UNIVERSIDAD DE OVIEDO

Department of Energy

Integration of the Iberian natural gas infrastructure into the European energy transition to renewable sources

PhD Thesis

Author: Pablo Fernández Fernández

Director: Jorge Xiberta Bernat

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RESUMEN DEL CONTENIDO DE TESIS DOCTORAL

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2.- Autor	
Nombre: PABLO FERNANDEZ FERNANDEZ	
Programa de Doctorado: Tecnología, diversificación, calidad y ahorro energético	
Órgano responsable: Departamento de Energía	

RESUMEN (en español)

Las emisiones de carbono relacionadas con el sector energético son y seguirán siendo el principal responsable de origen humano en el calentamiento global. Como consecuencia, existe un amplio consenso internacional en la necesidad de una descarbonización de la energía con el objetivo de invertir esta tendencia. Mejoras en eficiencia energética y la paulatina sustitución de combustibles fósiles por otros de bajo contenido en carbono son las principales opciones para hacer realidad esta transición energética.

Se deben analizar diferentes planes que reduzcan las emisiones de carbono, asegurando a la vez la competitividad y seguridad de suministro. El gas natural, siendo el combustible fósil más limpio y con abundantes reservas dispersas geográficamente, está llamado a ser un combustible de transición hacia las energías renovables.

Sin embargo, en la UE con el agotamiento de las reservas del Mar del Norte y las posibles interrupciones de suministro por gaseoducto (Rusia y el Norte de África), hacen que la seguridad de suministro dependa en gran medida de un emergente mercado global. En este contexto, la implantación de un mercado único europeo, así como el uso eficiente de las infraestructuras existentes y futuras son los principales retos de la UE.

Las infraestructuras ibéricas pueden jugar un papel determinante como puerta de entrada al suministro de gas por gaseoducto procedente del Norte de África y al mercado de GNL, aprovechando su localización geoestratégica y la amplia capacidad de regasificación.

En la presente tesis se construye un modelo básico de equilibrio espacial del mercado global del gas natural para optimizar las infraestructuras de transporte europeas, enfatizando la región Ibérica y demostrando la importancia de incrementar la capacidad de interconexión con el resto de la UE según diversos escenarios.

RESUMEN (en Inglés)

Under current trends, researchers estimate energy- related carbon emissions to continue leading human contribution to global warming. Consequently, it is broadly agreed that an energy decarbonization must be tackled in order to reverse this tendency. Improvements on energy efficiency and a gradual substitution of fossil fuels for low carbon sources are the main drivers in this energy transition.

Different pathways must be explored in order to abate carbon emissions, while ensuring competitiveness and security of supply. Natural gas, as the cleanest fossil fuel with abundant widely dispersed resources, is envisaged as a transition fuel to renewable sources.

However, with reserves in the North Sea depleting and the continuous risk of disruptions from the pipeline partners (Russia and North Africa), EU security of supply will strongly depend on an emerging global gas market. As a result, the implementation of a European single gas market, and an effective use of existing and future infrastructures are key points to be addressed by the EU.

In this context, the Iberian infrastructures could play an essential role as a gateway to the African pipeline supplies and the LNG market, taking advantage of its geostrategic location and large capacity of receiving plants.

A basic spatial equilibrium model is used in the present thesis to simulate the global gas market and the European transport infrastructures, emphasizing the Iberian subregion. The importance of expanding the interconnection capacity with the rest of the EU is stated under different scenarios.

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Abstract

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Las emisiones de carbono relacionadas con el sector energético son y seguirán siendo el principal responsable de origen humano en el calentamiento global. Como consecuencia, existe un amplío consenso internacional en la necesidad de una descarbonización de la energía con el objetivo de invertir esta tendencia. Mejoras en eficiencia energética y la paulatina sustitución de combustibles fósiles por otros de bajo contenido en carbono son las principales opciones para hacer realidad esta transición energética.

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Acknowledgments

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Abbreviations

bcm	billion cubic meters
bcma	billion cubic meters per annum
CAPEX	Capital expenses
CCS	Carbon capture and storage
ETP	Energy Technology Perspectives
EU	European Union (28 member countries)
FED	Final Energy Demand
GAMS	Generic Algebraic Modelling System
GDP	Gross domestic product
GHG	Greenhouse gases
GTL	Gas To Liquids
IEA	International Energy Agency
LCA	Life cycle assessment
LCOE	Levelized cost of energy
LNG	Liquefied natural gas
NG	Natural gas
NGL	Natural gas liquids
NLP	Non- linear programming
OPEX	Operating expenses
RES	Renewable Energy Sources

tcm	Thousand cubic meters
Tcm	Trillion cubic meters

1

Energy and fuels

1 Energy and fuels

1.1 Introduction

The Law of conservation of energy states that the change in the energy of a system equals the energy transfer into the system, assuming the former as the sum of the potential, kinetic and internal energy, and the latter as transferred both by work and heat. When the Law is applied to an opened control volume, in addition to the energy transferred across their boundaries, energy can also accompany the mass flow through the control volume.

The conservation of mass and energy when considering only one inlet and one exit can be expressed as follows:

$$\dot{m}_e = \dot{m}_i$$

$$\dot{Q}_{cv} + \dot{m}_e h_e + KE_e + PE_e = \dot{W}_{cv} + \dot{m}_i h_i + KE_i + PE_i$$

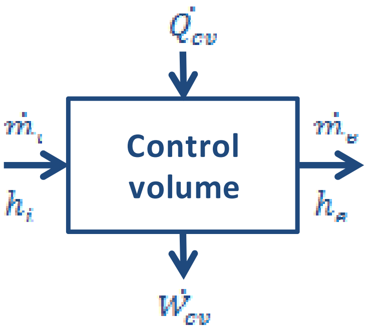


Figure 1-1: Mass and energy conservation principles

Where $\dot{m}_i$ and $\dot{m}_e$ are the inlet and exit mass flows, h_i and h_e are the inlet and exit enthalpies, and Q_{cv} and W_{cv} are the work and heat transferred, respectively.

Therefore, mass and energy flow between different equipments (turbines, compressors, pump, etc.) while heat and work are exchanged with the surroundings. But, where does energy come from? So far, the most widely exploited resource is contained in the bonds within the molecules of the fossil fuels. Heat is released by an exothermic combustion reaction, completed when all the reacting elements are oxidized and the products rejected back into the surroundings.

In a broader sense mass and energy flows can be extended to a general structure of the energy system, as shown in Figure 1-2.

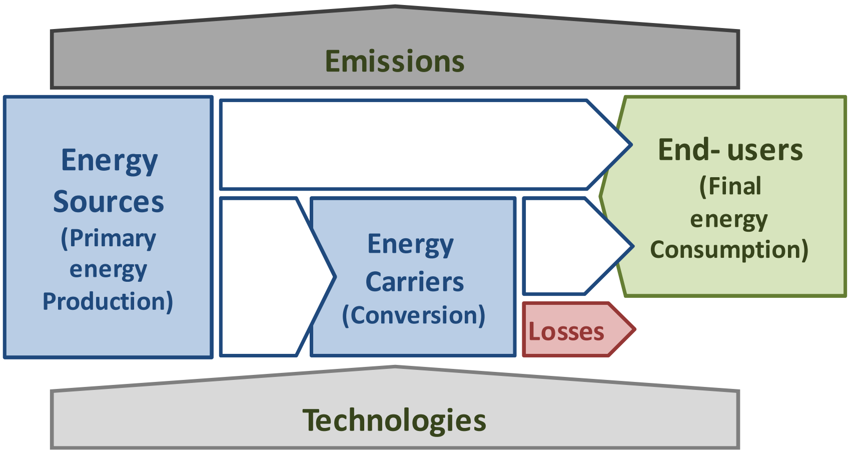


Figure 1-2: Energy system structure

Basically, the primary energy found in different fuels is supplied to the end users for consumption. Since not every primary source is convenient for every end use, intermediate conversions are commonly involved to obtain other energy carriers. The framework is finally completed by the required technological developments and the resulting energy- related emissions, both greenhouse gas emissions (GHG) and local atmospheric pollutants.

On a global level, primary energy production in 2011 amounted to 549 EJ or 13,111 million tonnes of oil equivalent (Mtoe, see factor conversion for energy units in Appendix I), while final energy consumption totalled 383 EJ (9,137 Mote), the rest being lost in conversion or transportation. As a result, 33,737 tonnes of CO2 were released to the atmosphere.

Such an integrated approach is used by institutions, such as the International Energy Agency (IEA) or the European Commission (EC) to represent the energy system and provide their models and long term projections, Energy Technology Perspectives (ETP, 2014) and Roadmap for moving to a low-carbon economy in 2050 (EC, 2011), respectively.

1.2 Energy demand

The total energy demand is the sum of the energy consumed by the equipment stock present in each end use sector (industry, transport, buildings, etc.), which in turn is a function of the corresponding activity variables. Technological advances enhance efficiency in the equipments by reducing the energy use per activity variable. Ultimately, sectoral activity is driven by socio-economic and political factors (GDP, population, sectoral policies, economy model, etc.).

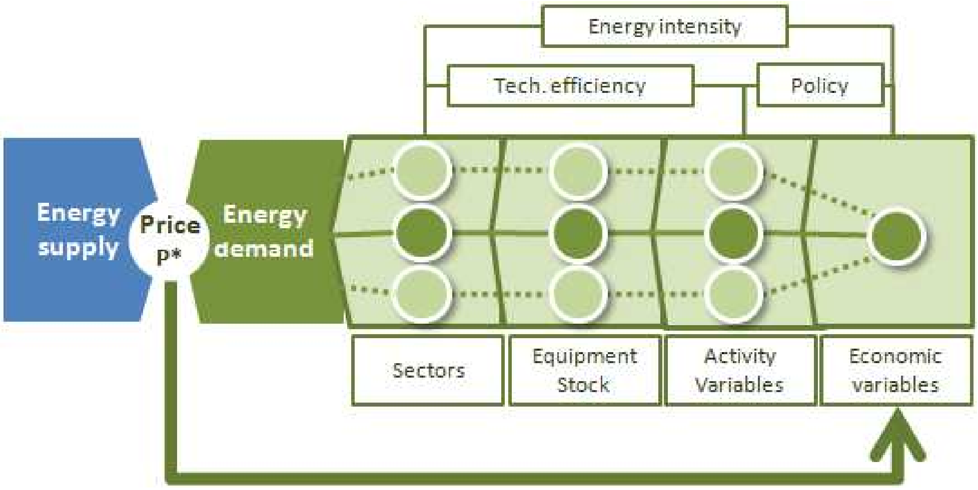


Figure 1-3: Energy demand overview

As an example, the energy consumed by the subsector road passenger transport is a function of the activity variable passenger-kilometer, which is related to a large extent with the global economy situation. Improvements on the engine efficiency of the vehicles turn into a lower fuel consumption, while European transport policies (public transport, new infrastructures, modal shift, etc.) are the main drivers to reduce the traffic intensity.

Reversely, economy is also influenced by the energy prices. As a production factor, energy accounts for a 5% weight in the economy, modest but probably underrated based on the cheap high-productive energy and the expensive low-productive labor (Kümmel and Lindenberger, 2014).

As a result of technical developments and the shift to a knowledge- based economy (Worldwatch, 2014), the energy intensity (energy demand divided by the GDP), has shown a steady decline over the last decades, i.e. GDP increased more than energy demand.

Corresponding subsectors and activity variables in the three main sectors are listed below.

	Industry	**Transport**	**Buildings**
Subsector	Iron and steel chemicals & petrochemicals cement pulp and paper aluminium	Passenger/freight road aviation rail navigation	space heating, space cooling, water heating, cooking, appliances, lightning.
Activity variables	Sectoral production Value added in the industry	passenger-kilometre tone-kilometre	floor space, number of households, appliances ownership, services value added

Table 1-1: Subsectors and activity variables

Global and European energy use in 2011 by sector is shown in the table 1-2. European demand is roughly equally divided into the three energy categories.

Even though energy intensity continues its downward evolution, global energy consumption is projected to grow by 2050 more than two-thirds, assuming current trends (ETP, 2014). GDP is expected to increase threefold in the same time period. Meanwhile, European demand is anticipated to increase by 12%, reducing its share in the global energy well below 10%.

	2011				**2050** (under current trend)			
	Global		**EU**		**Global**		**EU**	
	Demand (EJ)	Share	Demand (EJ)	Share	Demand (EJ)	Var.	Demand (EJ)	Var.
Industry & non-energy	153,261	40%	16,080	31%	272,937	78%	17,522	4%
Transport	99,721	26%	17,239	32%	178,527	79%	17,540	2%
Buildings & others	129,641	34%	19,122	36%	205,654	59%	24,719	29%
	382 623	**100%**	**53 161**	**100%**	**657 118**	**72%**	**59 780**	**12%**

Table 1-2: Energy demand in 2011 and projection to 2050 (in EJ)

1.3 Energy supply

Energy resources are found in many forms and locations, and classified in renewable (hydro, wind, solar, biofuels, etc.) and depletable energies (fossil fuels and uranium). When recoverable under the prevailing technical and economical conditions, resources are considered as reserves. Advances in technologies and new discoveries increase these stocks.

The production of energy sources is traded between supply and demand regions, either directly or transformed into a more convenient energy carrier (electricity, oil products, etc).

Energy supply is roughly driven by technological issues, as shown in the figure 1-5.

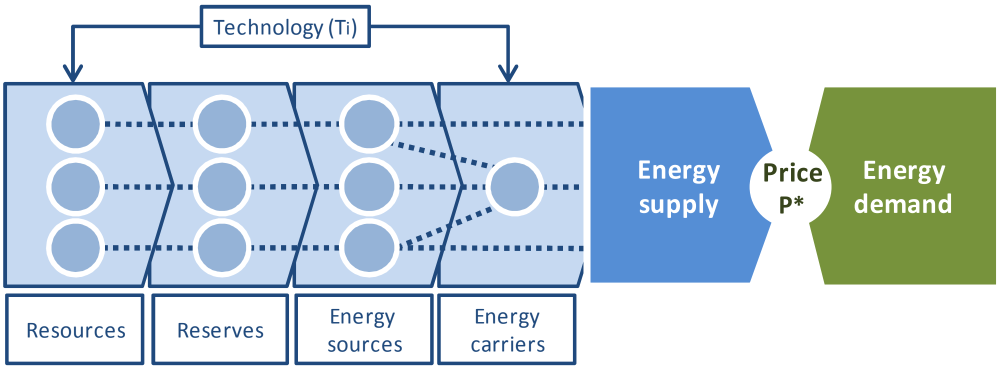


Figure 1-4: Energy supply overview

Various factors influence the selection of the most suitable energy source or carrier by end- use sector and conversion.

Technological: the technology life cycle (TLC) describes the phases followed during its adoption: research, development, demonstration, deployment, maturity and decline. Large scale deployment requires mature technologies.

Environmental: the life cycle assessment (LCA) considers the environmental impact through the product life (materials, construction, operation and decommission), including air local pollutants (sulphur and nitrogen oxides, particulate matter, etc.) and greenhouse gas emissions (carbon dioxide, methane, etc.). After- treatment technologies are used to abate these emissions, including carbon capture and storage (CCS), selective catalytic reduction (SCR) for SOx or scrubbers for NOx.

Economic: the Levelized cost of energy (LCOE) includes the capital expenses (CAPEX), fixed and variable operations and maintenance (O&M) expenses (OPEX), incurred by the end user equipment.

The CAPEX refers to the investments on fixed assets both for new buildings and retrofitting of existing ones (including shift to another fuel).

When applicable, fuel costs are normally the most relevant component of the OPEX. Available fuel prices are referred to certain reference locations. In order to compare different options fuel costs are considered delivered to the end user either directly or through refueling stations in the transport sector. As a result, distribution costs and the underlying infrastructure from the reference point are required.

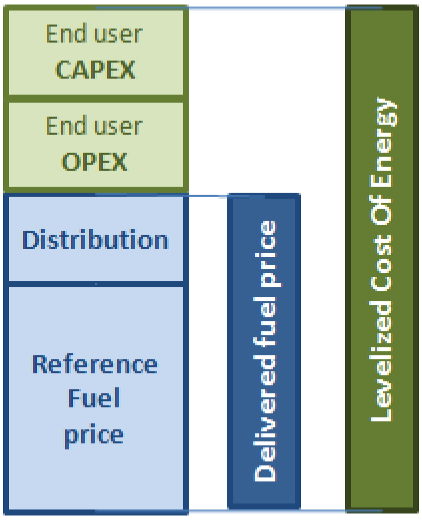


Figure 1-5: Levelized cost of energy approach

Political: energy policy mechanisms such as regulations, taxation and subsidies are introduced by the governments normally to boost environmental issues, but also security of supply or simply national strategic industries.

These mechanisms can have an impact either on the OPEX, such as the emission trade system (ETS), or on the retrofitting CAPEX incurred to comply with new regulations, such as retrofitting Industrial Emissions Directive 2010/75 (EP, 2010).

Taxation includes the excise duty rates applicable to the fuels according to their end use. Information about Member States levels of taxation are published in (EC, 2015).

Previous factors have been largely reviewed to compare a range of existing technologies in the electricity sector. As a reference, the estimated LCOE in the US by 2019 (EIA, 2014) and the LCA of greenhouse gas emissions (IPCC, 2011) for different sources are shown in the table 1-3.

	LCA (gr. CO2/KWh) 50th percentile	LCOE (2019) (2012 $/MWh) average
Biomass	18	103
Solar PV	46	130
Solar CSP	22	243
Geothermal	45	48
Hydropower	4	84
Ocean	8	496
Wind on shore	12	80
Nuclear	16	96
Natural gas	469	66
Coal	1001	96
Gas with CCS	155	91
Coal with CCS	247	147

Table 1-3: Economical and environmental indexes in the electricity sector

Prevailing merit order mechanism in EU rank these sources in cost ascending order, being those with the lowest values, the first to come online. In that situation, investments in cleaner but more expensive renewable technologies must be supported.

As a result, many governments have opted for the feed in tariff scheme, to ensure the payment of a fixed tariff based on LCOEs above the market price. Different results have been achieved depending on the country and technology (Fernandez, Villacaña, Xiberta, 2013) (Fernandez, 2011), with wind power accounting for more than one sixth of Spanish electricity net generation in 2012 (Aguilera, Xiberta and Fernandez, 2013).

1.4 The energy system and the role of natural gas

The evolution and projections of the EU energy system are analyzed according to the following relevant variables: gross domestic production (GDP), primary energy demand (PED), final energy demand (FED) and CO_2 emissions.

Based on the evolution 1990–2011 and projections by 2050 under current trends, the development of the previous variables is shown in Figure 1-6 and table 1-4, being the main conclusions:

- GDP and FED have clearly decoupled.
- Though a gradually RES substitution for fossil fuels major contribution of fossil fuels is stated, even by 2050 with two thirds of the primary demand. Furthermore, a gradual substitution of natural gas for coal and to a lesser extent oil is shown.
- GHG emissions abatement of 8% in 2011 and 17% in 2050 compared to 1990.

