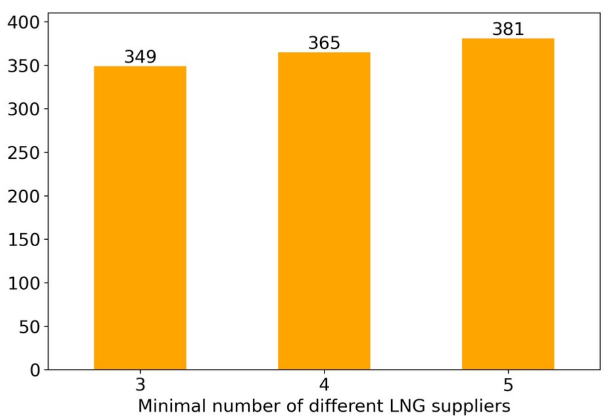


*Figure 20: Number of LNG carriers depending on minimal number of different LNG suppliers*

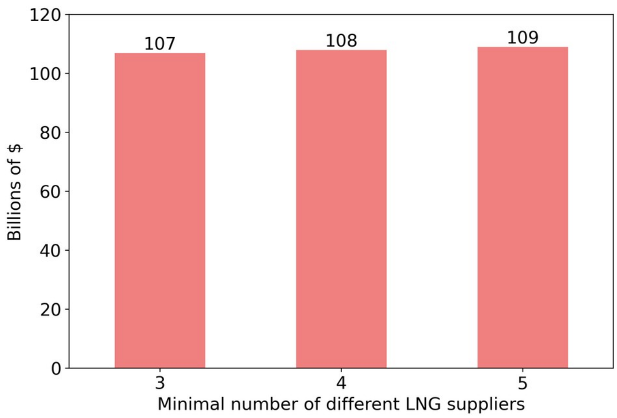


*Figure 21: Total import costs depending on minimal number of different LNG suppliers*

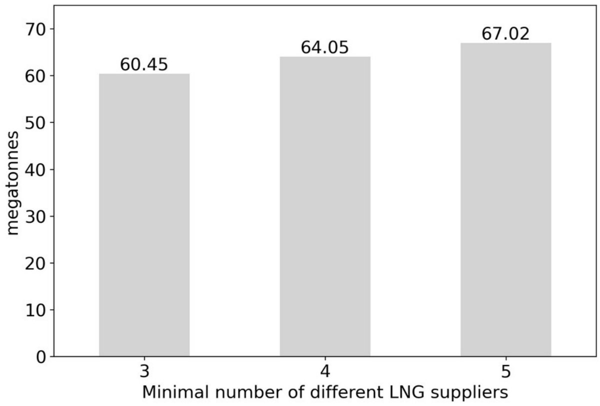


*Figure 22: $CO_2$ emissions depending on minimal number of different LNG suppliers*

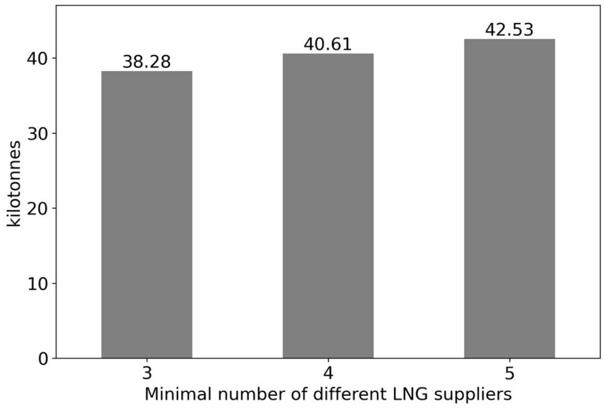


*Figure 23: $CH_4$ emissions depending on minimal number of different LNG suppliers*

## 5.2 Reduced LNG transport capacity at Strait of Hormuz

This scenario is modeled to investigate the impacts of reduction to two thirds (-33,3%) of maritime traffic capacity at Strait of Hormuz (one of the world's most strategically important choke points) and accordingly the reduction of LNG shipments from Middle Eastern exporters. The larger capacity reduction can not be taken into account, since the demand in some import nodes would remain unsatisfied in that case.