	1990	2011	2050 6°C	2050 4°C	2050 2°C
Oil	631	728	583	519	255
Coal	453	323	178	93	65
NG	295	455	719	542	327
Nuclear	203	266	130	192	229
RES	75	208	436	534	720
Total PED	**1657**	**1980**	**2046**	**1880**	**1596**
Industry	470	401	418	369	338
Buildings and others	522	457	590	551	457
Transport	312	412	419	372	259
Total FED	**1304**	**1270**	**1428**	**1292**	**1054**
CO2	100%	88%	79%	59%	27%
GDP	100%	140%	254%	254%	254%

Table 1-4: EU GDP, energy demand (in Mtoe) and CO2 emissions

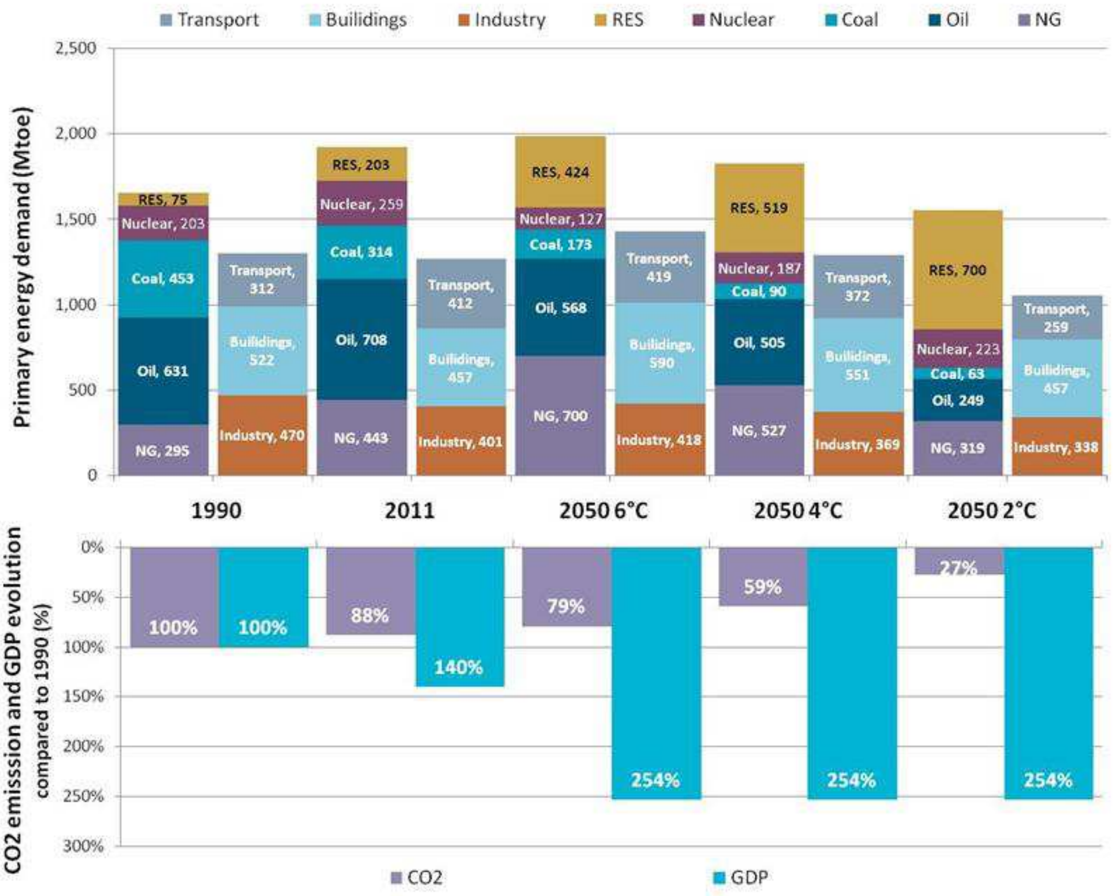


Figure 1-6: EU Energy demand (Mtoe) and development of GDP and CO_2 emissions

GHG emissions have a global impact on the planet warming. As a result of the corresponding regional contributions (20% reduction in the EU), the average global temperature is expected to rise by 6°C above pre-industrial levels in the long run.

It is broadly agreed that global action and additional measures should be taken to stabilize the climate change. Researchers estimate an increase of 2°C, if a 50% reduction in GHG emissions is attained by 2050. Taking into account the additional effort from the developing countries and their growth outlooks the EU should achieve the objective of 80% reduction.

Consequently, an energy decarbonization is required, based on three hierarchal compliance dimensions:

- Energy efficiency in conversion and end user equipments, or alternatively energy intensity, including sectoral policies.
- Fuel substitution for low carbon energies, or alternatively "*lower carbon as usual*" sources.
- Post treatment of emissions.

Energy system is aimed to move from a centralized energy system based on fossil fuels to a greater diversity of low carbon fuels within a more distributed and highly inter-related system. To what extent such an energy transition will evolve is highly uncertain and dependent on the technological developments and energy policies in place.

A set of scenarios and pathways to 2050 has been proposed by different organizations, based on their environmental and economical impact. Global projections set by the IEA in the ETP2014 are used in the present thesis. Depending on the number of degrees expected in global temperature rise, three scenarios are distinguished in Figure 1-6 (2°C, 4°C and 6°C).

In all of them natural gas post the best performance among the fossil fuels. As the cleanest fossil fuel with abundant and widely dispersed resources, natural gas is believed to be a transition fuel to renewable sources, continuing a history of successive primary energy substitutions, as shown in Figure 1-7 (F. Aguilera and Aguilera, 2011).

The role of the natural gas in the energy transition will not only depend on exogenous factors but will also be influenced by specific factors from their market as analyzed in the following chapters.

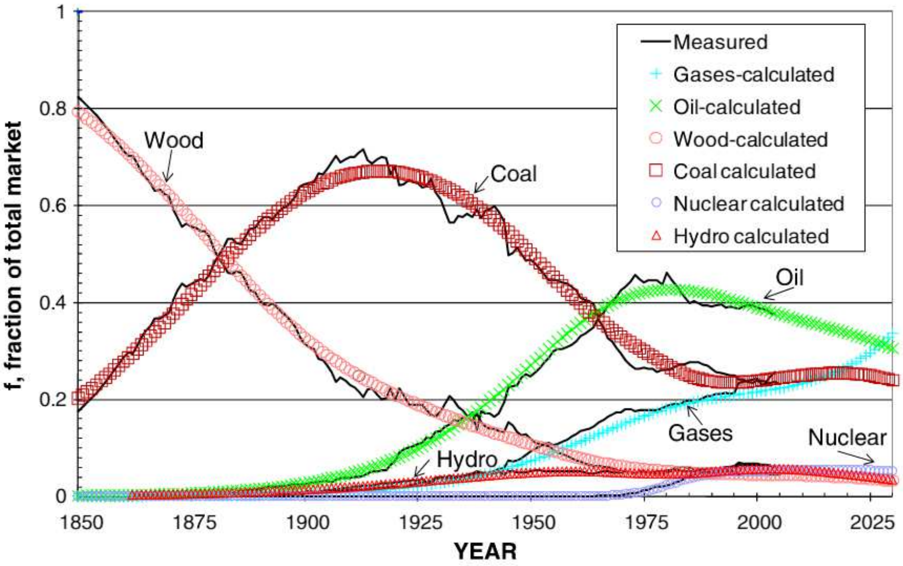


Figure 1-7: World substitution curves (F. Aguilera and Aguilera, 2011)

2

Natural Gas: Technical review

2 Natural gas technical review

This chapter provides a brief introduction to the natural gas and the technologies from the wellhead to the end user.

2.1 The product

2.1.1 History

Natural gas was originated by the combination of sediments and organic matter (plants, algae, plankton, animals) in an aqueous environment. As a result, the source rock and a mud-like substance, called kerogene, were formed.

The gradual accumulation over millions of years caused the deep burial and subsequent exposure to increasing temperatures. In those conditions the carbon bonds in the kerogene long molecules were cracked into smaller hydrocarbons: molecules of oil at 50-150°C, and the shortest molecules of methane (the main component of natural gas) at 150-200°C. Existing high pressures enabled hydrocarbons to split from the source rock and move upwards until being trapped by an impermeable layer.

Methane can not only be obtained from such underground thermogenic processes, but also from anaerobic decay of organic matter. This biogenic mechanism can be naturally produced in shallow depths, or reproduced with other feedstock, such as manure, into bio-gas.

First human contacts with natural gas were accidental. Fissures in the earth's crust allowed natural gas leakages from underground. However, first broad use as lightning in late 18th century was not supplied by primary natural gas, but manufactured as from the coal coking process. Unfeasible to be marked due to its low density, natural gas continued to be an unwanted by- product from oil fields, which was either reinjected back into the well, or simply flared on site.

Metallurgical improvements, new welding techniques and pipe rolling in mid 20th century, made pipeline construction feasible, deploying a wide natural gas transmission network to a number of end users. On the other hand, liquefaction and regasification processes enabled natural gas to be transported by sea in large carriers raising the distance and the trade flexibility between supply and demand.

2.1.2 Properties

The raw gas obtained from the reservoir, known as *wet gas*, primarily consists of methane (CH_4), but also in lower quantities of heavier hydrocarbons and impurities which must be extracted in order to meet the requirements by transportation and end users. Such a processed natural gas is known as *dry gas*.

Natural gas composition and properties vary considerably depending on the reservoir. A typical range composition by mole fraction is shown in table 2-1.

Component		Range (mole %)
Methane	CH_4	70 - 90%
Ethane	C_2H_6	0 - 20%
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon Dioxide	CO_2	0 - 8%
Oxygen	O_2	0 - 0.2%
Nitrogen	N_2	0 - 5%
Hydrogen sulphide	H_2S	0 - 5%
Rare gases	A, He, Ne, Xe	trace

Table 2-1: Natural gas range composition (Speight, 2007)

Regarding natural gas main component the combustion reaction of methane can be expressed, as follows:

$$CH_4 + 2\,O_2 \;\rightarrow\; CO_2 + 2H_2O + 891\ kJ/mol$$

Where 891 KJ is the heating value, or the difference between the enthalpy of the products and the enthalpy of the reactants when the complete combustion occurs.

Based on its lower carbon-hydrogen ratio, methane produces the highest heat per mass unit (55.5 KJ/g) and the lowest CO_2 emissions during the combustion.

Methane physical properties are compared with other fossil fuels compounds in table 2-2. Its boiling point at atmospheric pressure is -161.5°C. At this point liquid – gas transition occurs and the liquid phase density equals 422.36 kg/m^3, more than 600 times the density at atmospheric pressure and ambient temperature (0.6797kg/m^3).

	Unit	Methane	Ethane	Propane	Butane
Molecular weight		16.042	30.068	44.094	58.120
Boiling point at 1 bar	ºC	-161.5	-88.6	-42.5	-5
Liquid density at boiling point	kg/m3	426.0	544.1	580.7	601.8
Vapour specific gravity at 15ºC and 1 bar		0.554	1.046	1.540	2.07
Gas/Liquid volume ratio at boiling point			619	413	311
Flammable limits	%	5.3-14	3-12.5	2.1-9.5	2-9.5
Auto ignition temperature	ºC	595	510	510/583	510/583
Gross Heating Value	kJ/kg	55559	51916	50367	49530
Vaporization heat at boiling point	kJ/kg	510.4	489.9	426.2	385.2

Table 2-2: Fossil fuel properties (Nasr and Connor, 2014)

Finally, typical carbon dioxide and air pollutants produced by the combustion of the main fossil fuels are shown in table 2-3. In addition to a virtual elimination of sulfur dioxides and particulate matter, important reductions are achieved by natural gas in terms of nitrogen oxides and to a lesser extent of carbon dioxide.

		Emissions (gr/MJ)		Emission reduction (compared with NG)	
Pollutant	**NG**	**Oil**	**Coal**	**Oil**	**Coal**
Carbon Dioxide	50,3	70,5	89,4	29%	44%
Nitrogen Oxides	0,04	0,19	196,5	79%	80%
Sulphur Dioxides	≈0	0,48	1113,9	100%	100%
Particulates	≈0	0,036	1179,7	92%	100%

Table 2-3: Combustion emissions by fossil fuel (EIA, 1999)

2.2 Technologies

The value chain to get natural gas to market is divided into upstream, midstream and downstream activities, represented in the figure 2-2.

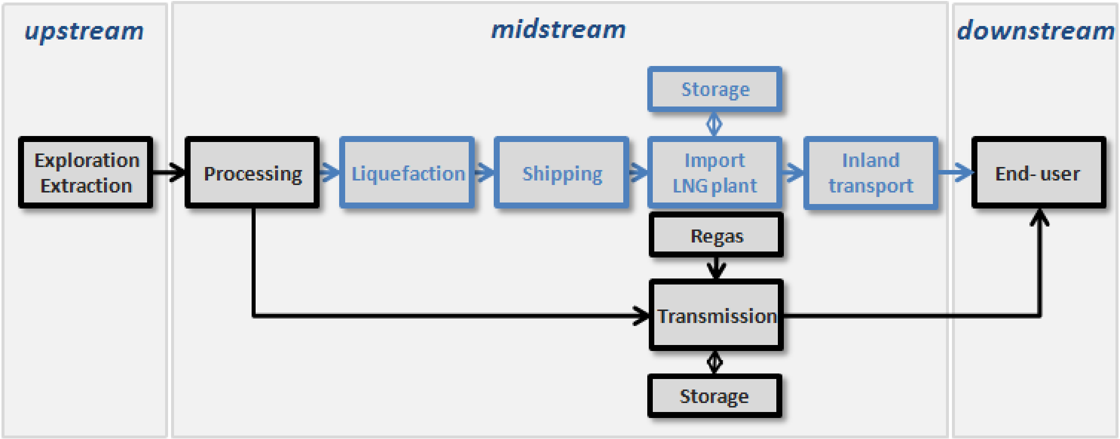


Figure 2-1 Natural gas value chain

2.2.1 Upstream

2.2.1.1 Exploration

Magnetic and gravity survey are firstly used to detect potential gas reservoirs, which are further confirmed by seismology methods. The idea is to emit small seismic waves, record the reflections and infer the properties by depth of the underground formations. Nevertheless, the only definitive method to validate the potential locations is by drilling an exploratory well.

Natural gas resources are classified into conventional and unconventional, as shown in the figure 2-3.

The conventional deposits are discrete, well- defined reservoirs with high permeability and subsequently high recovery rates. Depending on whether the gas is isolated or found within oil deposits, the gas is classified as associated and non- associated.

On the other hand, the unconventional deposits are dispersed reservoirs with low permeability and recovery rates. Three main types can be distinguished according to the rock formations trapping the natural gas:

- Tight gas (similar rocks to the conventional deposits but less permeable),
- Coal- bed methane (coal seams),
- Shale gas (within the pores of a fine-grained sedimentary rock, called shale).

In addition, still in an early stage of development are the methane hydrates, which are solids, composed of natural gas molecules surrounded by water molecules.

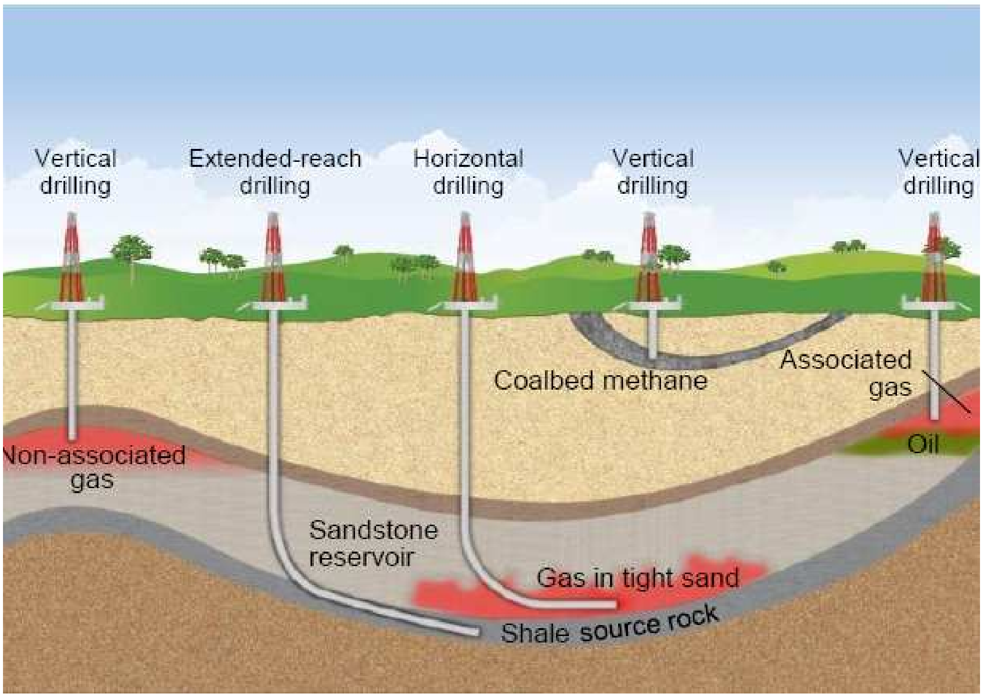


Figure 2-2: Natural gas resources

2.2.1.2 Extraction

The natural extraction basically consists of drilling and fracturing the source rock to get to the trapped gas. In conventional deposits buoyant forces are enough to seep the gas into the wellbore once the cap rock is fractured. Thus, vertical drilling is the basic technique.

On the other hand, additional forces are required to flow the gas from the wellhead in unconventional reservoirs. Directional drilling expands the area covered by the wellhead. Furthermore, fracturing techniques are applied when the gas flow is not enabled either. A mixture of water, sand and chemicals at high pressure cracks the source rock.

2.2.2 Midstream

The natural gas processing and transportation to the end user, either by pipeline or by sea after being transformed into liquid form, are involved at the midstream stage.

2.2.2.1 Feed gas processing

As mentioned above the “wet gas” from the reservoir contains significant amounts of contaminants and other heavier hydrocarbons. These condensates (ethane, propane, butane, pentane, etc.) and impurities (water vapor, carbon dioxide, nitrogen, helium, hydrogen sulfide, etc.) must be removed to prevent the equipments from damages. Moreover, condensates are valuable gases that can be further marketed as natural gas liquids (NGL). As a result, a “dry gas” is obtained that meets specifications by the transportation and the end users.

The process roughly consists of the following stages:

- Slug catcher: initial separation of water and condensates.
- Removal of carbon dioxide in an amine plant and pipe back to the gas field.
- Dehydratation to prevent from ice forming.
- Removal of acid gases (H_2S and CO_2) to prevent from corrosion.
- Extraction of mercury and nitrogen.
- Fractionation of natural gas liquids (NGLs), ethane, propane, butane and pentane.

In case of small quantities of condensates and impurities, the raw gas may be purified in the production site and directly diverted to the transmission grid.

2.2.2.2 Gas transportation

The gas transportation entails a dense network of pipelines and underground storage facilities. Gas pipelines range in diameters, working pressures and materials according to their purpose (Borraz- Sanchez, 2010):

- Gathering system: many small diameter pipelines from multiple wells to either the processing plant or the transmission system.

- Transmission system: long pipelines with large diameters, made of carbon steel, from the processing plant to the distribution system or large- volume end users (power plants, large industrial facilities), working at high pressures. Compression stations are located every 100-150 kilometres to maintain the gas flow and reduce its volume increasing the transport efficiency.

- Distribution system: shorter and smaller pipelines made of cast iron or plastic, from the transmission system to the end user, working at low pressures.

On the other hand, natural gas can be stored underground to balance supply and demand. There are three main types of facilities:

- Depleted reservoirs (natural gas or oil) take advantage of the existing infrastructure and large capacity. Their location away from consumers and low flexibility are their main disadvantages.

- Natural aquifer: similar to depleted reservoirs in geology, but with higher base gas requirements (minimum operating stock), are used as seasonal balance.

- Salt cavern formations: more flexible and lower base requirements, but normally new built and with limited capacity, are used as daily balance.

2.2.2.3 LNG transportation

LNG transportation comprises the activities from liquefaction to regasification, including the corresponding transports, transfers and storages.