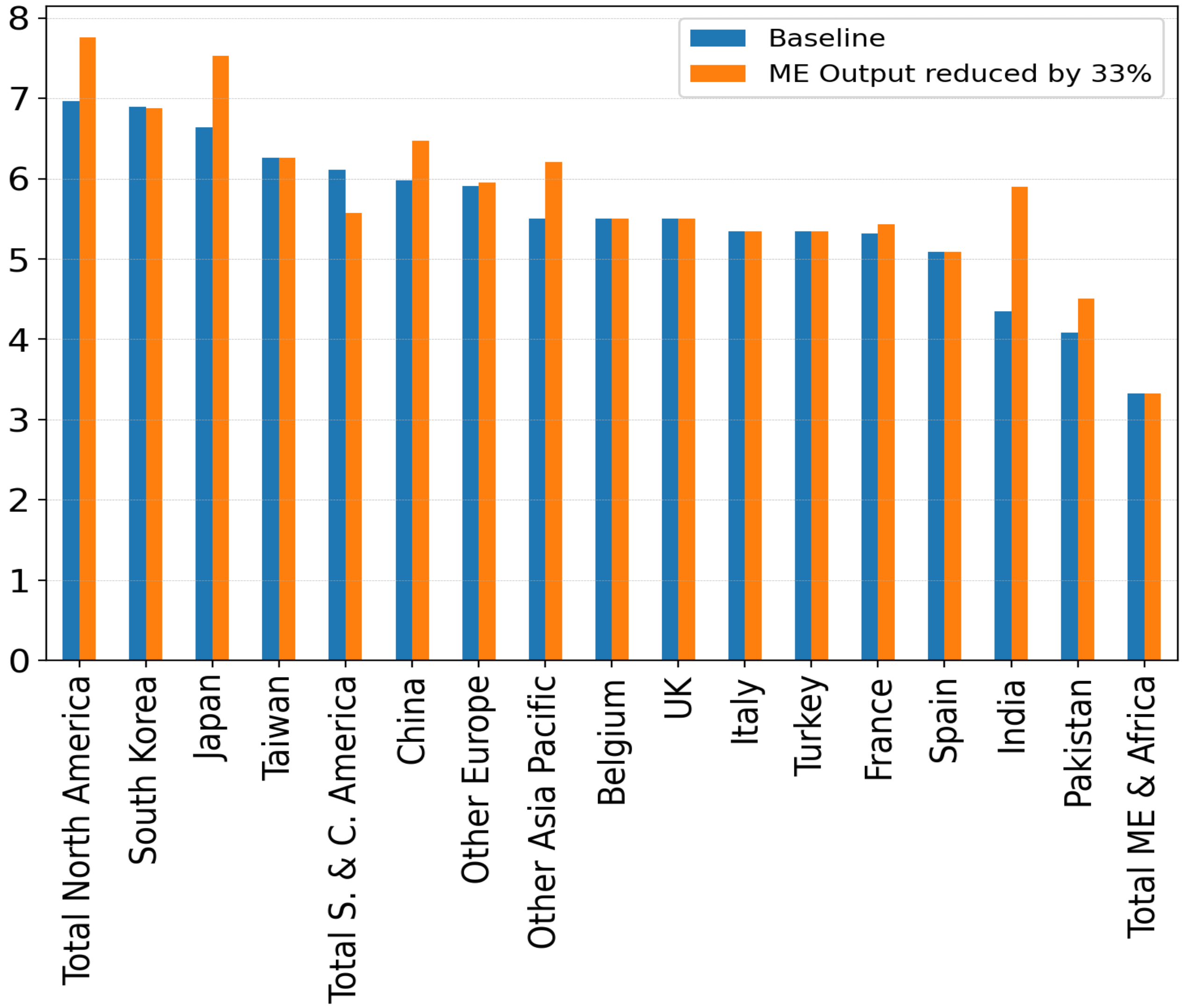


*Figure 24: DES Prices: Baseline vs Strait of Hormuz partially closed*

The aforementioned LNG flows in base model, shown on Figure 4, reveal the reason for increase of DES prices in almost all Asian importers (Figure 24): reduced shipments from the most important low cost suppliers from Middle East are compensated with much more expansive offtakes from marginal supplier Australia, which would significantly increase her capacity utilization. The sharpest price growth occurs in India, the fourth largest world LNG importer that is in close proximity to Middle East. India's drawback is twofold – not only it is forced to import more from exporters with less competitive prices, but also from geographically much more distant ones, hence much higher additional transportation costs in final price as well. One additional mmBtu delivered by any exporter (except Australia) would much more reduce the overall import costs than in base model (Figure 25). Almost no DES price increases in Europe and even decrease in Total S. & C. America once again confirm the geographical division of LNG importers: a glance at potential one mmBtu demand raise in any of import nodes always results in total cost increases (Figure 26), but effect of additional demand in nodes from Atlantic Basin (all of which are on the right half of the Figure 26) is in both cases lower.

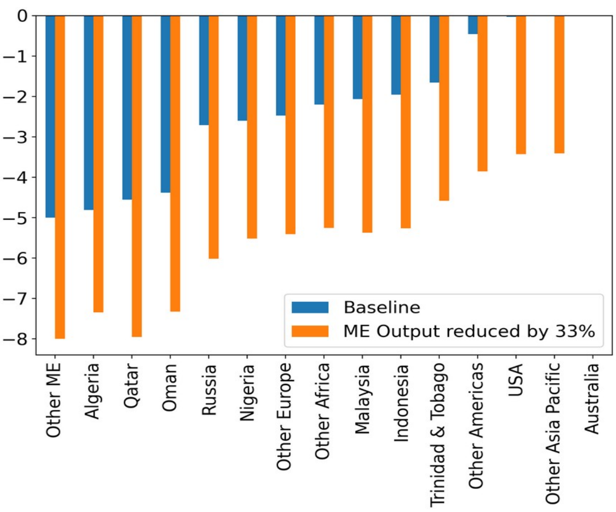


*Figure 25: Exporters shadow prices: Baseline vs Strait of Hormuz partially closed*

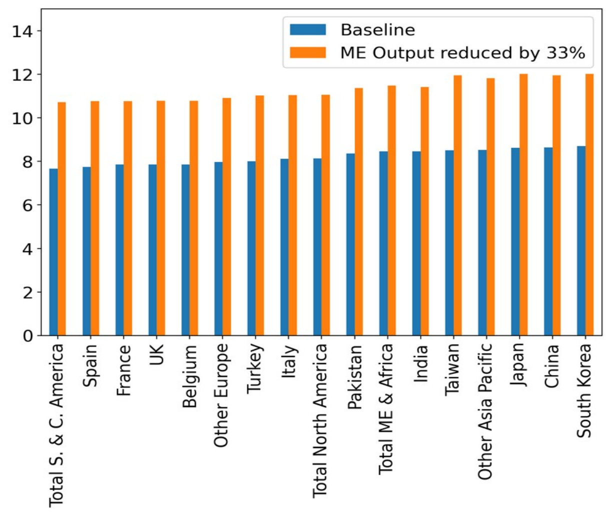


*Figure 26: Importers shadow prices: Baseline vs Strait of Hormuz partially closed*

The slightly lower minimal number of LNG tankers (Figure 27) is the implication of forced substitution of Middle Eastern LNG in the world largest LNG importers located in Asia Pacific with superchilled fuel from much closer Australia. Although the *status quo* for LNG shipment companies would remain, the import nodes as a whole would have to pay over the odds for imported LNG (Figure 28).

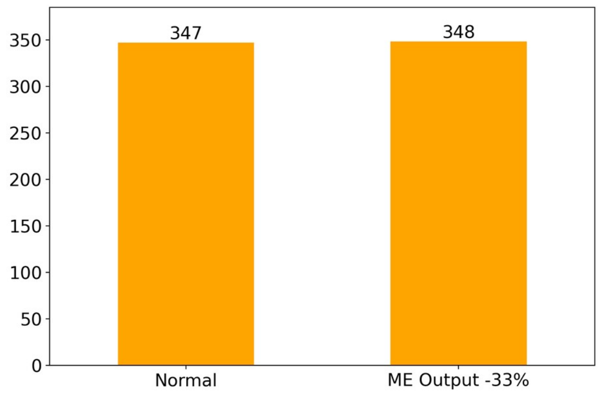


*Figure 27: Number of LNG carriers: Baseline vs Strait of Hormuz partially closed*

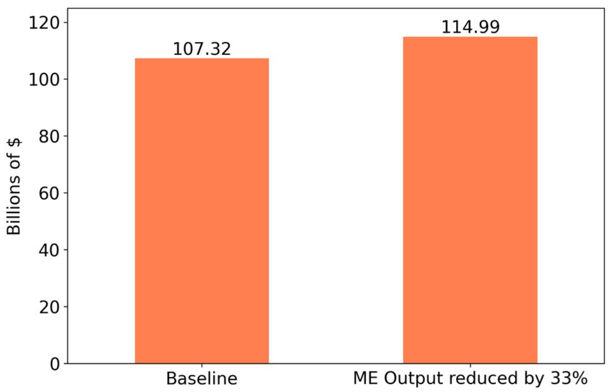


*Figure 28: Total costs: Baseline vs Strait of Hormuz partially closed*

The environmental impact, namely the CO2 and CH4 emissions, would remain almost the same and therefore the costs for offsetting them would also not change.

## 5.4 Increased LNG demand in Europe by one third

In the last decade, the European gas market was effectively the market of last resort for LNG exporters[(12)(13)]. Characterized by gas pipeline connections to relatively cheap gas sources in Norway, Russia, Azerbaijan and North Africa, not negligible domestic production[14] unlike most of Asian importers (mainly from gigantic Groningen gas field that is going to be closed (in) next year(s) though[15]) and maybe most importantly by large storage capacities, European importers had a certain comfort that allowed them, especially in recent years when large LNG liquefaction capacities came online and the market was oversupplied, to take advantage of low LNG spot prices. To see what would happen in case of emergency, i.e. sudden surge in demand, the sensitivity analysis was performed with European demand increased by third. Since one of the measures to achieve energy security is by diversifying gas supplies[(16)], the minimal number of different LNG suppliers used both in base model and this one is four.