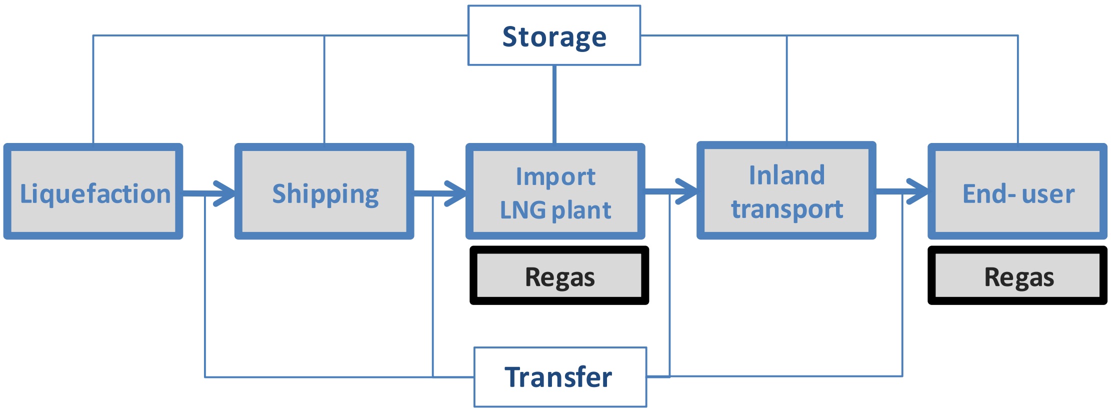


Figure 2-3: LNG transportation overview

2.2.2.3.1 Liquefaction

Liquefaction plants consist of one or more independent LNG trains entailing the following stages (Arrow, 2014):

- Removal of impurities: in addition to corrosion, the different freezing points of these components may block the liquefaction process.
- Pre cooling and fractionation of the heavy hydrocarbons. Some of them are further used in the process as refrigerants.
- Liquefaction stage is based on successive refrigeration cycles with the refrigerant compression and a heat exchanger to transfer cool into the natural gas. Depending on the type of refrigerant used in the process, two different technologies are distinguished: pure components operating on their specific ranges, and mixed refrigerants best fitting the natural gas cooling curve.
- Sub cooling to a temperature whose vapor pressure equals the atmospheric pressure.

After liquefaction LNG is stored in large tanks until being loaded into LNG carriers berthed in a jetty (breasting and mooring dolphin).

Floating liquefied natural gas (FLNG) and small- scale liquefied natural gas (SSLNG) are further developments in liquefaction. However, less efficient liquefaction technologies are used in SSLNG, such as a single mixed refrigerant or nitrogen expander (IGU, 2014). The onshore- large- scale process is presented above.

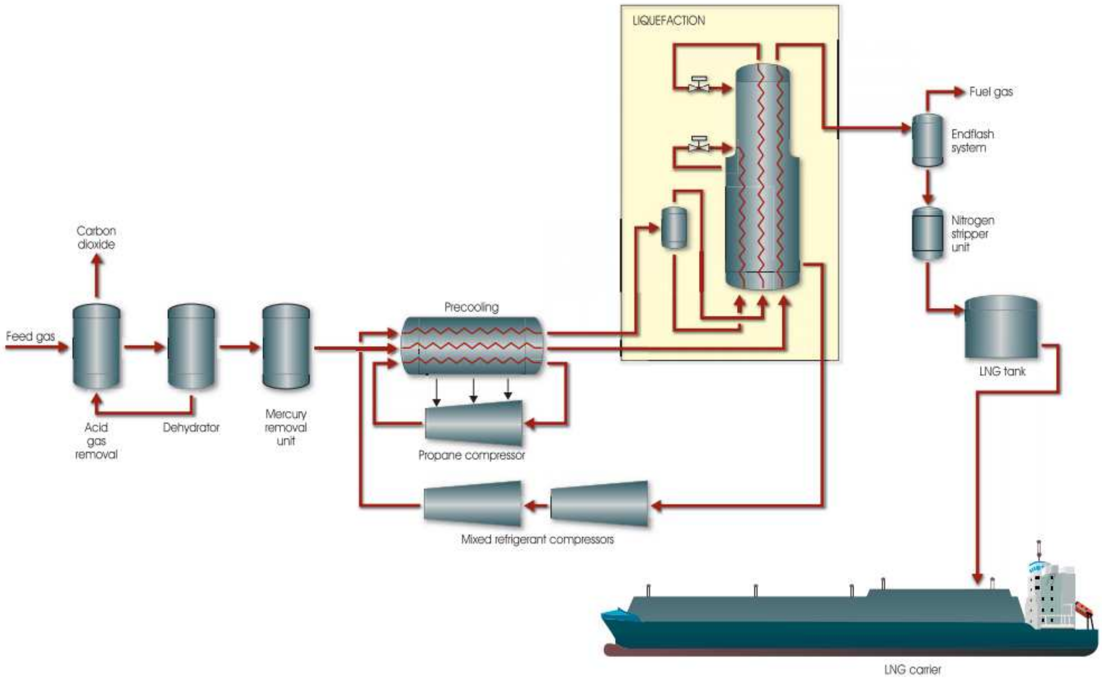


Figure 2-4: Liquefaction process (Arrow, 2014)

2.2.2.3.2 Storage and transfer

Once liquefied, LNG supply chain basically consists of successive transfers between different tanks located in fixed storage plants and mobile transport units. Both tanks and transfer equipments must work in cryogenic conditions while minimizing the heat exchange. As a result, structural materials with high toughness in low temperatures and insulation materials with low thermal conductivity are employed.

Materials used as structural barriers include 9% nickel steel, austenitic stainless steel, INVAR 36% nickel- steel alloy and aluminum alloys. On the other hand, polyurethane, polystyrene, perlite or vacuum- isolated spaces, are used as insulation solutions.

Nonetheless, heat exchange with the environment is inherent, and the LNG is constantly warming. As a result, boil off gases (BOG) are generated while the tank pressure increases accordingly. Once the maximum working pressure is reached the BOG must be vented or flared. Hence, BOG must be managed beforehand by the following strategies: use as fuel on-site (low pressure), send-out to the gas grid (high pressure) and reliquefaction.

Boil off rate (BOR) and the maximum holding time, depends on the selected insulation material. As a result, material and BOG strategy selections must match the supply chain requirements.

Transfer is a critical operation that requires to guaranteeing operational and safety conditions in the sending and receiving tank (compositions, pressures, temperatures). LNG flow is established either by a cryogenic pump or by a higher gas pressure in the sending tank. During transfer operation BOG formation increases, so that insulation of the equipments (pipes, hoses, etc.) must be addressed.

2.2.2.3.3 Transport

- **Shipping**

LNG carriers are double hulled ships, normally fueled by steam turbines and dual boilers running on oil and BOG. The typical BOR is 0.1-0.25% per day.

LNG is stored in four to six tanks, connected by pipe to the manifold. Depending on their containment system, two types of vessels are used: self supporting system (spherical Moss- type tanks) and hull supported system (membrane- type tanks). The latter is more common since containment is better adapted to the hull shape, reducing the void space.

Figure 2-5: Membrane and Moss type LNG carriers

- **Inland transport**

End- users unconnected to the gas grid require LNG inland transportation byroad. Two different types of tank trucks are available: double-walled vacuum- insulation, more robust and providing a lower BOR of 0.13% per day, and single-walled polyurethane insulation, with BOR of 1.3%.The limited holding time enables that a BOG handling strategy is not required.

In an early stage of development are also LNG railcars and tank containers, providing intermodal solutions on the LNG distribution.

2.2.2.3.4 Regasification

Once the LNG carrier is berthed in the jetty, the LNG is transferred by the ship pumps through unloading arms to the onshore tanks. The most common containment technology for large LNG tanks (150,000 m3) in receiving terminals is the full containment (Thiercault, 2013). It comprises a primary container of 9% nickel steel, a secondary of pre- stressed concrete and thermal insulation between them, so that a low BOR of 0.05% per day is achieved.

Specifically, LNG regasification process consists of two fundamental stages (Ertl et al, 2005):

- <u>BOG handling</u>: Apart from the low pressure compression into a fuel gas system, compressed BOG can be also headed to the BOG recondenser, where the heat required for the condensation is absorbed by sub- cooled LNG taken from the LP in- tank pump.

- <u>Vaporization</u>: A HP booster pump takes the LNG from the LP pump to the vaporizers. Two main technologies are used: open rack vaporizers with seawater and submerged combustion vaporizers with send-out gas as fuel. The gas is finally sent out at the required pipeline pressure.

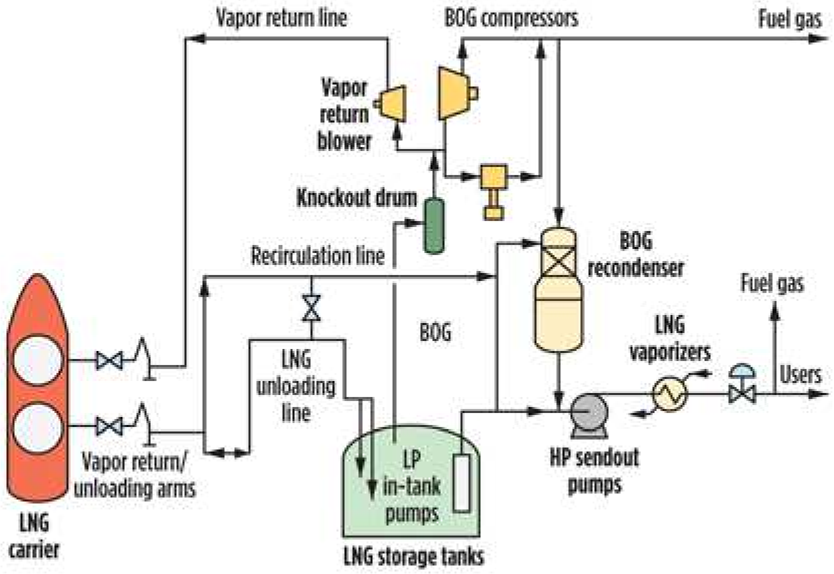


Figure 2-6: Regasification terminal flow (Lemmers, 2014)

2.2.3 Downstream

To conclude the value chain overview, natural gas is supplied to the end user and consumed by the equipments and processes either as a fuel or as feedstock for conversion into another energy carrier or non- energy product.

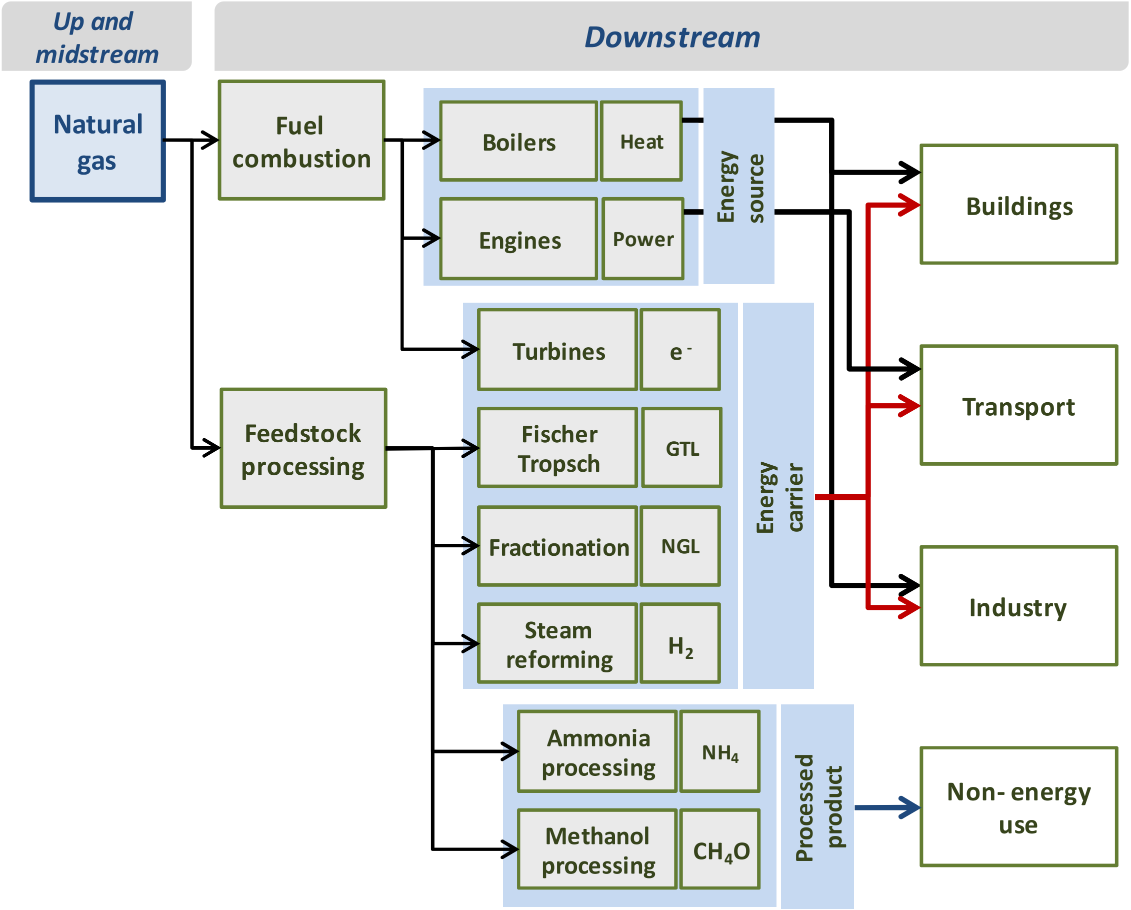


Figure 2-7: Downstream technologies (own illustration)

2.2.3.1 Natural gas a fuel

The heat carried out with the combustion products of natural gas can be transferred to the end users through different working fluids and equipments:

- Boilers**:** the heat is transferred to the feed water in a boiler obtaining hot water (residential and commercial sector) or vapor (industrial processes).

- <u>Internal combustion engines:</u> the heat is converted into work by the expansion of the combustion products
    - Otto cycle: heat transfer occurs when the compressed air is ignited by the injection of the natural gas. Such engines can run alternatively either on natural gas or gasoline.
    - Diesel cycle: heat transfer occurs when the mixture of air, natural gas is compressed and ignited by a pilot of diesel injected either before or after the compression.

<u>Turbines:</u> the heat is transferred to a working fluid whose expansion is converted into work further used to generate electricity.

- Rankine cycle: high temperature and pressure vapor from the natural gas combustion in a boiler expands through a vapor turbine to produce work.
- Brayton cycle: high temperature and pressure combustion products from the combustor expand through a gas turbine to produce work.
- Combined cycle: heat from the hot gas turbine exhaust gases can be transferred to a second vapor cycle in a heat exchanger and produce additional work.

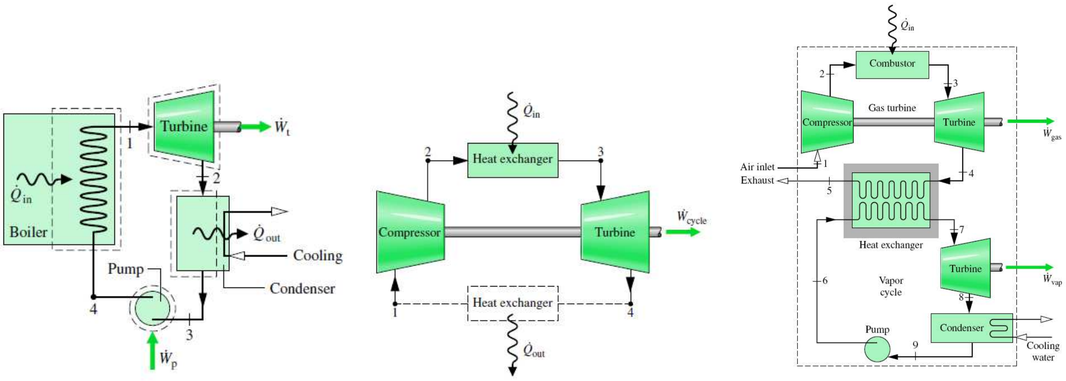


Figure 2-8: Turbine cycles (Moran Shapiro, 2006)

2.2.3.2 NG as a feedstock

Natural gas is also used as a feedstock to produce chemical organic and inorganic products and other energy carriers, similarly to the electricity generation from a combustion reaction.

- NGL fractionation: heavier hydrocarbons found in the natural gas can be cooled and condensed. Condensates such as ethane, propane or butane, are then refined in oil refineries.

- Steam reforming: steam at high pressure and temperature reacts with methane to produce hydrogen and carbon monoxide, also known as syngas. This reaction is followed by a shift conversion of carbon monoxide to recover additional hydrogen.

$$CH_4 + H_2O \rightarrow CO + 3\ H_2 - 206\ kJ/mol$$

$$CO + H_2O \rightarrow CO_2 + H_2 + 41\ kJ/mol$$

  The resulting synthetic gas, also known as syngas, is used to produce synthetic fuels and primary chemicals.

- Ammonia production: oxygen containing compounds in syngas must be removed from the hydrogen gas before reacting with nitrogen gas to produce ammonia.

$$3\ H_2 + \ N_2 \rightarrow 2\ H_2O \quad + 92.4\ kJ/mol$$

- Methanol production: syngas is converted into methanol in fixed-bed reactors at high pressure:

$$2H_2 + \ CO \ \rightarrow CH_3OH + 92\ kJ/mol$$

- Gas to liquids (GTL): syngas is converted into long- chain liquid hydrocarbons by a Fischer- Tropsch process.

$$(2n+1)H_2 + \ n\ CO \ \rightarrow C_nH_{2n+2} + n\ H_2O$$

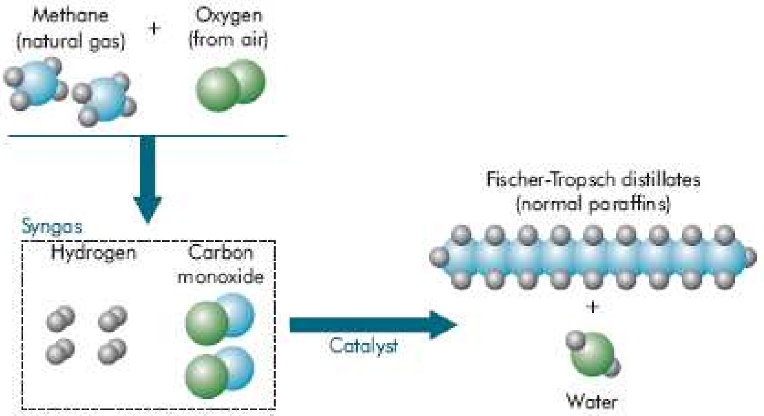


Figure 2-9: GTL process (source: IEA, 2013)

Resulting paraffinic hydrocarbons can be further cracked to produce naphtha, transport synthetic fuels (synfuels) or bases for lubricants.

Synfuels can also be obtained from methanol:

- Methanol to dimethyl ether (DME) for power diesel engines.

$$CH_3OH \rightarrow (CH_3)_2O + H_2O$$

- Methanol to gasoline (GTR): DME is further dehydrated to produce ethylene

$$CH_3O\,CH_3 \rightarrow C_2H_4 + H_2O$$

3

Natural Gas:
Market review

3 Natural gas market review

3.1 Demand

The evolution of the EU gas consumption from 1990 and three different scenarios to 2050 are shown in the figure 3-1. A downward trend is stated in recent years as a result of the economic downturn and the higher price of natural gas compared with coal in the power generation sector.

The figures are given in billion cubic meters (bcm), which is the unit commonly used in trade and production of natural gas. However, a bcm can differ in terms of energy content, depending on the supplier country. Thus, an average Russian bcm (at 15ºC) contains 38.2 PJ compared with 41.4 PJ for a bcm from Qatar. In this thesis, the Russian value is selected based on the weight of the Russian supplies for the EU.