Surge in DES prices at import nodes in Atlantic Basin in general and at European ones in particular is striking (Figure 29): larger shipped LNG volumes from Qatar to Spain, UK, Italy and Turkey than in base model only partially mitigate the price increases caused by large offtakes from much more expansive marginal supplier Australia (Figures 30 and 31), which would in this scenario significantly increase her capacity utilization. The sharp price growth occurs also in importers that are in close proximity to Middle East: India, Pakistan and Total ME & Africa, since some of the volumes from Middle Eastern exporters are diverted towards Europe. Drawback of all of these import nodes is twofold – not only they are forced to import more from exporters with less competitive prices, but also from geographically much more distant ones, hence much higher additional transportation costs in final price as well. In this way, DES prices in Asia Pacific and Europe would become more convergent.

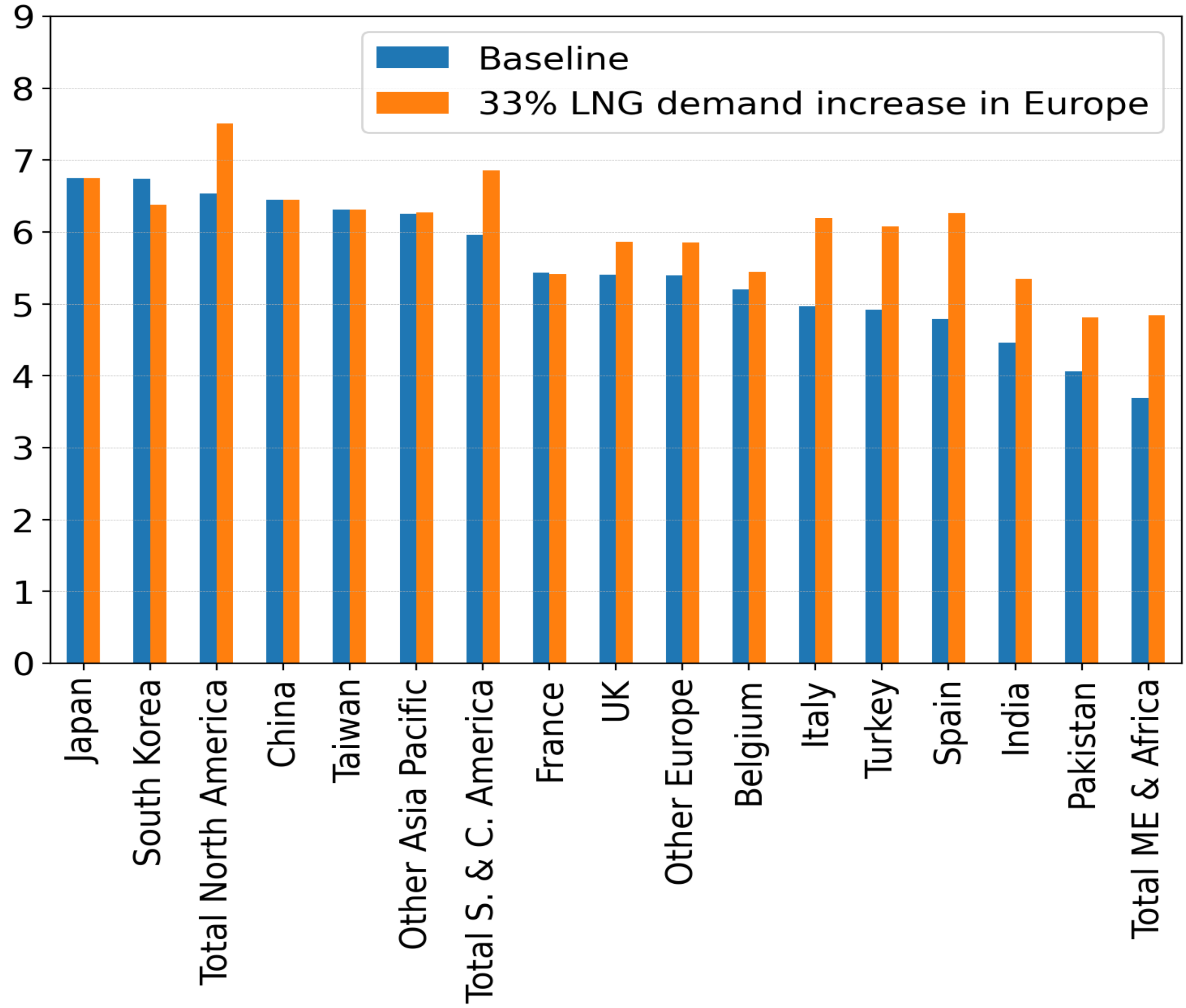


*Figure 29: DES Prices: Baseline vs 33% increase in European demand*

| | Japan | China | South Korea | India | Taiwan | Pakistan | France | Spain | UK | Italy | Turkey | Belgium | Other Asia Pacific | Other Europe | Total North America | Total S. & C. America | Total ME & Africa |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Qatar** | 26.400 | 21.225 | 13.900 | 8.225 | 5.8 | 3.1 | 0.000 | 5.475 | 0.000 | 3.575 | 3.3 | 2.146 | 7.650 | 0.000 | 2.8 | 0.000 | 2.725 |
| **Australia** | 26.400 | 21.225 | 13.900 | 0.000 | 5.8 | 0.0 | 0.000 | 0.000 | 0.000 | 0.000 | 0.0 | 0.000 | 7.358 | 0.000 | 0.0 | 0.000 | 0.000 |

*Figure 30: LNG Flows (in bcm) from Qatar and Australia: Baseline*

| | Japan | China | South Korea | India | Taiwan | Pakistan | France | Spain | UK | Italy | Turkey | Belgium | Other Asia Pacific | Other Europe | Total North America | Total S. & C. America | Total ME & Africa |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Qatar** | 26.400 | 21.225 | 13.900 | 8.225 | 5.8 | 3.1 | 0.000 | 7.300 | 0.829 | 4.767 | 4.4 | -0.0 | 7.650 | 0.000 | 0.0 | 0.000 | 2.725 |
| **Australia** | 26.400 | 21.225 | 13.900 | 8.225 | 5.8 | 3.1 | 0.000 | 7.300 | 3.812 | 4.767 | 4.4 | 0.0 | 7.650 | 0.000 | 2.8 | 3.375 | 2.725 |

*Figure 31: LNG Flows (in bcm) from Qatar and Australia: 33% LNG demand increase in Europe*

Looking at the exporters dual variables (Figure 32), unlike in base model, even additional mmBtu delivered from USA and Other Asia Pacific would make significant reduction in overall costs. On the other hand, an additional mmBtu in demand would result in much higher total costs than in base model. Even in this case, because of the proximity of Asian nodes to the marginal supplier (Australia), the extra unit of demand from these nodes would still cause highest overall costs.

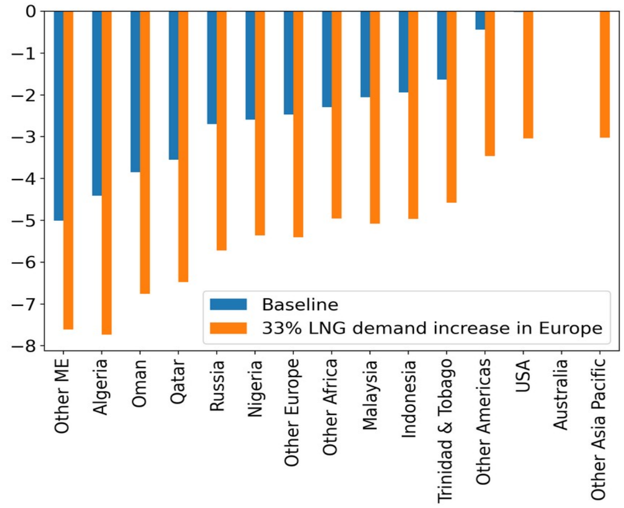


*Figure 32: Exporters shadow prices: Normal vs 33% increase in European demand*

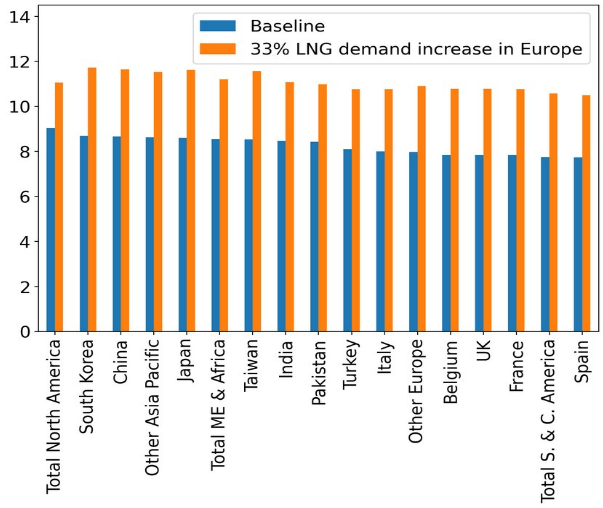


*Figure 33: Importers shadow prices: Normal vs 33% increase in European demand*

The minimal number of LNG carriers necessary to transport all the additional demand would jump by more than 13% (413 vs 365 in baseline), resulting in higher spot charter rates too. The overall import costs would also rise significantly, since the offtakes from marginal supplier Australia would be needed to meet the increased demand. Much higher $CO_2$ and $CH_4$ emissions would mean much higher costs for offsetting them. Importers with shipments from exporters from far away would be particularly hard hit.

## 5.5 Decreased LNG demand in Asia Pacific by one fifth

In the previous subchapter was shown that increased demand in Europe results in higher DES prices in European nodes and consequently to more or less convergent DES prices in Asia Pacific and on Old Continent. Here, the effects of a 20% lower demand in the largest import nodes in Asia Pacific (Japan, China , South Korea, Taiwan and Other Asia Pacific) are examined.