Based on the reduction of GHG emissions achieved by 2050, EU demand projections range from about 670 bcm in the high case scenario (ETP2014 6DS) to 300 bcm in the low case scenario (ETP2014 2DS). EU consumption slightly increases from current levels at 450-500 bcm in the base case scenario (ETP2014 4DS).

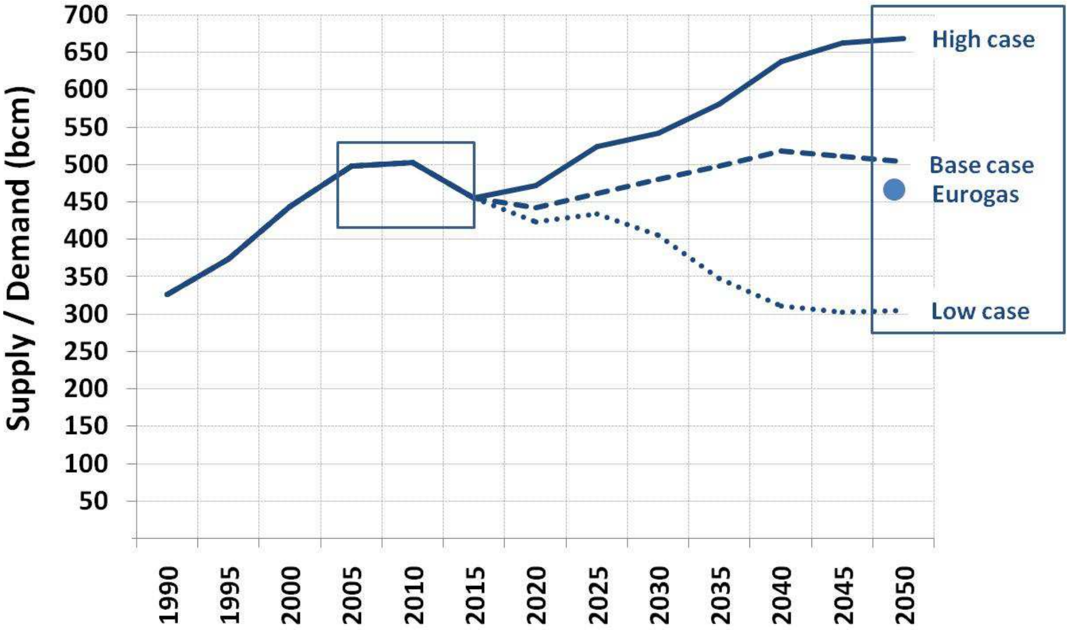


Figure 3-1: EU Natural gas demand: evolution and projections

Other benchmark projections also ranged between these upper and lower bounds, with EC Roadmap 2050 scenarios at the low end and even below in case of high RES penetration. On the other hand, European gas industry association (Eurogas) produced its own projections at 462 bcm by 2050, while complying with a reduction in GHG emissions of 82% (Eurogas, 2011)

Similar uncertainty is shown in global terms but with better perspectives, ranging between +75% in the high case and a slight decrease in the low case (-17%). As a result, Asia Pacific region is expected to gain weight in the global market at the expenses of the EU, as shown in the table 3-1.

		High case	**Low case**
	2015	**2050**	**2050**
EU	455	668	304
North America	898	1,151	522
Asia Pacific	782	2,072	919
Middle East	437	800	254
Former Soviet Union	731	946	468
Africa	118	210	210
Total	**3,421**	**5,848**	**2,786**

Table 3-1: Natural gas demand by region 2011 and 2050 (in bcm)

Primary energy demand (measured in bcm) as well as natural gas and RES share in the EU are shown in the table 3-2.

		High case		**Low case**		**Eurogas**	
	2015	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Total	1,867	1,872	1,902	1,616	1,483		
Natural gas	450	542	668	406	304	544	462
Share natural gas	**24%**	**29%**	**35%**	**25%**	**21%**		
Share RES	12%	17%	21%	26%	45%		

Table 3-2: Energy and natural gas consumption in EU (in bcm)

In order to gain insight into the EU demand and the underlying GHG emissions, a sectoral market overview is provided below, based on the compliance dimensions presented in the previous chapter (energy efficiency/ intensity, fuel substitution and post treatment of emissions).

3.1.1 Industry

Industry is a mature sector envisaged as the “business as usual”, whose contribution to the total energy related GHG emissions is around 15%.

Activity variables (indices for industrial production) are expected to remain stable, based on the acknowledgement of the role of industry in the EU economy. The sector has already made an important effort to improve the energy efficiency in the past. European industry has been exposed to a strong global competition with energy costs playing an important role in the production costs. As a result, further developments will have a limited impact.

Technologies and processes are well established in each subsector. For example, coal is largely selected in the steel and cement industries, while electricity is the first option in the aluminum industry. Thus, natural gas substitution for other fossil fuels is only expected in certain cases. Hybrid solutions combining gas and renewables are another option to research.

Further improvements in CO2 emissions can be only achieved by post treatment of emissions by promoting the development of carbon capture and storage (CCS).

In the table 3-3 energy demand in the industry sector is shown by fuel.

		High case		Low case		Eurogas	
	2015	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Total	325	342	347	294	277		
Oil	36	47	46	38	26		
Coal	55	54	58	49	47		
Electricity	98	98	99	100	90		
Heat	17	14	14	8	13		
Renewable	27	31	35	35	46		
Natural gas	91	97	96	65	54	114	112
Share natural gas	**28%**	**28%**	**28%**	**22%**	**20%**		

Table 3-3: Industry energy demand (in bcm) by fuel

3.1.2 Buildings

Buildings is another mature sector envisaged as the “business as usual efficiently”, whose contribution to the total energy related CO2 emissions is around 18%.

Relevant changes are expected neither in the European population nor in their standards of living beyond some behavior evolutions, such as a decrease in the average size of the housing stock. Demand is mainly driven by the seasonal heating consumption, which in turn is largely influenced by the climate and the number of heating degree days.

Increased efficiency is set by standards both in new buildings and the refurbishment of existing houses, limiting their energy use in terms of kWh per m2. Further improvements can also be achieved by replacing the existing equipment stock by highly efficient technologies, such as gas condensing boilers, gas and electric heat pumps and hybrid solutions.

Some of these technologies involve the fuel substitution for biofuels, electricity or district heating and cooling. Since much of the new technologies are also natural gas based its share is not expected to undertake significant changes.

In the table 3-4 energy demand in buildings is shown by fuel.

		High case		Low case		Eurogas	
	2015	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Total	501	555	618	479	479		
Oil	78	46	32	26	5		
Coal	14	10	8	3	2		
Electricity	158	193	218	174	159		
Heat	37	46	59	39	42		
Biomass and waste	48	61	78	78	133		
Natural gas	165	198	224	159	138	199	126
Share natural gas	**33%**	**36%**	**36%**	**33%**	**29%**		

Table 3-4: Demand in buildings, agriculture and others by fuel (in bcm)

3.1.3 Transport

Alternative fuels to the strong dominance of oil products must be supported in the growing transport sector, which is envisaged as the “great gas hope”. Transport contribution to the total energy related CO2 emissions is around 30%.

Transport is divided into two distinct subsectors: passenger and freight. Both are expected to continue growing until 2050 as a result of the GDP developments, with passengers performing at slower rates based on the stagnant and eventually decreasing population (EC, 2013a).

Transport mode (road, rail, aviation and navigation) selection is driven by a trade-off between mobility and cost- effectiveness. Road transport is by large the main option, 84% in passenger and 71% in freight subsector by 2010. A slight modal shift to rail transport is expected in both subsectors by 2050.

Little room for improvements on car engine efficiency is expected in existing mature technologies and fuels. Post treatment of CO2 emissions is not achievable in the transport sector.

In this context, fuel substitution is the only viable GHG compliance strategy. The EU Clean Power for Transport package aims to facilitate the development of alternative fuels for transport and their infrastructure in Europe (EC, 2013b). No single a solution is presented but a set of options, depending on the mode and range of transport, as shown in the table 3-5.

Fuel		Mode: Road-passenger			Road-freight			Air	Rail	Water		
	Range	short	medium	long	short	medium	long			inland	short-sea	maritime
LPG		▨	▨	▨	▨	▨	▨			▨	▨	
Natural Gas	LNG	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨
	CNG	▨	▨	▨	▨	▨						
Electricity		▨			▨				▨			
Biofuels (liquid)		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Hydrogen		▨	▨	▨	▨	▨			▨	▨		

Table 3-5: Coverage of transport modes and travel range by the main alternative fuels

LNG is suited for long-distance road freight and marine transport for which alternatives to oil diesel are limited. CNG is also an attractive option for light duty and passengers.

In the table 3-6 energy demand by fuel is shown. Oil is largely substituted by biofuels and to a lesser extent by electricity, with a modest share of natural gas vehicles (NGV).

		High case		Low case		Eurogas	
	2015	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Total	451	425	439	321	271		
Oil	428	395	402	274	144		
Coal	0	0	0	0	0		
Electricity	6	5	5	9	27		
Renewables	15	24	27	34	96		
Natural gas	1	2	4	4	4	28	33
Share natural gas	**0.3%**	**0.5%**	**0.9%**	**1.4%**	**1.6%**		

Table 3-6: Transport demand by fuel (current and projections)

As a result of the increasing interest on substitution potential for natural gas in the transport sector, a number of organizations have developed their own outlooks. The forecasts range from the IEA’s conservative projections (3.8 bcm by 2035) to the optimistic European Expert Group on Fuels for the future (EEGFTF) (43 bcm by 2030), as shown in the table 3-7 based on (Le Favre and Madden, 2014).

	2015	**2020**	**2025**	**2030**	**2035**
IEA road only					3.8
Citi Base	3.0	5.0		8.0	
Eurogas	3.0		7.0		16.0
EGF baseline	1.2	1.5		2.9	
EGF alternative	1.3	2.6		14.0	
EEGFTF/NGVA		24.0		43.0	
DMA marine only	3.0	6.0		10.0	

Table 3-7: EU demand for gas in road transportation (in bcm) (Le Favre and Madden, 2014)

According to the large potential and disparity between studies, a deeper insight into the transport sector is taken in the present thesis.

Energy demand by transport segment is expressed in bcm in the table 3-8. As mentioned above, the greatest potential for natural gas is likely to be the heavy duty vehicles (HDV) and marine segments, ranging by 2050 between 120 and 150 bcm depending on the scenario.

	2011	2050 High case	2050 Low case
Total	**444**	**439**	**271**
Passenger	**267**	**249**	**127**
Freight	**177**	**190**	**144**
Light road	41	41	28
Rail	2	2	3
Heavy road	**70**	**78**	**52**
Shipping	**64**	**69**	**62**

Table 3-8: Energy consumption by transport segment (in bcm)

The factors driving the fuel selection are environmental regulations and economics.

<u>Regulations:</u>

- **HDV:** current regulations focus on NOx emissions and particulate matter based on Euro VI (EC, 2009), with CO2 emissions only intended for cars and light duty vehicles.

- **Marine:** the MARPOL Annex VI (IMO, 1997) introduced regulation on fuel sulfur content and NOx emissions, both globally and for more stringent areas, or emission control areas (ECA). In the EU, the North Sea and the Baltic Sea were designated sulfur ECAs. As a result, sulfur content from 2015 is limited to 0.1%, as shown in figure 3-2. Future ECA adoption in the Atlantic and Mediterranean Sea is under discussion. Compliance alternatives comprise: install scrubbers to remove SOx from exhaust gases, shift to expensive marine gasoil (MGO) or move to LNG. Based on future NOx and GHG regulations.LNG is considered a promising option.

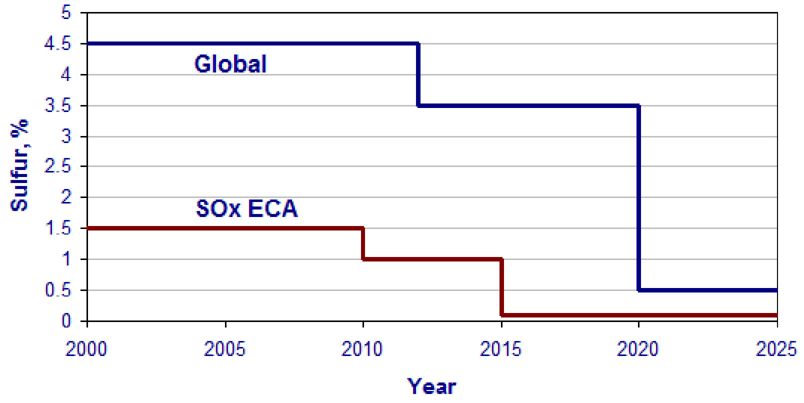


Figure 3-2: Fuel sulfur content calendar

<u>Economics:</u>

According to the structure introduced in the chapter 1, following components are considered when comparing different fuels:

- Fuel price: price differentials with competing fuels are shown in figure 3-3. Price spreads with oil gasoil and fuel oil are expected to remain stable.

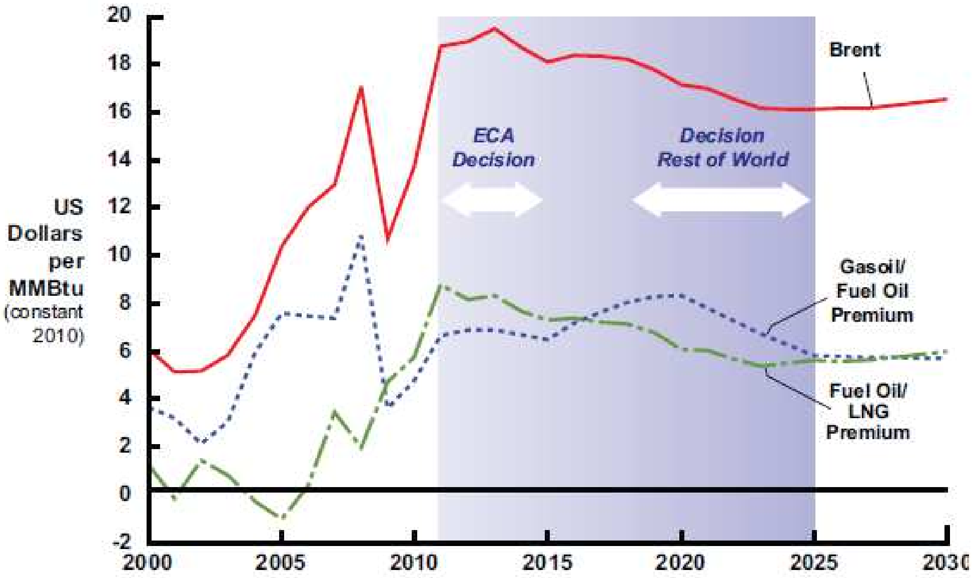


Figure 3-3: Fuel price differential outlook (in $/MBtu)

- Distribution costs: infrastructure deployment is a key issue to be addressed and break the egg and chicken dilemma. Insufficient refueling stations inhibit growth in new vehicles, which in turn inhibits investment in new stations.

According to the initial poor economies of scale, subsidies might be used during the phase out stage. Trans- European Transport Network (TEN-T) funding is available both for construction of infrastructure and feasibility studies (NGVA, 2013).

- Taxation: favorable excise duties for natural gas in HDV play an essential role today, unexpected to be maintained in case of a large scale switching. Taxation is not applicable in the marine segment.
- Capital expenses: Upfront costs premium, both in case of new- building and retrofitting of existing, should be reduced as improvements on gas engine technology are developed.
- Operating expenses: lower energy density of natural gas means the necessity of larger tanks, comprising the space in the vehicle.

Natural gas penetration will basically depend on the extent to which price discount outweighs the cost of gas- powered vehicles or vessels (OIES, 2014a).

Transitions driven by fuel economics over policy changes typically follow an S Curve (logistic function) (Yuen, 2014).

In the absence of reliable substitution logistic models in the literature a simple approach is proposed, assuming an asymptotic limit of growth of 50% in marine and 25% in the HDV segment, according to the simple logistic curve (Kucharavy and De Guio, 2008)

$$S(t) = \frac{A}{1 + e^{-\alpha \cdot (t - t_0)}}$$

Where *S(t)* is the new entry share in the year *t*, *A* is the asymptotic limit, α is the “width“ of the S- Curve and t_0 is the initial year (2015).

Yearly entry shares in both segments are depicted in the figure 3-4 as well as the demand, considering a time replacement of 20 years in marine and 10 years in the HDV segment.

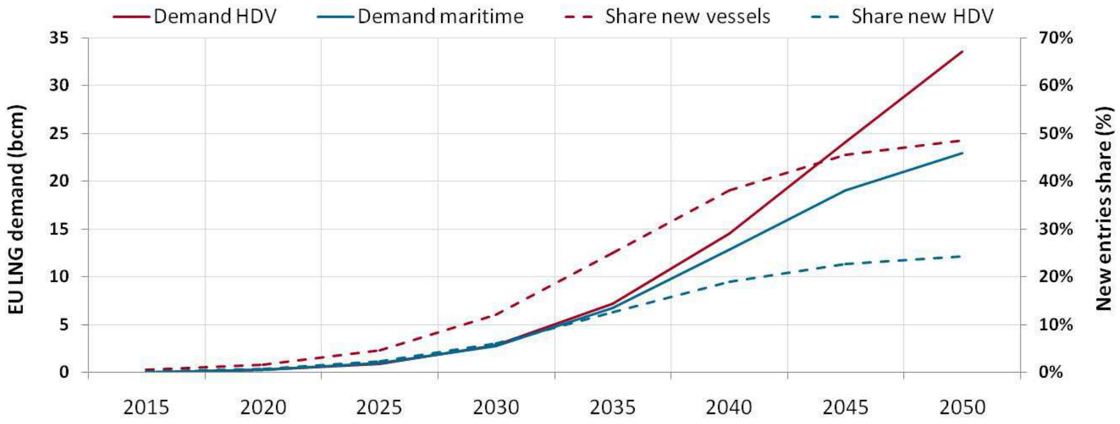


Figure 3-4: Natural gas demand in Europe (own illustration)

3.1.4 Power generation

Power generation is the sector where more fuels and technologies are competing and therefore envisaged as the *"Battleground"*. Power contribution to the total energy related CO_2 emissions is around 35%.

Power demand is driven by the previous sectors and the underlying activity variables, where electricity is the best option.

With the nuclear power being limited by political decisions and the deployment of renewable sources constrained by mostly higher costs and intermittence, fossil- fired plants will continue to be a base load and backup capacity. Natural gas competition with coal will strongly depend on fuel and emission prices. A higher efficiency and flexibility together with the lower capital costs are the main advantages of combined cycle gas turbines.

Further improvements in CO_2 emissions can be only achieved by post treatment of emissions by promoting the development of CCS.

In the table 3-9 energy demand in the power sector by fuel is shown.

		High case		Low case		Eurogas	
	2015	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Total	779	723	690	670	650		
Oil	23	8	1	4	0		
Coal	239	152	66	35	10		
Nuclear	259	202	121	262	213		
Renewable	110	182	252	242	369		
Natural gas	148	179	249	128	58	162	203
Share natural gas	**19.0%**	**24.7%**	**36.1%**	**19.0%**	**8.9%**		

Table 3-9: Power generation demand by fuel (in bcm)

To conclude the section, natural gas demand by sector in the high and low case scenarios is summarized in the table 3-10.

		High case		Low case	
	2015	**2030**	**2050**	**2030**	**2050**
Industry	91	97	96	65	54
Buildings	165	198	224	159	138
Transport	1	2	4	4	4
Power generation	148	179	249	128	58
Non energy and losses	44	67	96	50	49
Total	450	542	668	406	304

Table 3-10: Natural gas demand by sector and scenario (in bcm)

3.2 Supply

The magnitude of existing global resources (discovered and undiscovered) has been estimated by (Aguilera et al., 2014) using a variable shape distribution model (VSD) in some 20,000 Tcm (trillion cubic meters), most of them being unconventional endowments (shale gas, tight gas and coal bed methane). In addition, vast volumes from natural gas hydrates could also be included once commercial production has been proven.