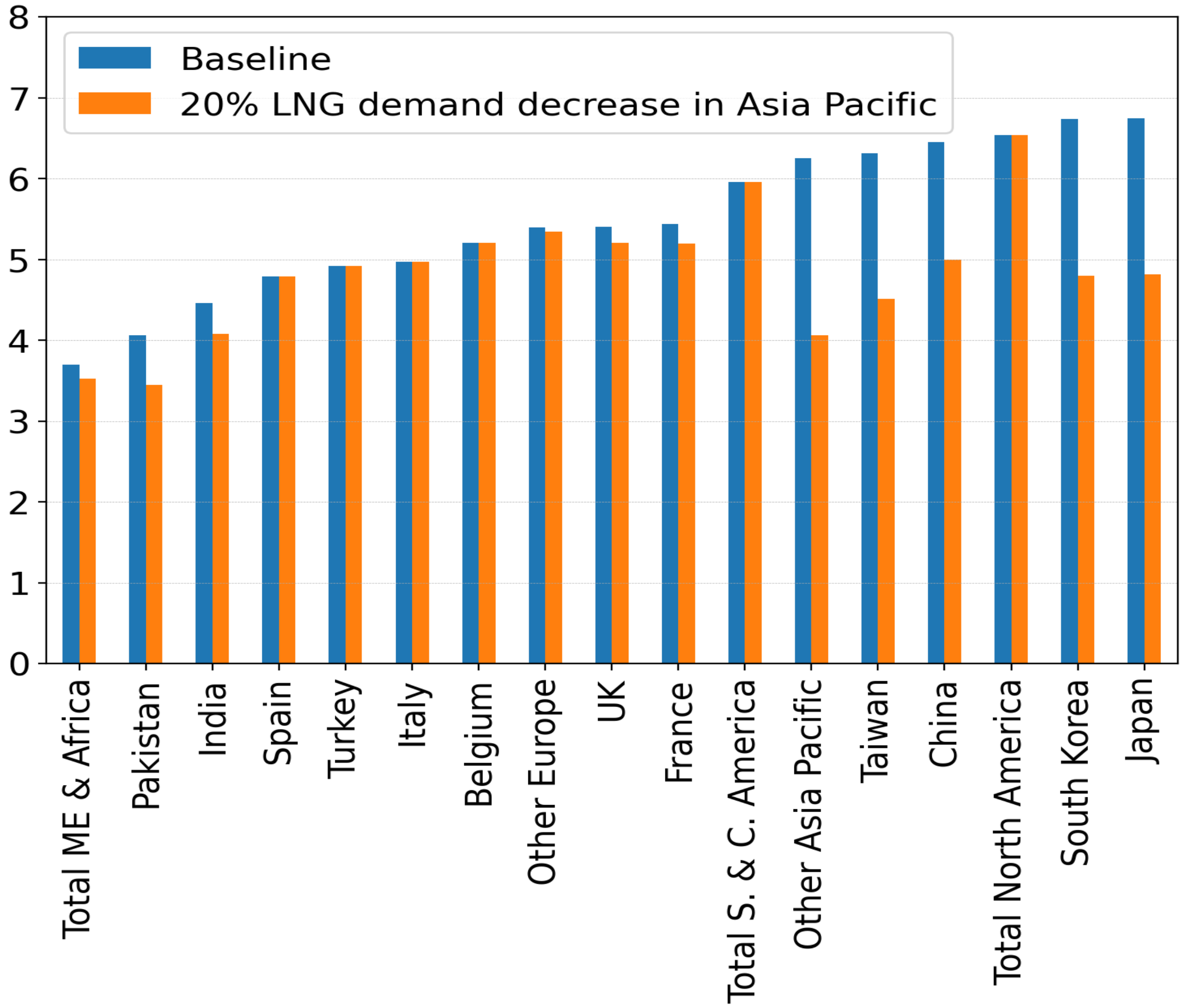


*Figure 34: DES Prices: Normal vs 20% decrease in Asia Pacific demand*

DES prices in Asian nodes with modeled lower demand plummeted and landed into or just under the price range of European importers (Figure 34). On the other hand, the shrinking DES price margins between the importers from the two Basins are to a lesser extent induced by slightly dropped DES prices in from the Middle Eastern exporters the most distant European nodes too, since part of the shipments from the Middle East dedicated to Asian importers, because of their lower demand, ended up exactly in these European importers in order to minimize the overall import costs. Pakistan, India and Total ME & Africa also profited from reduced demand in their Asian counterparts.

Impact of additional available unit of LNG from export nodes on overall import costs is lower than in base model (Figure 35). The utilization rate of liquefaction facilities in Australia and Asia Pacific is even lower and zero dual variables in these two nodes and USA remain unchanged. Generally, lower overall demand has negative influence on all exporters and particularly on those with low/zero shadow prices.