However, ultimately recoverable resources in discovered fields account for round 800 Tcm, being economically recoverable under current conditions some 200 Tcm (IEA, 2013). Thus, available proven reserves are enough for over 60 years at current production levels (3,500 bcm per year), in line with oil but well below the coal ratio, as shown in the figure 3-5.

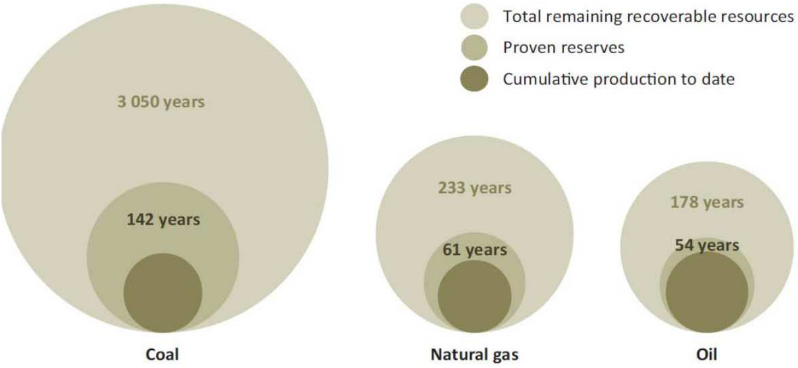


Figure 3-5: Resources, reserves and cumulative production

As long as natural gas consumption continues growing in the coming years, proven reserves are expected to grow accordingly, based on the correlation between both variables over the past decades stated in (Shafiee and Topal, 2008).

Production costs differ considerably between conventional and unconventional reserves. The most easily accessible part of the remaining conventional resources amounts to about 220 Tcm, with typical production costs ranging between 0.20$/MBtu and 9$/MBtu. Unconventional resources totaling 330 tcm (including 80 tcm tight gas, 200 tcm shale gas and 50 tcm CBM) could be produced at costs between 3$/MBtu and 10$/MBtu, as shown in figure 3-6.

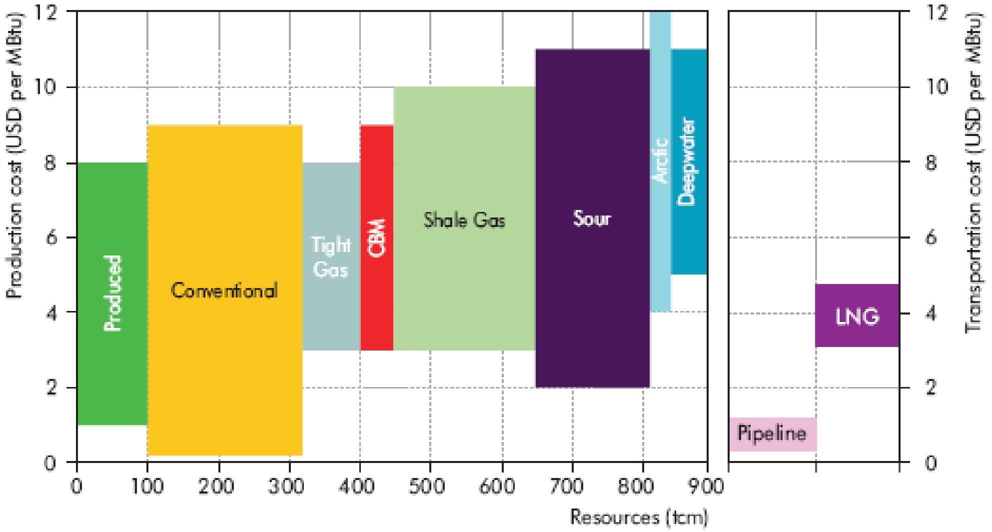


Figure 3-6: Long term gas supply cost curve (IEA, 2013)

Conventional reserves are not equally distributed by region, with the main consuming regions (Europe, North America and China) depleting their reserves by 2035 at their current consumption rate, as outlined in figure 3-7.

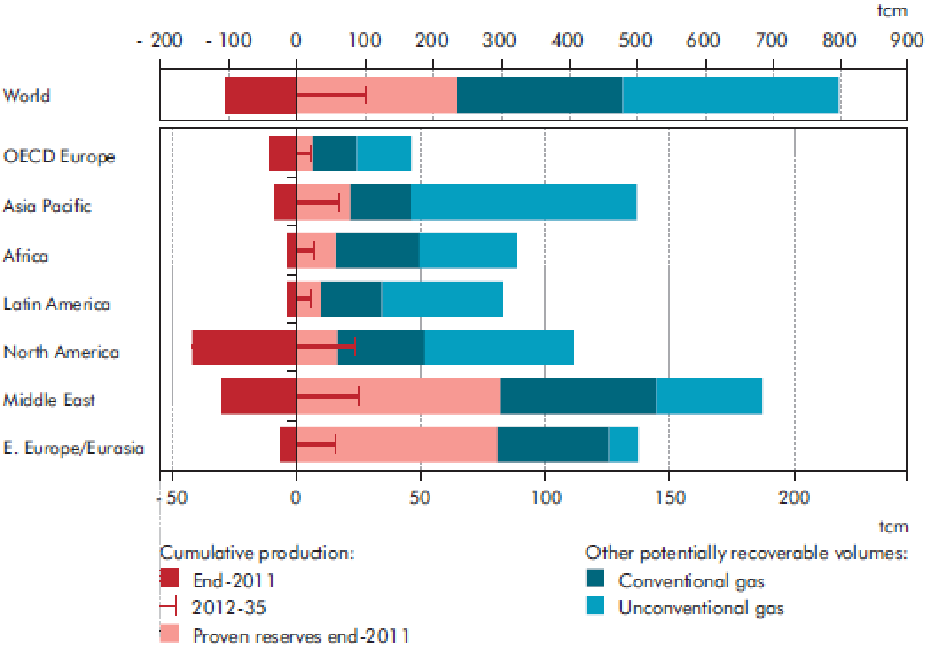


Figure 3-7: Cumulative production, proven reserves and resources by region (IEA, 2013)

While conventional resources are mainly located in the Middle East and the Former Soviet Union (FSU), unconventional resources are spread worldwide including those consuming areas. However, in Europe it is still uncertain the actual unconventional potential under environmental regulation requirements.

Depending on the demand pathway to 2050 security of supply will be a real issue amid declining volumes from the North Sea, even though Norwegian imports are considered. As a result, current domestic shares at 60% will only remain stable in the low case scenario, being required new supplies for the rest of scenarios. Thus, in the high scenario less than a 30% is produced in the North Sea, as shown in the figure 3-8.

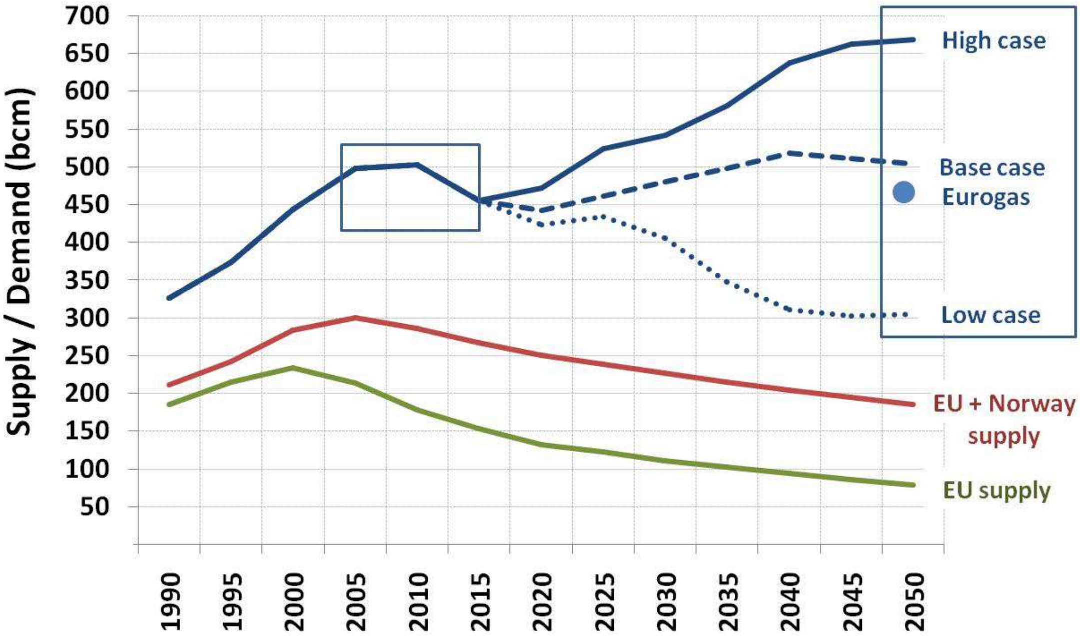


Figure 3-8: EU demand and domestic production (including Norway)

In this environment, the EU must attract gas supplies from the global markets. Net importers and net exporters on a regional basis in 2015 are derived from figure 3-9 (Timera, 2015), with Europe and Asia competing for Russia and Middle East surplus.

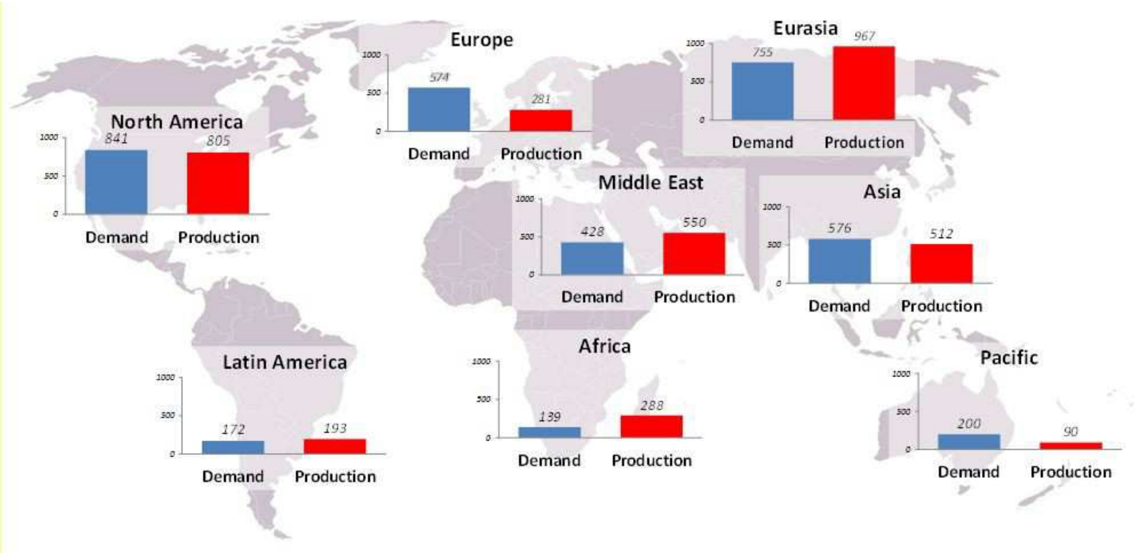


Figure 3-9: Supply and demand by region in 2015 (Timera, 2015)

Depending on the quantities transported and the distance to market, it may be more cost-effective to transport gas via pipeline than converting it to LNG, as illustrated in Figure 3-10. At short distance gas will be transported via pipeline, while for large gas fields, large distances can be covered through LNG. If the field is large enough, intermediate long-distance pipelines can still be more cost-effective than LNG. In some instances, neither pipeline nor LNG is cost-effective, which leaves the gas resource "stranded" (IEA, 2013)

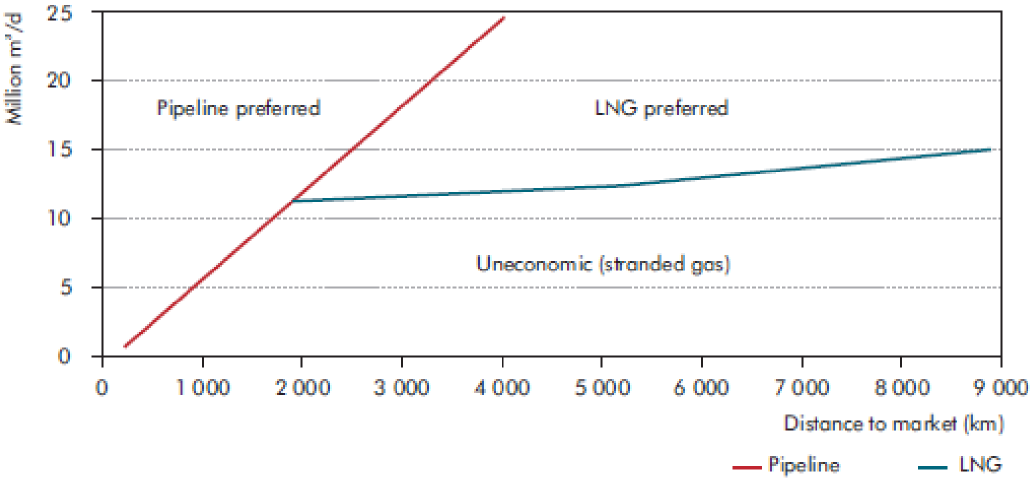


Figure 3-10: Preferred transportation mode by volume and distance (IEA, 2013)

3.3 Logistics and infrastructure

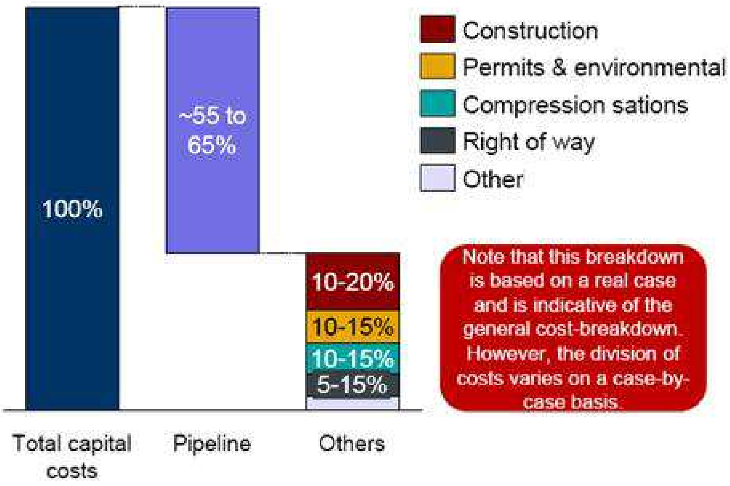
Natural gas transportation, either by pipeline or by LNG tankers, requires large up-front investments. The initial infrastructure capacity and capital expenses (CAPEX) related to the components in the natural gas supply chain are reviewed below.

3.3.1 Pipelines

Pipeline design capacity depends on the diameter and the operating pressure. With the practical limit in pipe diameter being approached at 48 inches, future capacity expansions must be achieved by increases in operating pressure (natgas.info).

The length of the EU high pressure pipeline network by 2013 reached 247,136 kilometres (ENTSOG, 2014), with a current cross- border import capacity with non- EU countries of about 450 bcm.

Despite the importance of non-pipeline-related, pipeline cost is the main driver in project economics as shown in figure 3-11 (SBC, 2014).



Note that this breakdown is based on a real case and is indicative of the general cost-breakdown. However, the division of costs varies on a case-by-case basis.

Figure 3-11: Pipeline cost breakdown

Investment capital expenses vary significantly between projects, depending on the diameter, operating pressure, length and terrain. Average costs for ongoing projects in US have come down in recent years from 3.6 million $ per kilometre in 2009 to 1.9 in 2013.

3.3.2 Liquefaction

Liquefaction plants comprise one or various trains with a typical capacity of 4-5 MTPA (million tons of LNG per annum).

Global nameplate capacity reached in 2013 was 291 MTPA (393 bcm). However, several liquefaction plants under construction will come online by 2018 to reach a capacity of about 400 MTPA (540 bcm) with the distribution by region shown in the figure 3-12 (IGU, 2014).

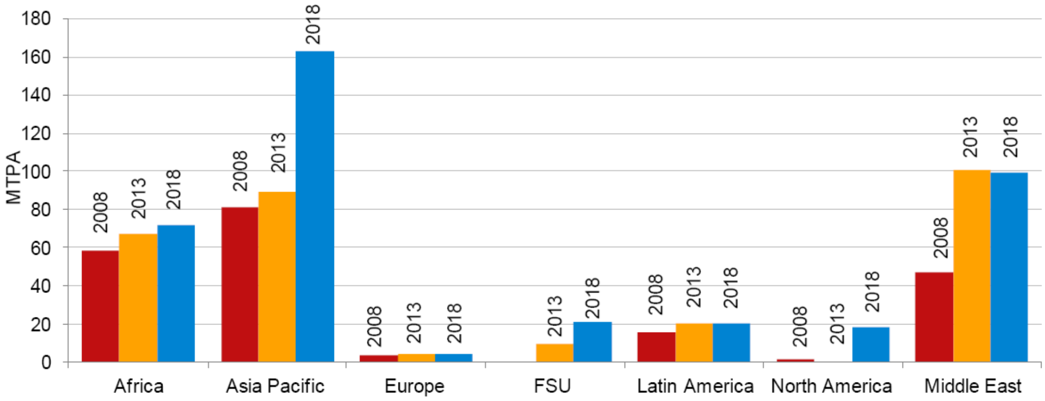


Figure 3-12: Liquefaction capacity by region in 2008, 2013 and 2018 (IGU, 2014)

Half of the liquefaction CAPEX is not directly related to liquefaction, such as off sites (storage, jetty and flare) or utilities (power generation, fuel gas, etc.). These costs are shared in case of multiple trains (brown field projects).

CAPEX has dramatically escalated after 2004, as shown in figure 3-13. However, it should be distinguished high- cost projects identified by complex designs in remote locations (mainly in Australia) and normal cost projects located in industrialized areas with good infrastructure and access to competitive construction resources (OIES, 2014b).

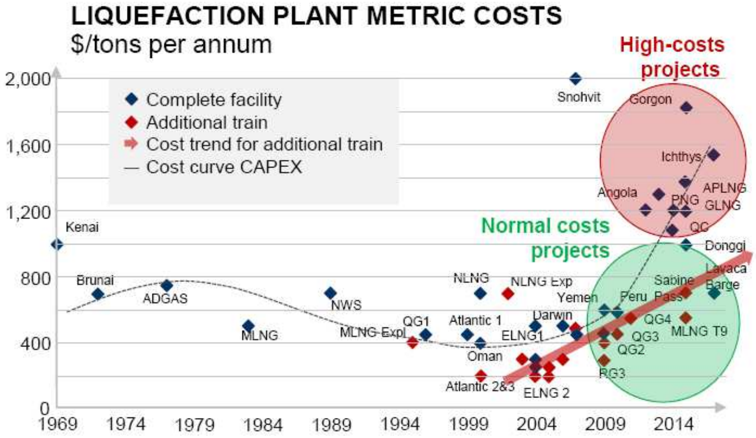


Figure 3-13: Evolution of the liquefaction plant costs (OIES, 2014b)

3.3.3 Shipping

Most existing LNG carriers are conventional sized round 120,000- 140,000 m3. However, a new generation of LNG mega- ships (Q-max and Q-flex) take advantage of the economies of scale created by their size (210,000 and 267,000 m3). The global fleet of 357 carriers amounted to a combined capacity of 31 equivalent bcm by 2013.

Shipping costs are determined by the ship rate, fuel costs and port fees. Additionally canal crossing fees (Panama or Suez) must be also accounted depending on the route.

Daily shipping rate, also called time charter, is a function of the LNG carrier market which is set by the demand (LNG trade and infrastructure capacity through the LNG supply chain) and supply (existing fleet, newbuilding orderbook and shipbuilding capacity struggling with the broader shipping industry). Every incremental 1 bcma requires between 1.5 and 2 LNG carriers to service. New building asset values have remained relatively unchanged in the time period 2009-2013 at approximately $200 million per vessel (Jefferies, 2013). As a result of the moving supply and demand conditions, short term rate (spot market) are highly volatile. Peaking at 150,000 $ per day early 2012 ship rates plummeted to less than half in mid 2014 (65,000 $).

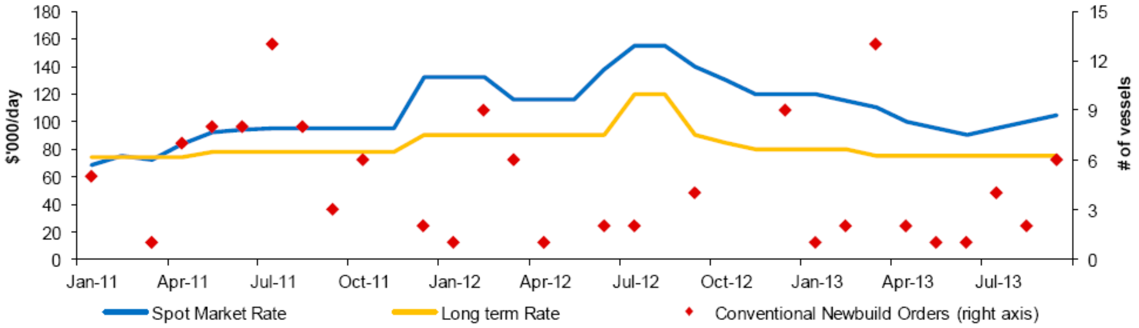


Figure 3-14: Estimate LNG charter rates and newbuilding orders (IGU, 2014)

Fuel costs depend on the ship consumption rate, estimated in 160 tonne per day, and the highly volatile fuel prices. At current prices of 600$ per tonne, a daily fuel cost close to 100,000$ can be assumed. In addition, LNG evaporation losses produce a boil-off cost of as much as 400,000$ per round trip, considering a boil off rate of 0.2% per 1,000 kilometre. Finally, fixed costs are charged in ports, amounting to 200,000$ per port call (IGU, 2014).

3.3.4 Regasification

The regasification plant capacity is expressed in terms of send out volume, either in GWh per day or in annual bcm. Global LNG receiving capacity by 2013 was 935 bcm, 200 bcm being located in the EU and distributed between Iberian, Mediterranean and Atlantic areas as shown in the table 3-11.

Atlantic excluding Iberia		**Mediterranean excluding Iberia**		**Iberia**	
Plant	**Capacity (bcm)**	**Plant**	**Capacity (bcm)**	**Plant**	**Capacity (bcm)**
Zeebrugge	9	**Fos Tonkin**	3	**Barcelona**	17.1
Montoir	10	**Fos Cavaou**	8.25	**Huelva**	11.8
Rotterdam	12	**Panigaglia**	3.4	**Cartagena**	11.8
Grain	19.5	**Levante**	6.56	**Bilbao**	8.8
Milford Sth. Hook	21	**Toscana**	3.75	**Sagunto**	8.8
Milford Dragon	7.6			**Mugardos**	3.6
Teeside	4.2			**El Musel**	7
Dunkerque	13			**Sines**	7.9
Total	**96.3**	**Total**	**25.0**	**Total**	**76.8**

Table 3-11: LNG receiving plants in the EU by region

Large regasification CAPEX escalations are expected over the next three years. The weighted average unit cost of onshore regasification coming online in 2013 based on a three-year moving average was $192/tonne of import capacity; that same number in 2016 is expected to be $274/tonne, as illustrated in the figure 3-15. The rise in onshore regasification costs has recently mirrored the trend in increased storage capacity; as countries add larger storage tanks to allow for higher imports and greater supply stability, the average storage capacity per unit of regasification capacity has increased (IGU, 2014).

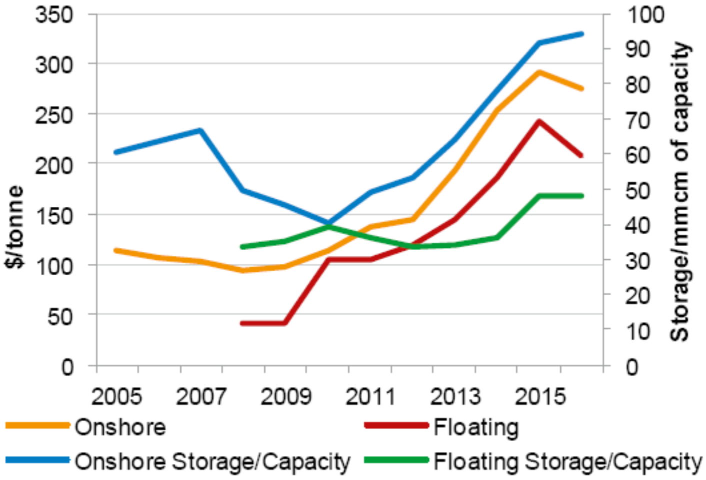


Figure 3-15: Regasification costs based on project start dates (IGU, 2014)

3.4 Pricing

Two main pricing mechanisms are used to trade natural gas internationally (Carnegie, 2010):

- Gas on gas competition, based on local trading hubs, such as Henry Hub in US, National Balance Point in UK and some emerging hubs in Europe.
- Oil indexation, based on the prices of other commodities (diesel, fuel oil, etc.)

Oil indexation pricing is more common in the LNG business in order to reduce risks on the required high upfront costs, such as Asia imports. Gas on gas competition is increasing its share progressively since markets become more liquid, such as North America. Europe is moving from the oil indexed formula to a hub- based pricing by enhancing transparency and non- discriminatory access to the gas transmission network.

As a result of these different mechanisms and the existing long- term rigid contracts and considering some disruptions in the last decade (shale gas boom, increasing demand in Asia and economic crisis in Europe) significant price differences are driven among the regional markets well above transportation costs, as shown in the figure 3-16.

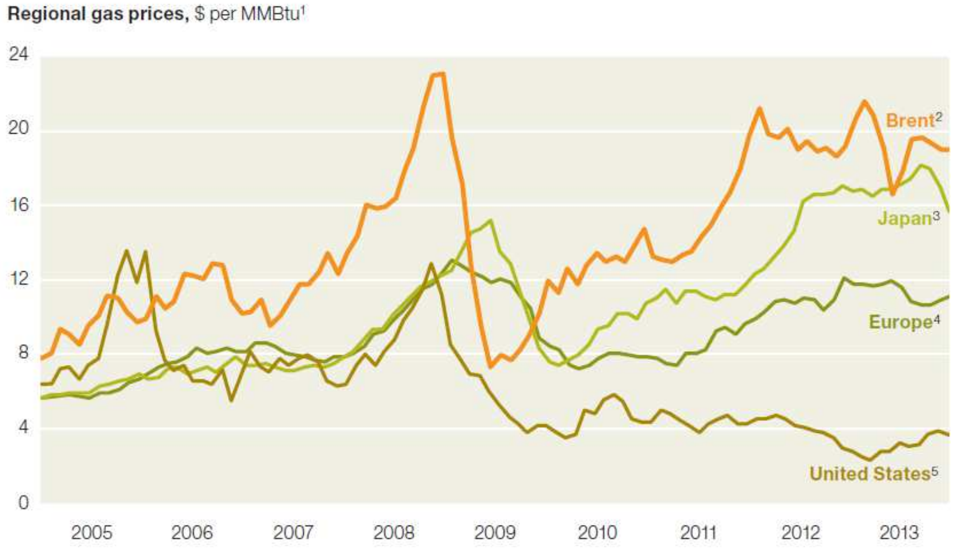


Figure 3-16: Regional gas prices evolution (Mc Kinsey, 2014)

4

Objective

4 Objective

As stated in the previous chapters natural gas is expected to be a transition fuel in the energy system, exposed to an increasing uncertainty both from the market and the supply chain. These events will be particularly challenging in Europe with the production in the North Sea declining and the unpredictable situation in the pipeline partners (Russia and North Africa).

The security of supply and the underlying competitiveness of European economy will strongly rely on the ability to diversify the imports among multiple sources. As a result, entry connection points at LNG plants and cross border pipelines with non- EU countries are essential gateways to the natural gas global network.

A general overview is provided in the figure 4-1 with all major regions, entry connections into the EU and the Iberian sub region being represented.

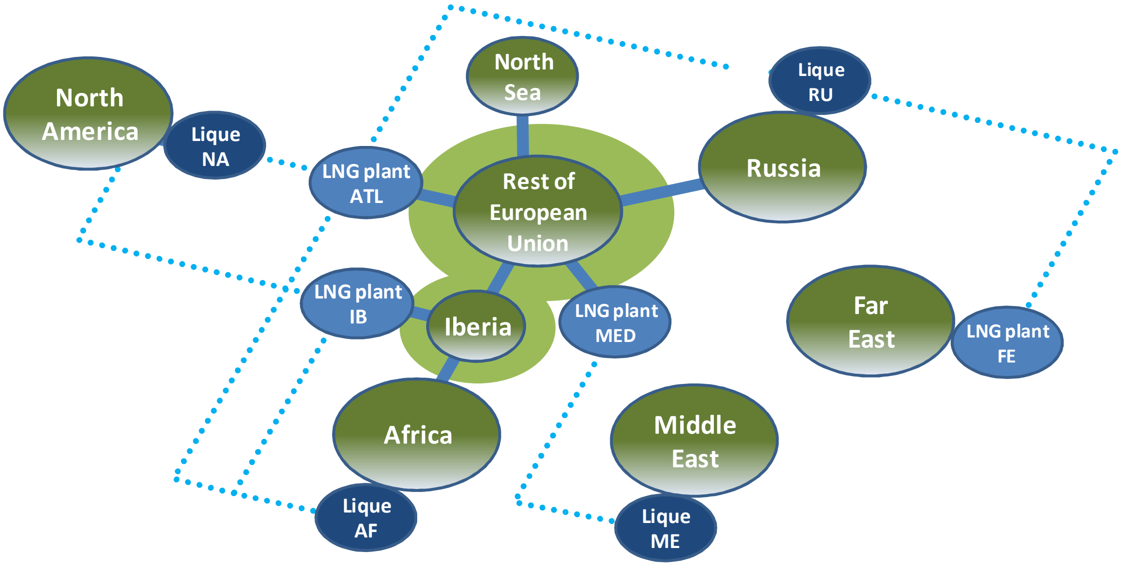


Figure 4-1: Natural gas global market overview (own illustration)

The strategic role of the Iberian infrastructures as a gateway to the African supplies and LNG imports has been broadly agreed, and recently stated by the Madrid declaration (Madrid, 2015).

On the other hand, cross border interconnections within the EU enhances integration into the targeted single market, while ensuring an efficient use of the existing and projected gas network. A supportive environment for infrastructure investment must be ensured and accompanied by EU financing instruments (IEA, 2014a).

The selection of new infrastructures is taken under high uncertainty conditions over supply and demand future conditions, with projections varying significantly between 304 and 668 bcm, as stated in the market review in the previous chapter.

As a result, decision making must be aided by support systems that combine the use of models, analytical techniques or data access.

<u>Thesis objective:</u>

*To build the model **IB**erian **EU**ropean **GAS** facility (IBEUGAS), which based on the existing infrastructures and a set of market scenarios, optimizes the deployment of the future European infrastructures within the period 2015-2050. The Iberian sub region is emphasized in order to screen the role of this sub region and its interconnection with the rest of the Europe.*

5

Methodology

5 Methodology

Once identified the system and the importance of using a model, IBEUGAS specification is aimed in this chapter.

5.1 Framework

Natural gas market and the underlying transport infrastructures are commonly represented as a network, where the commodity flows through a set of nodes and arcs following the spatial equilibrium logic.

"A good which is mobile move from the market where its value is lower to the market where its value is higher, until the differences of values are not larger than transportation costs" (Cournot, 1838).

In the figure 5-1, the price in the market 2 P_{2i} is higher than in the market 1 P_{1i}. Since the price difference is larger than the transport costs (TC) between the markets, the volume x_{12} is traded from the market 1 to the market 2. As a result, the price in the market 2 P_{2f} decreases and the price in the market 1 P_{1f} increases.

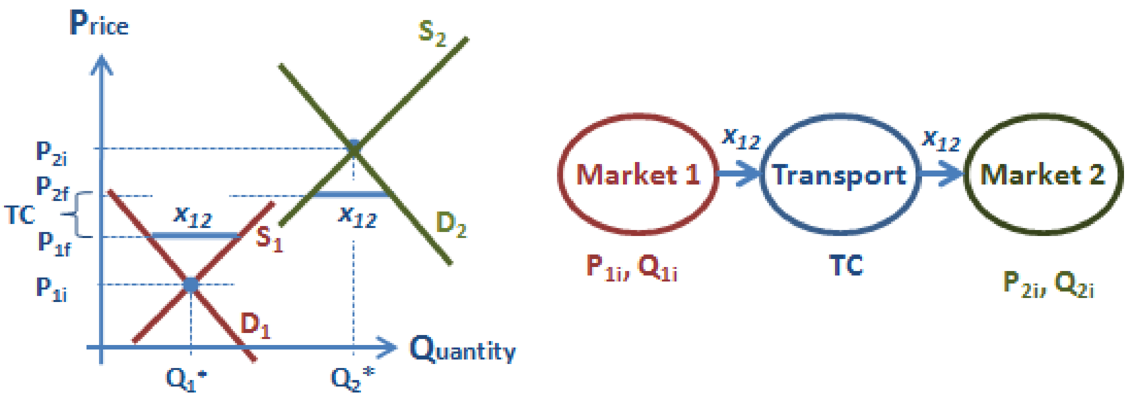


Figure 5-1: Spatial equilibrium logic

The system to be represented is characterized by the following dimensions: commodity, market, transport, time and uncertainty. How all these dimensions are depicted in the model is defined by two properties:

- Size (number of entities by dimension)
- Extent (degree to which the dimensions are represented in these entities).

Assumptions will be taken in both properties while complying with the thesis objective.

Firstly, the size depends on the targeted level of detail. Thus, for example a supply node can represent from a single gas field to all the projects in a given country or an entire region. A basic model has been assumed in the model, representing the main global regions and the Iberian sub region within the EU.

Unlike general equilibrium models, which represent the interaction between markets of different related commodities (oil, coal, electricity, etc.), partial equilibrium only considers single markets. Although correlation between the commodity markets is present in real world (fuel substitutions, natural gas price indexation to oil products, etc.), the model in the present thesis is formulated as a partial equilibrium problem in terms of *gas on gas competition*.

Such a pricing mechanism is driven by the prevailing market structure, or in other words, the interaction between the different market agents and the way they exert their power. In the natural gas markets the Cournot oligopoly is the most representative structure (Holz, 2009), with the strategic behavior of the competitors being commonly modeled by game theory. However, a perfect competitive market is assumed in the model, where prices and quantities are determined endogenously from the supply and demand curves.

Time dimension granularity also defines the model framework. Few large time periods are used in static models where each period is independently optimized, normally on a yearly basis. In addition, variables at different timeframes are related in the intertemporal models so that planning problems can be represented. As the time granularity grows scheduling and storage can also be depicted. A model with intertemporal investment decisions has been selected.

Since a long term timeframe is aimed in the model, every parameter faces a high uncertainty, fitted by different distribution functions. Such a stochastic dimension can be worked out by providing different scenarios, managed either inside or outside the optimization model.

Under the previous assumptions the system is represented by ***a basic inter temporal spatial equilibrium model with perfectly competitive markets.***

5.2 Literature

Two different techniques can be used to represent the system depending on the extent to which previous dimensions are depicted in the model.

Complex stochastic systems evolving over time are normally modeled by simulation (Hillier and Lieberman, 2005). Applications are found in multiple areas, financial risk analysis, distribution systems or manufacturing systems (Fernandez, 1999). On the other hand, the system can be expressed in a mathematical notation and optimized by an algorithm programming. This approach is used in the thesis model.

A growing interest in modeling has been stated in recent years to improve the understanding of natural gas markets, with a range of research teams developing models applied to strategic and policy issues (IAEE, 2009).

Three different approaches can be distinguished in this task:

- Transport problem solved by linear programming (LP). The objective is to minimize the supply costs (production, storage and transport costs) given the supply and demand volumes by region. Different models have developed by the Institute of Energy Economics at the University of Cologne (EWI), such as the Intertemporal infrastructure optimization in EUGAS, the dispatch optimization in TIGER (Lochner, 2009) and the extension to a global perspective in MAGELAN (Seeliger, 2006).
- Spatial equilibrium problem solved by non linear programming (NLP). The objective is to maximize the global welfare assuming a perfect competitive market. An example is found in (Neuman et al., 2011) where cross border capacity bottlenecks in the European Natural Gas markets are analyzed.
- Strategic behavior of the market players (producers, traders, etc.) solved by mixed complimentary programming (MCP). The objective is to maximize the profit of the different players. This is the approach which more attention has gained in the last years with multiple teams modeling the natural gas market at

different geographical levels: global, European (Holz, 2009) or Australian (Wagner, 2014), among others.

To my knowledge previous works have not emphasized yet the Iberian natural gas interconnection using a spatial equilibrium model.

5.3 Formulation

The model is further defined on a set of dimensions in order to determine certain variables given certain parameters and restrictions.

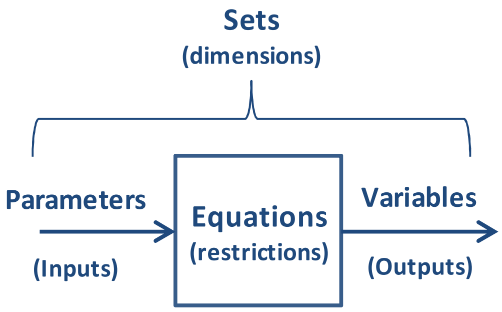


Figure 5-2: Model backbone

Optimization problem:

Given a function $f: A \rightarrow R$ from a subset of R^n to the real numbers

Search: an element x_0 in A such that $f(x_0) \geq f(x)$ for all x in A

5.3.1 Dimensions

As stated in the framework the system is represented as a network of nodes and arcs. An example of such a natural gas supply chain is shown in the figure 5-3.

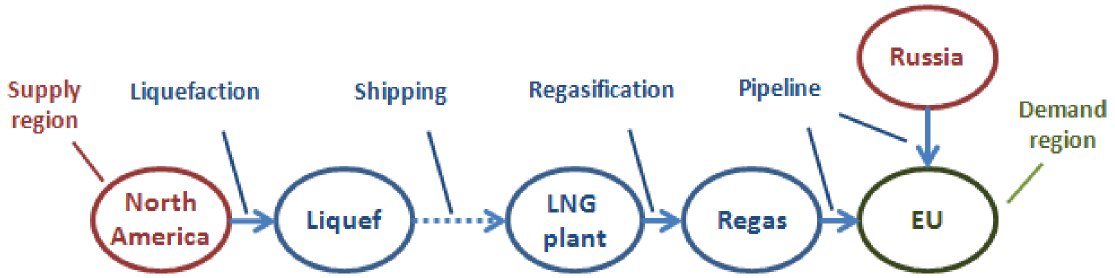


Figure 5-3: Natural gas supply chain

The nodes represent different positions in the natural gas supply chain: regions and transit nodes. Each region can be either a supplier or a consumer, or both of them.