Additional mmBtu in demand in this scenario results in lower overall import costs compared to the base model (Figure 36). Lower importers dual variables reflect the aforementioned freed larger volumes of LNG from Middle East and their redirection towards Europe.

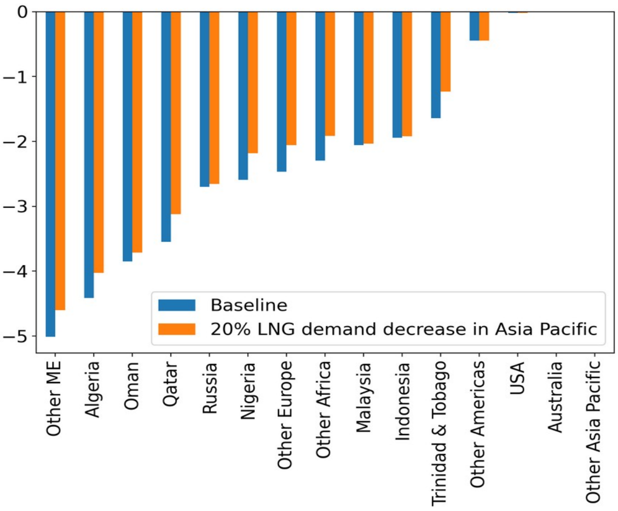


*Figure 35: Exporters shadow prices: Normal vs 20% decrease in Asia Pacific demand*

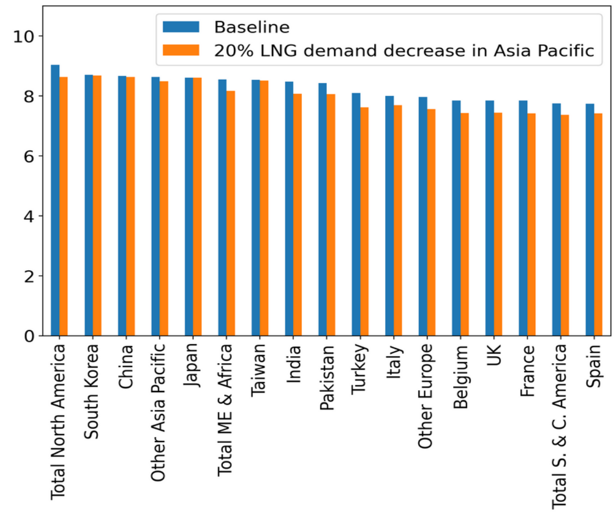


*Figure 36: Importers shadow prices: Normal vs 20% decrease in Asia Pacific demand*

Decreased demand in Asia Pacific has not only bad repercussions on LNG exporters, but on shipping companies also, since the necessary number of LNG carriers also diminishes (342 vs 365 in baseline). This, on the other hand, has positive environmental effect, since the GHG emissions are lower.

# Apendix 1

The expected growth of the world's population and economic development will be the main drivers of increased demand for energy resources in the future. To meet this demand, while curbing climate change and improving air quality, gas in general and LNG in particular will play significant role. The LNG market analysts[17][18][19][20] anticipate almost doubling of LNG imports till 2040 (Figure 37). The majority of this demand increase will be driven by energy security, increasing penetration of gas in energy mix (coal-to-gas switch, transport sector…) and Asia's economic growth.

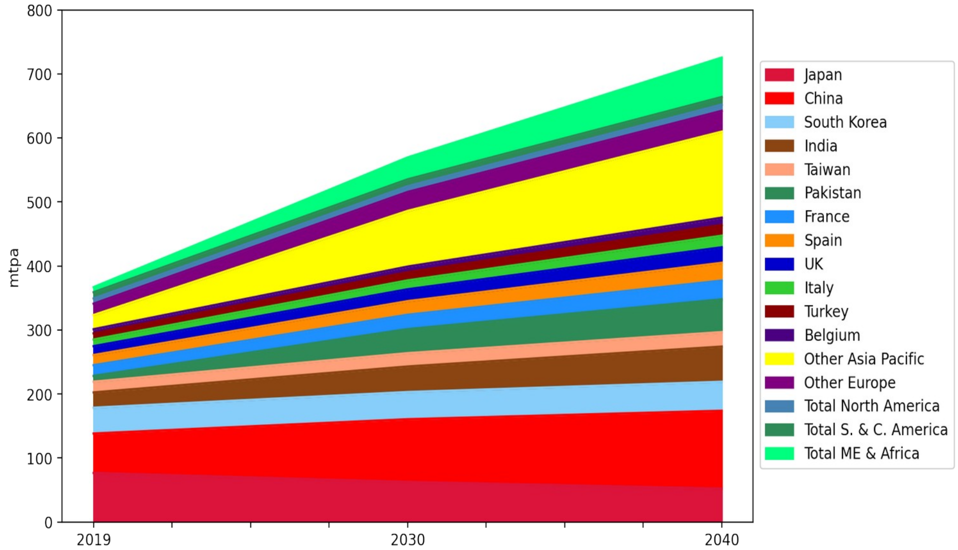


*Figure 37: Importers outlook*

On the supply side, the highest LNG export capacity additions are expected to come from USA (has already surpassed Qatar and Australia in December 2021 to become the largest exporter of LNG in the world[21]), Qatar, Russia and African countries (Figure 38).