- Supply region node: natural gas is produced and available for transportation.
- Demand region node: natural gas is available for consumption.
- Transit node: natural gas is located between two transitions.

The arcs represent in turn the transitions between the nodes:

- Natural gas transmission by pipeline,
- LNG transportation by sea,
- Natural gas state transformation, liquefaction or regasification.

Some transitions are considered unlimited while upper bounds are applied to the others. Furthermore, arcs related to the targeted infrastructures must also be distinguished in the model.

The modeling horizon 2015-2050 is divided into discrete time periods. Different timeframes have been selected in the optimization problem for the transport and the investments on infrastructures.

Finally, stochasticity is added to the model by considering different scenarios and the corresponding distribution function, defined by each scenario probability.

Selected sets and subsets in the model are illustrated in the table 5-1.

Set	Subset	Definition
n		nodes
	dr(n)	demand regions
	sr(n)	supply regions
arc (n, np)		arcs
	limited (arc)	bounded arcs
	targeted (arc)	targeted arcs
t		modelling time
	p	infrastructure planning period
sc		scenarios

Table 5-1: Model sets

5.3.2 Parameters

Parameters represent the model inputs, which are defined either as constants or as function of one or various sets.

Market:

Price equilibrium in perfectly competitive markets are characterized by their supply and demand curves, which are estimated for each region, time period and scenario, assuming a reference point *(P*, Q*)* and the corresponding price elasticity *(ε)*.

The price elasticity is defined as the response of the demand (alternatively, supply) to a change in its price. Elasticities are considered independent of the region and time period in the model. Unlike the supply curve, the demand curve has a downward slope and negative price elasticity, as stated in the figure 5.4 and the mathematical notation.

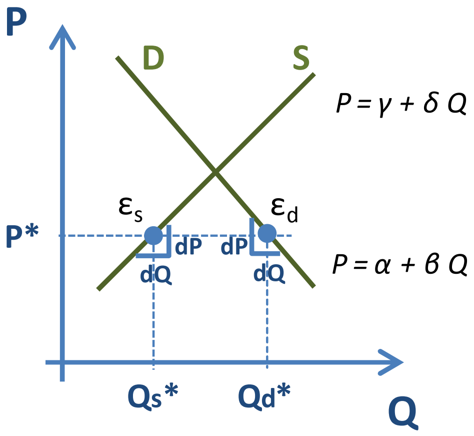


Figure 5-4: Linear supply and demand curves

$$\varepsilon = \frac{dQ}{dP} \cdot \frac{P}{Q}$$

$$\boldsymbol{P} = \gamma + \ \delta \cdot Q = P_s^* \cdot \left(1 - \frac{1}{\varepsilon_s}\right) + \frac{P_s^*}{Q_s^*} \cdot \frac{1}{\varepsilon_s} \cdot \boldsymbol{Q}$$

$$\boldsymbol{P} = \alpha + \ \beta \cdot Q = P_d^* \cdot \left(1 - \frac{1}{\varepsilon_d}\right) + \frac{P_d^*}{Q_d^*} \cdot \frac{1}{\varepsilon_d} \cdot \boldsymbol{Q}$$

Transport:

Transport costs are assigned to each arc, divided into variable operating expenses per transported volume (OPEX) and capital expenses per time period capacity (CAPEX). While both components are considered separately for the targeted arcs, in the rest of cases a unit transport cost (UTC) is estimated, adding the levelized CAPEX to the OPEX.

Levelized CAPEX is calculated considering an investment period of 25 years, a discount rate of 8% and two different levels of utilization, high (90%) and normal (60%).

Initial capacity and maximum capacity investment in a given planning period are also provided for the bounded arcs.

Selected parameters in the model are illustrated in the table 5-2.

Parameters	Definition
PrefS (sr, t, sc)	supply price reference
PrefD (dr, t, sc)	demand price reference
QrefS (sr, t, sc)	supply volume reference
QrefD (dr, t, sc)	demand volume reference
elastD (sc)	price elasticity of demand
elastS (sc)	price elasticity of supply
p (sc)	scenario probability
opex (arc)	operating transport cost
capex (arc)	capital investment cost
capini (arc)	initial capacity
capinv (arc)	investment capacity
share (arc)	arc share
life (t)	life time within the planning horizon

Table 5-2: Model parameters

5.3.3 Variables

The objective in a spatial equilibrium problem is to determine the optimal flows between supply and demand nodes for each time period. Equilibrium prices on each node can be further calculated from the volumes and the inverse price curves. New investments and the resulting arc capacities for each planning period are also accounted.

Selected variables in the model are illustrated in the table 5-3.

Variables	Definition
x (arc, t)	arc volume (in bcm)
s (n, t)	supply volume (in bcm)
d (n, t)	demand volume (in bcm)
inv (arc, p)	Arc investment (in bcm)
capa (arc, t)	Arc capacity (in bcm)
obj	objective value/s

Table 5-3: Model variables

5.3.4 Equations

Finally, the conditions to be fulfilled by the variables and parameters are declared. The first two equations are established by the very network logic so that the traffic through each node must be balanced. Consequently, the sum of all supplies must also equal the sum of all demands.

$$\sum_{dr} d(dr, t, sc) = \sum_{sr} s(sr, t, sc)$$

$$\sum_{arc=n,np} x(arc, t, sc) = \sum_{arc=np,n} x(arc, t, sc)$$

Volumes through the arcs are limited by their capacity, which must be updated by the successive expansions within each planning period. Such expansions cannot exceed the corresponding upper bounds either.

$$capa(arc, t) = cap\_ini(arc) + \sum_{p \le t} inv(arc, p)$$

On the other hand, in order to guarantee the security of supply to a given demand region, a maximum share can be established on the related arcs.

$$x\ (arc(n, np), t, sc) < share\ (arc) \cdot \sum_{n} x(n, np, t, sc)$$

Finally the objective function is declared in terms of economic welfare that maximizes the sum of consumer and producer surplus, once the transport costs are subtracted.

$$
\begin{aligned}
MinTotalCost = \sum_{sc}\Bigg\{\Bigg(&\sum_{t}\sum_{dr}\Big(\alpha(dr,t,sc)\cdot d(dr,t,sc)+\frac{1}{2}\cdot\beta(dr,t,sc)\cdot d(dr,t,sc)^{2}\Big)\\
&-\sum_{sr}\sum_{t}\Big(\gamma(sr,t,sc)*s(sr,t,sc)+\frac{1}{2}*\delta(sr,t,sc)*s(sr,t,sc)^{2}\Big)\\
&-\sum_{arc}\sum_{t}\big(OPEX(arc,t)*x(arc,t,sc)\big)\\
&-\sum_{targeted(arc)}\sum_{p}\big(CAPEX(arc)*inv(arc,p)*life(t))\big)\,)\Bigg)*p(sc)\Bigg\}
\end{aligned}
$$

The consumer surplus (CS) represents the difference between its willingness to pay for a good and what is actually paid. Similarly producer surplus (PS) represents the benefit of selling the good at market prices.

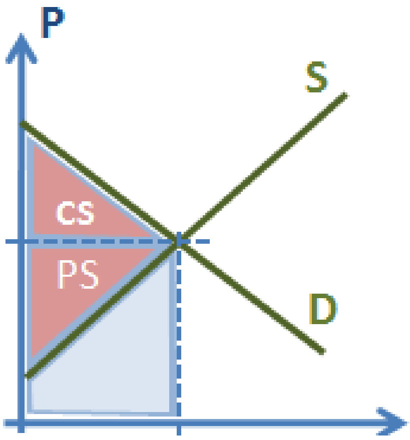


Figure 5-5: Consumer and producer surplus representation

The first and second terms of the equation are the areas under the demand and supply curves while the third and fourth depict the operating and capital transport costs. Capital expenses are charged according to the investment date considering their lifetime within the modelling horizon.

Equations	Definition
bal (t, sc)	supply demand balance
nbal (n ,t, sc)	node balance
capac (arc, t, sc)	arc capacity upper bound
capainv (arc, p)	arc investment capacity upper bound
invest (arc, t)	capacity update
share (arc, t, sc)	arc share in the destination node
objdef	objective function definition

Table 5-4: Model equations

5.4 Parameterization

5.4.1 Sets

The model IBEUGAS consists of 20 nodes and 34 arcs to represent the system yearly over the period 2015-2050.

Nodes

All major regions (North America, Asia- Pacific, Middle East and Europe) are represented in the model so that the global trade of natural gas is provided, and the supplies to Europe are given as a result of a global spatial equilibrium. Main European partners by pipeline (Russia and North Africa) as well as supplies from the North Sea basin are also depicted. In addition, a liquefaction node is available in each exporting region to represent the natural gas in liquid state and available for being shipped.

The consumption of natural gas and LNG in the EU are represented in the model, emphasizing the Iberian subregion. Three LNG entry options are considered. One is dedicated to the Iberian market, while the rest of the EU is attended through two gateways, representing the LNG receiving plants in the Atlantic and Mediterranean). In addition, two states (before and after regasification) are distinguished to depict gas and liquid supplies from the plants.

The nodes are summarized in the table 5-5 and outlined in the figure 5-5

Arcs

Connecting the corresponding nodes, natural gas transmission and liquefaction together with LNG transportation and regasification are also depicted in the model.

- Liquefaction facilities in Middle East, Russia, North America and Africa, limited.
- LNG shipping routes linking liquefaction plants and receiving plants, unlimited.
- LNG plants in Iberia, Atlantic and Mediterranean, limited and targeted.
- Natural gas delivery to market by pipeline, unlimited.
- LNG tank trucks. LNG tanker capacity, unlimited.

- European gateways from North Sea, Africa and Russia, limited and targeted.
- Iberia – Europe interconnection (both ways), limited and targeted.

The arcs are summarized in the table 5-6 and outlined in the figure 5-5

Code	Node	Supply	Demand	Transit
IB	Iberia		+	
EU	EU (excluding Iberia)		+	
L_IB	Iberia LNG		+	
L_EU	EU (excluding Iberia) LNG		+	
in_ATL	Plant Atlantic			+
in_IB	Plant Iberia			+
in_MED	Plant Med			+
reg_ATL	Regas Atlantic			+
reg_IB	Regas Iberian			+
reg_MED	Regas Med			+
liq_RU	Liquefaction Russia			+
liq_AF	Liquefaction Africa			+
liq_ME	Liquefaction Middle East			+
liq_NA	Liquefaction North America			+
RU	Russia	+	+	
NS	North Sea	+		
AF	Africa	+	+	
NA	North America	+	+	
ME	Middle East	+	+	
AP	Asia Pacific	+	+	

Table 5-5: Model nodes

Time

Infrastructure investments require long time periods to be assessed. A horizon of 35 years on a yearly basis was selected in the model, with a five- year investment plan.

Stochasticity

Uncertainty is included in the market. Demand projections strongly differ between scenarios (high, base and low case). On the other hand, supply disruptions from Russia are plausible but unpredictable within the time frame 2015-2050, such as the Ukraine political crisis.

From	To	Type	Limited	Targeted
IB	EU	**pipeline**	+	+
EU	IB	**pipeline**	+	+
RU	EU	**pipeline**	+	+
NS	EU	**pipeline**	+	+
AF	IB	**pipeline**	+	+
in_IB	reg_IB	**regas**	+	+
in_ATL	reg_ATL	**regas**	+	+
in_MED	reg_MED	**regas**	+	+
reg_IB	IB	**pipeline**		
reg_ATL	EU	**pipeline**		
reg_MED	EU	**pipeline**		
in_IB	L_IB	**truck**		
in_ATL	L_EU	**truck**		
in_MED	L_EU	**truck**		
liq_NA	in_IB	**shipping**		
liq_NA	in_IB	**shipping**		
liq_NA	in_IB	**shipping**		
liq_ME	in_IB	**shipping**		
liq_ME	in_ATL	**shipping**		
liq_ME	in_ATL	**shipping**		
liq_RU	in_ATL	**shipping**		
liq_RU	in_ATL	**shipping**		
liq_RU	in_MED	**shipping**		
liq_AF	in_MED	**shipping**		
liq_AF	in_MED	**shipping**		
liq_AF	in_MED	**shipping**		
liq_NA	FE	**shipping**		
liq_ME	FE	**shipping**		
liq_RU	FE	**shipping**		
liq_AF	FE	**shipping**		
AF	liq_AF	**liquef**	+	
NA	liq_NA	**liquef**	+	
ME	liq_ME	**liquef**	+	
RU	liq_RU	**liquef**	+	

Table 5-6: Model arcs

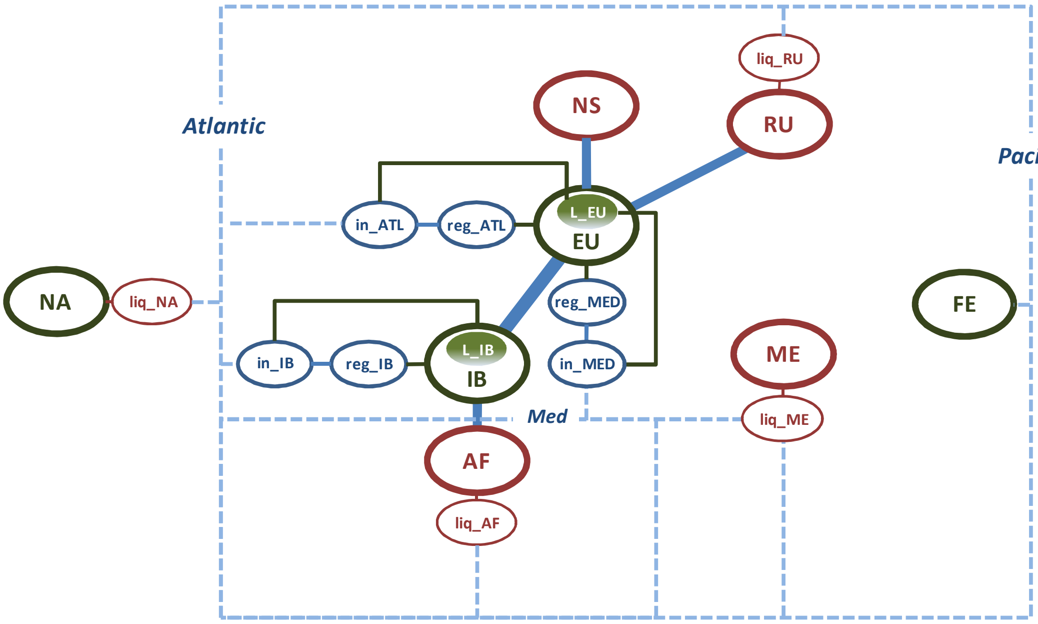


Figure 5-6: Nodes and arcs represented in the model

5.4.2 Parameters

Based on the market review in Chapter 3 and other references, values are assigned to the parameters presented in the table 5.2.

5.4.2.1 Market

The market is defined by the linear supply and demand curves for each region, time period and scenario, which are inferred from the given reference points and the corresponding elasticities.

Elasticities are estimated either empirically or implied from energy models, with a wide range of estimates based on the survey in (Arora, 2014). The National Energy Modeling System (NEMS) gives a median value of 0.50 for the price elasticity of supply.

Empirical demand studies are more numerous but focused on the residential and commercial sectors. In the electricity sector estimates are frequently analyzed in terms of elasticity of substitution for other fuels (mainly coal). A price elasticity of demand of (-0.4) is assumed in the long term. Since the demand curve is highly inelastic in the short term, an elasticity of (-0.1) is selected and used in the event of supply disruptions.

Prices 2015-2050 are considered at constant prices, related to the reference year 2012 in the case of the ETP2014 projections.

Based on the market review, different demand scenarios are considered (high, base and low). References by region in the high case scenario at three time periods (2015, 2030 and 2050) are shown in the table 5-7. Prices are considered in constant 2013 prices based on the ETP2014 assumptions. Iberian share in EU demand is assumed at 9% based on the consumption 2008-2013 (Eurostat, 2015a).

	Supply (bcm)			**Demand (bcm)**			**Price (€/tcm)**		
	2015	**2030**	**2050**	**2015**	**2030**	**2050**	**2015**	**2030**	**2050**
IB				41	49	60			
EU				414	493	608	390	450	523
NA	893	1,026	1,200	898	995	1,151	133	207	257
AP	582	827	1,375	782	1,232	2,072	563	530	623
ME	565	722	1,138	437	594	800			
RU	893	1,136	1,433	731	810	946			
AF	221	402	517	118	166	210			
NS	267	226	185						
Total	**3.421**	**4.339**	**5.848**	**3.421**	**4.339**	**5.848**			

Table 5-7: *Supply, demand and price references (high case scenario)*

As an example, demand curves in Asia- Pacific and EU regions by 2015 and 2050 are represented in the figure 5-7.

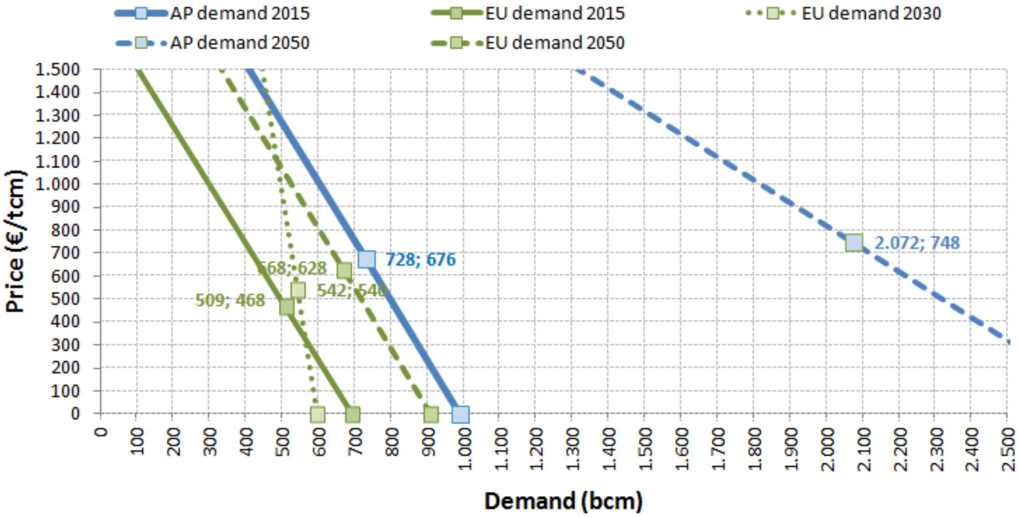


Figure 5-7: Demand curves (high case scenario)

Such an expansion scenario results in an outward shift in the curves. Furthermore, EU demand response to an unexpected supply disruption in Russia by 2030 is depicted.

Unknown supply prices are calculated by subtracting the transport costs to the given demand prices. Russian supply price is therefore assumed 338 €/tcm in 2015, considering the European demand price of 468 €/tcm and the unit transport costs between both markets of 130 €/tcm. Supply curves in the three main regions (Russia; North America and Middle East) by 2015 and 2050 are illustrated in the figure 5-8.