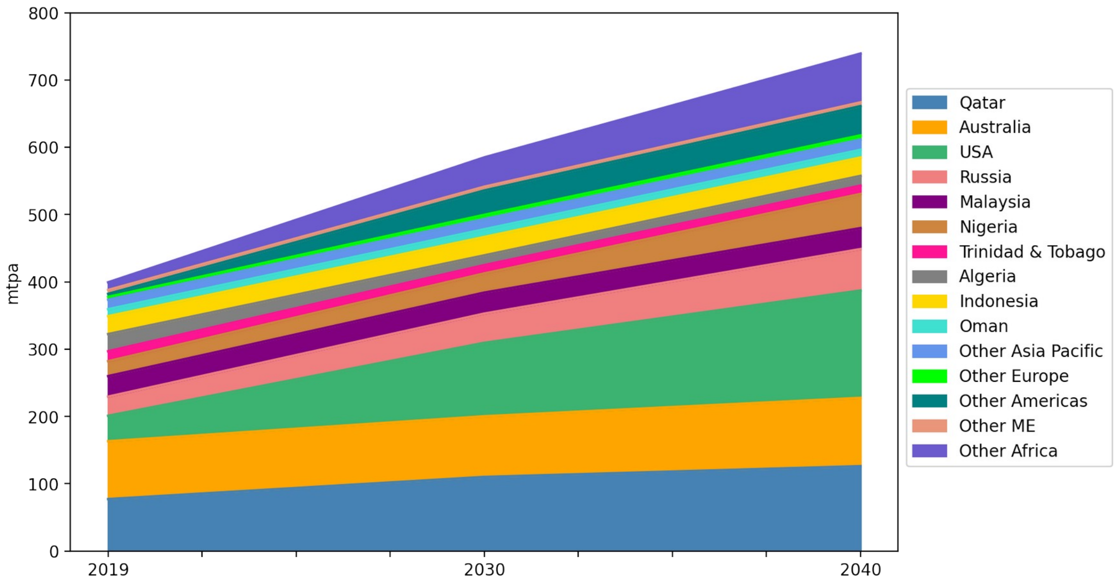


*Figure 38: Exporters outlook*

1 https://ihsmarkit.com/research-analysis/how-will-chinas-gas-storage-development-alter-lng-import.html
2 https://ukcop26.org/cop26-goals/
3 https://ec.europa.eu/info/publications/220202-sustainable-finance-taxonomy-complementary-climate-delegated-act_en
4 https://energy.ec.europa.eu/topics/oil-gas-and-coal/methane-emissions_en
5 https://www.iea.org/articles/global-co2-emissions-in-2019
6 https://www.investing.com/commodities/carbon-emissions
7 https://www.oxfordenergy.org/publications/measurement-reporting-and-verification-of-methane-emissions-from-natural-gas-and-lng-trade-creating-transparent-and-credible-frameworks/
8 https://timera-energy.com/how-fsrus-are-impacting-lng-market-evolution/
9 https://www.oxfordenergy.org/publications/developments-in-the-lng-to-power-market-and-the-growing-importance-of-floating-facilities/
10 https://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng/lng-outlook-2022/_jcr_content/par/relatedtopics.stream/1645193450146/ed695841d8b65ab7ac1caf58bd3718808b8f0a93/shell-lng-outlook-2022-infographic.pdf
11 https://www.investing.com/commodities/carbon-emissions
12 https://www.gasworld.com/europe-dominates-lng-import-story-in-2019/2018290.article
13 https://www.oxfordenergy.org/publications/quarterly-gas-review-issue-9/
14 https://www.eia.gov/todayinenergy/detail.php?id=51258
15 https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/062821-full-groningen-gas-field-closure-possible-as-early-as-2023-dutch-gts
16 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:108:FIN
17 https://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng/lng-outlook-2022/_jcr_content/par/relatedtopics.stream/1645193450146/ed695841d8b65ab7ac1caf58bd3718808b8f0a93/shell-lng-outlook-2022-infographic.pdf
18 https://www.mckinsey.com/industries/oil-and-gas/our-insights/~/media/0B218D0C0A6749679268EDCB0E83F57D.ashx
19 https://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng/lng-outlook-2021.html#iframe=L3dlYmFwcHMvTE5HX091dGxvb2svMjAyMS8
20 https://www.offshore-technology.com/comment/us-lng-capacity-2025/
21 https://www.instituteforenergyresearch.org/international-issues/u-s-becomes-the-largest-lng-exporter-aids-europe-through-its-energy-crisis/