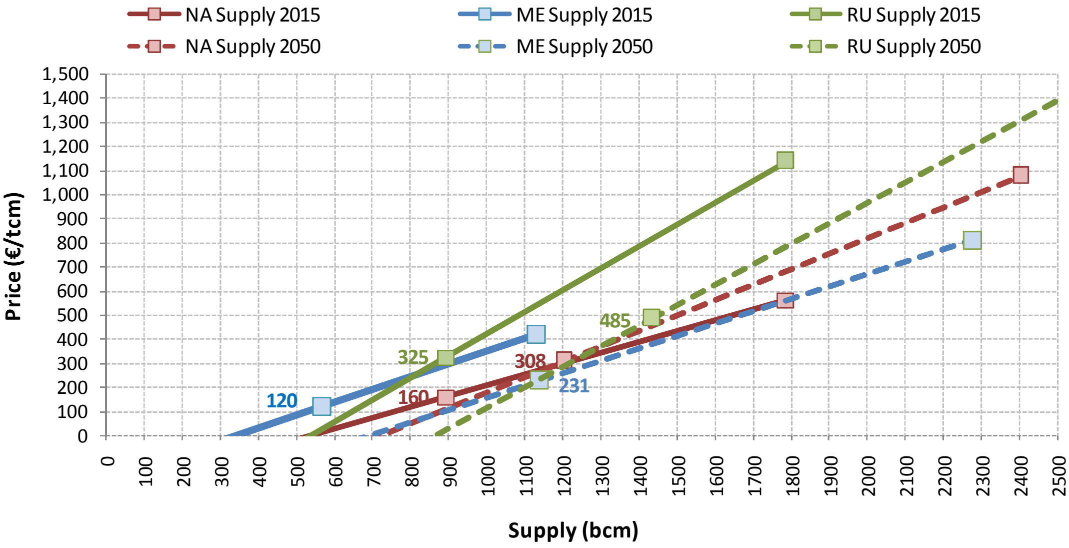


Figure 5-8: Supply curves (high case scenario)

Demand and price references for less expansive scenarios (base and low case) are presented in the table 5-8.

	Demand base case (bcm)			Price base case (€/tcm)			Demand low case (bcm)			Price low case (€/tcm)		
	2015	**2030**	**2050**	**2015**	**2030**	**2050**	**2015**	**2030**	**2050**	**2015**	**2030**	**2050**
IB	41	43	45				41	37	27			
EU	414	436	458	390	410	460	414	369	277	390	340	293
NA	898	877	1,035	133	200	247	898	816	522	133	190	180
AP	782	1.008	1,480	563	480	537	782	840	919	563	407	360
ME	437	427	504				437	397	254			
RU	731	670	638				731	607	468			
AF	118	166	210				118	166	210			
Total	3,421	3,628	4,370				3,421	3,232	2,676			

Table 5-8: Demand references (base and low case scenarios)

Known high case supply references are used to infer the supply curves for the rest of scenarios. Resulting oversupply is updated in an iterative process, where market clearing conditions in each step are incorporated as the supply conditions in the following step. In the figure 5-9 the evolution followed by the Russian supply curve in the iterative process is represented.

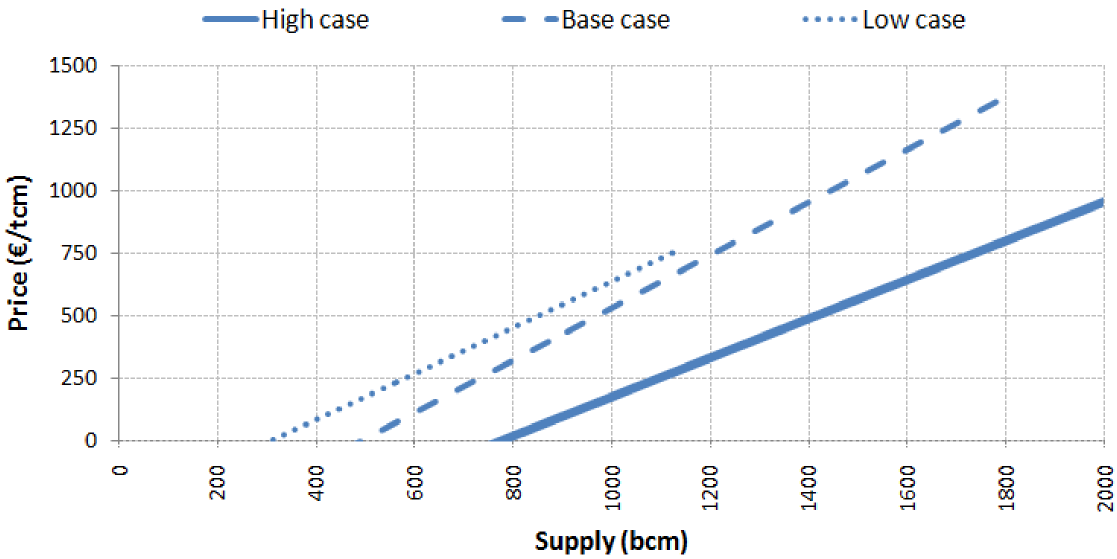


Figure 5-9: Russian supply curve in 2050 scenario- adjusted

In the previous scenarios European LNG demand share is assumed to remain stable in the current levels of 3% in Iberia and 1% in the rest of the EU. As stated in the market review, the use of natural gas as a transport fuel could increase significantly the LNG demand projections. As a result, a new scenario is presented adding the demand in the marine and HDV sectors to the low base scenario, as shown in table 5-9 based on the figure 3-4.

Iberian shares amount to 13% in marine based on the tones-kilometers by country (Eurostat, 2015b) and 12% in HDV segments based on the Gross Tonnag e in the European ports (Eurostat, 2015c).

	2015	2020	2025	2030	2035	2040	2045	2050
IB	0.0	0.1	0.2	0.6	1.6	3.1	4.8	6.3
EU	0.1	0.5	1.7	5.0	12.4	24.3	38.3	50.2

Table 5-9: *Incremental LNG demand in the transport scenario*

5.4.2.2 Transport

OPEX and CAPEX are considered constant throughout the period 2015-2050, assuming currency units (prices and costs) in the model at constant prices.

The transport parameters are defined by type of arc, as follows:

- Pipelines

Both CAPEX and OPEX are assumed linearly distance-related. The location of the gas fields and trunk pipelines are obtained from the oil and gas map by (Harvard, 2015), while the lengths are calculated through the distance facility in Google Maps.

A CAPEX of 140 € per tcma of capacity and 1,000 kilometers, and an OPEX of 1.7 € per tcm transported over 1,000 kilometers are selected based on (Lochner, 2011), being the ratio OPEX/CAPEX of 1.2%. A unit CAPEX of 23€ per tcm and 1,000 kilometers is obtained considering a normal utilization rate, as defined on the parameter formulation. Offshore pipeline sections are considered five times more expensive.

Initial gateway capacities amount to 126 bcma from Norway, 178 bcma from Russia and 21 bcma from Africa. Iberian interconnection capacity is initialized to 5 bcma in each direction (ENTSOG, 2015).

- Regasification

The average unit cost of onshore regasification in 2013 was 193$ per ton of LNG import capacity, or alternatively 109 € per tcma (IGU, 2014). According to the ratio OPEX/CAPEX of 3.5% found in (Avidan et al., 1998) a regasification OPEX of 3.8 € per tcm imported is assumed.

Initial regasification capacities amount to 77 bcma in Iberia, 96 bcma in the Atlantic and 26 bcma in the Mediterranean (ENTSOG, 2015).

- Liquefaction

Liquefaction CAPEX has increased to round 600 € per tcma by 2013. According to the ratio OPEX/CAPEX of 3% found in (White, 2012) a liquefaction OPEX of 18 € per tcm exported is assumed. As an unlimited arc in the model an annualized CAPEX of 100€ per tcm and a total unit transport cost of 118€ per tcm are assumed.

The initial capacities by region as of 2013 were 138 bcma in Middle East, 92 bcma in Africa, 13 bcma in Russia and a negligible 0.1 bcma in North America (IGU, 2014).

- LNG shipping

Shipping costs mainly consist of distance related components: tanker daily rate, fuel costs and boil off losses. Considering the rates introduced in the chapter 3.3, a variable unit transport cost of 6€ per tcm and 1,000 kilometers is assumed, resulting in significant differences between European receiving plants. Thus, shipping costs from Middle East can vary up to 20 € per tcm between an Iberian and an Atlantic port according to a corresponding shorter voyage of 3,000 kilometers for Iberia, as shown in the table 5-10 from (IEA, 2014b). On the other hand, fixed costs ranges 4-12 € per tcm depending on whether a canal crossing is required.

	in_IB	**in_ATL**	**in_MED**
liq_NA	68	64	80
liq_ME	68	88	56
liq_RU	60	40	72
liq_AF	52	64	48

Table 5-10: From – To table of maritime costs (in €/tcm)

- LNG distribution

LNG is currently distributed by truck to the inland end users, with a capacity of 50 m3 per unit, or alternatively 85 tcm. Trucking costs are divided into a fixed loading- related and a variable distance- related term. A truck loading tariff of round 500€ per service is assumed (Fluxys, 2013). On the other hand, distances can largely vary according to the current reduced infrastructure. 800 kilometers round- trip and a unit transport cost of 1.25€/kilometer are considered.

Adding fixed and variable costs a total cost of 50 €/tcm is assumed.

5.5 Model implementation

The optimization problem formulated and described in the previous chapters is translated into the program GAMS (Generic Algebraic Modeling System). This language was developed for high level large-sized modeling of systems. A complete reference to the program is provided by the user guide (McCarl, 2014). Furthermore, a specific review on the spatial equilibrium problem in GAMS is presented in (Kalvelagen, 2003).

GAMS has been broadly used in the type of problem presented in this thesis, including the majority of the works in the literature regardless of the selected approach (linear programming, non linear programming or mixed complimentary problem). As a result, other options, such as AMPL, were not considered when deciding on the implementation tool.

The programming structure is similar to the backbone presented in the model formulation, as shown in the table 5-10.

Data
Set declaration and definitions
Parameter declaration and definitions
Assignments
Model
Variable declarations
Equations declarations
Equation definitions
Model definition
Solution
Solve
Displays

Table 5-11: GAMS programming structure

The GDX facility is used to read sets and parameters from Excel and write the results back to Excel.

Since the objective function in the model is nonlinear, the optimization problem must be solved by nonlinear programming (NLP). The optimal solutions were obtained by the solver CONOPT. Despite being a basic model, the number of equations (2,285) and variables (16,145) are large enough to prevent from being solved by a spreadsheet. In round 20 seconds and after about 200 iterations, CONOPT find an optimal solution where the gradient of the objective is less than a given tolerance.

Taking advantage of the expandability and augmentation properties in GAMS, the number of entities in the model could be easily extended.

The GAMS program used in this Thesis is included in the Appendix II.

6

Results

6 Results

The model IBEUGAS introduced in the previous chapter consists of a set of restrictions relating “known” parameters (inputs) and unknown variables (outputs). As long as the model horizon covers the period 2015-2050, those parameters must be forecasted and subsequently subject to uncertainty. A range of different scenarios are simulated in order to enhance the robustness of the results from the model.

Although different scenarios could be managed simultaneously in the model using the stochasticity dimension and the probability distribution, each scenario will be solved separately in order to obtain their stand alone effects. The results are presented in this chapter, focusing on the entry connections into the EU (pipeline and regasification gateways) and the Iberian interconnection (both northbound and southbound), represented in the figure 6-1.

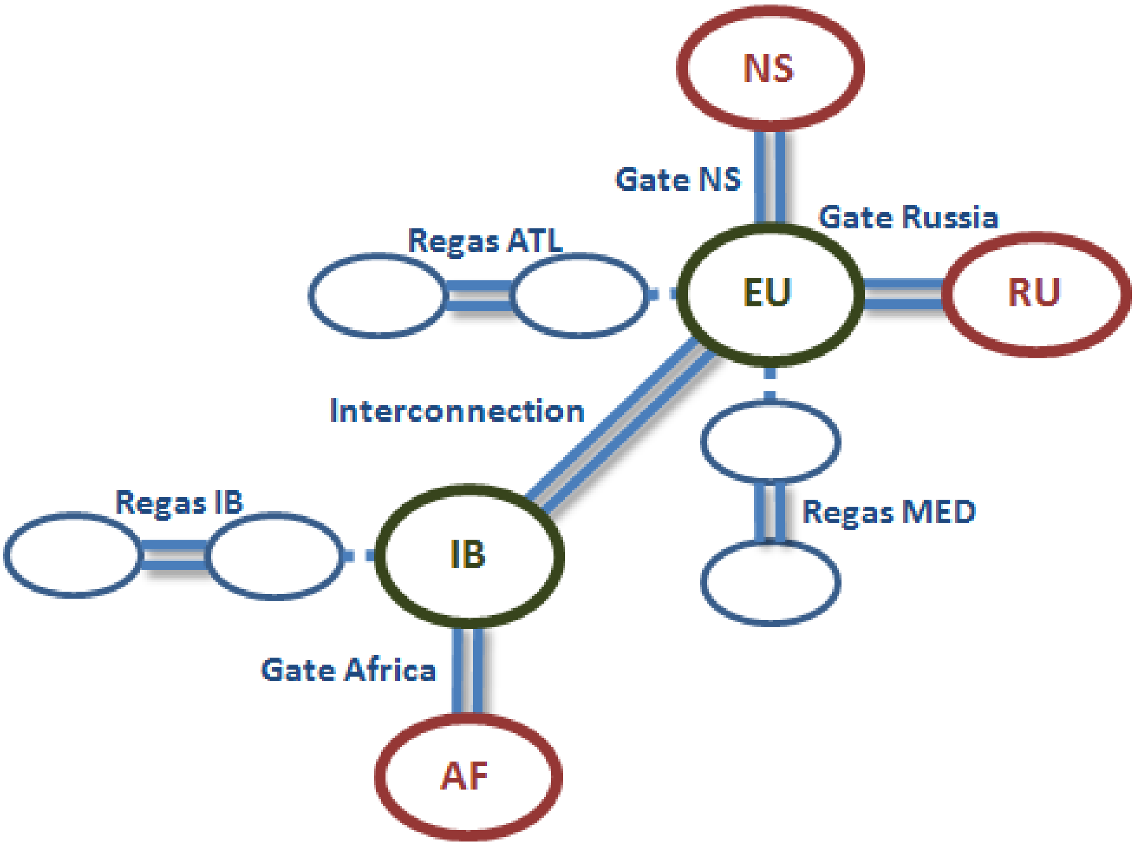


Figure 6-1: EU gateways and Iberian interconnection (own illustration)

With the traffic from the pipeline gateways limited either in absolute terms (North Africa and North Sea) or in relative terms (Russia), remaining volumes must be managed through the regasification plants. Corresponding volumes must be balanced by the Iberian interconnection accordingly.

6.1 Demand scenarios

Firstly, the results obtained by the model IBEUGAS, considering the demand scenarios (high, base and low) and assuming the rest of parameters invariable, are presented.

- **Base scenario**:

Although the European gas demand in the base scenario basically remains stable during the period 2015-2050 at 450-500 bcm, LNG supplies gradually grow up to 24.9% by 2050, mainly from Africa through the Iberian (944 bcm) and Mediterranean plants (407 bcm) and from North America through the Atlantic (1,049 bcm). Middle East exports are basically supplied to the higher- valued Asia Pacific market (7,358 bcm). The Iberian interconnection capacity should be expanded northbound from the initial 5 bcma to 13.2 bcma in 2025.

Natural gas entries by European gateway every five years and global flows over the period 2015-2050 are shown in tables 6-1 and 6-2.

	2015	2020	2025	2030	2035	2040	2045	2050
Regas IB	8.2	12.0	20.8	35.2	36.8	38.5	38.0	37.3
Regas ATL	3.7	3.7	10.1	20.1	30.1	44.3	53.6	61.8
Regas MED	0.0	0.0	15.2	6.8	17.7	25.0	25.0	25.0
Regas total	11.9	15.7	46.1	62.1	84.6	107.8	116.6	124.1
Regas share (%)	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.2
African gate	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Russian gate	144.6	154.4	162.7	166.4	172.7	179.1	177.2	174.5
North Sea gate	235.7	250.0	235.1	226.0	215.0	203.8	191.5	179.0
EU demand	**413.2**	**441.1**	**465.0**	**475.5**	**493.3**	**511.8**	**506.3**	**498.7**
Interconnect North	0.0	0.0	0.0	13.2	13.2	13.2	13.2	13.2
Interconnect South	0.6	5.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6-1: Traffic by gateway (base case scenario)

		To					
		AP	**EU**	**IB**	**in_ATL**	**in_IB**	**in_MED**
From	**EU**			31.0			
	IB		305.0				
	liq_AF	182.0			**36.0**	**944.0**	**407.0**
	liq_ME	7358.0				**99.0**	**43.0**
	liq_NA				**1049.0**	**5.0**	
	liq_RU	1422.0					

Table 6-2: From – To table (base case scenario)

- **High scenario**:

The most growing scenario posts the highest LNG supply share (ranging from 3% in 2015 to 32% in 2050). Additional LNG supplies should be captured from Africa through the Iberian (up to 2,271 bcm) and Atlantic plants (up to 464.2 bcm). The interconnection capacity should be increased northbound by 39.7 bcma by 2025, while Russian gateway in turn from initial 180 bcma to 221.2 bcma by 2050.

Natural gas entries by European gateway every five years and global flows over the period 2015-2050 are shown in the tables 6-3 and 6-4.

	2015	2020	2025	2030	2035	2040	2045	2050
Regas IB	8.2	26.0	65.2	71.6	74.8	79.6	80.8	80.8
Regas ATL	3.7	4.1	10.1	20.1	31.5	72.0	89.3	98.8
Regas MED	0.0	0.6	0.0	5.6	25.0	25.0	25.0	25.0
Regas total	11.9	30.7	75.3	97.4	131.3	176.6	195.1	204.6
Regas share (%)	2.9%	6.6%	14.6%	18.4%	23.2%	28.5%	30.9%	32.4%
African gate	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
Russian gate	144.6	162.5	180.0	185.4	197.8	216.5	221.2	221.2
North Sea gate	235.7	250.0	238.0	226.0	215.0	204.5	194.6	185.1
EU demand	**413.2**	**464.2**	**514.3**	**529.8**	**565.0**	**618.7**	**631.9**	**631.9**
IB Interconnect North	0.0	5.0	39.8	44.7	44.7	44.7	44.7	44.7
IB Interconnect South	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6-3: Traffic by gateway (high case scenario)

		To					
		AP	**EU**	**IB**	**in_ATL**	**in_IB**	**in_MED**
From	**EU**			0.6			
	IB		1256.1				
	liq_AF	2346.2			**464.2**	**2271.6**	**465.5**
	liq_ME	7500.0					
	liq_NA				**1053.6**		
	liq_RU	2640.0					

Table 6-4: From – To table (high case scenario)

- **Low scenario:**

In the lowest demand scenario the traffic overview changes entirely. Natural gas from the North Sea would recover the prominent role played decades ago at the expenses of the LNG supply, accounting for a maximal 6.6% share. The Iberian market would be supplied by pipeline, both Northbound from Africa and Southbound through the interconnection, which should be expanded from initial 5 bcma to 9.8 bcma.

Natural gas entries by European gateway every five years and global flows over the period 2015-2050 are shown in the tables 6-5 and 6-6.

	2015	2020	2025	2030	2035	2040	2045	2050
Regas IB	6.8	9.3	9.0	5.8	0.6	0.5	0.5	0.5
Regas ATL	3.9	1.8	10.1	12.4	4.5	2.6	2.7	18.0
Regas MED	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
Regas total	10.7	12.8	19.1	18.2	5.1	3.2	3.2	18.5
Regas share (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
African gate	21.0	21.0	21.0	21.0	21.0	18.9	21.0	21.0
Russian gate	144.0	150.1	148.2	142.8	122.4	116.6	106.9	107.5
North Sea gate	235.7	250.0	235.1	226.0	201.2	194.5	174.4	160.1
EU demand	**411.4**	**433.9**	**423.5**	**408.0**	**349.6**	**333.2**	**305.5**	**307.2**
Interconnect North	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Interconnect South	2.1	5.0	8.0	9.8	9.8	9.8	5.9	6.1

Table 6-5: Traffic by gateway (low case scenario)

		To				
		AP	**EU**	**IB**	**in_ATL**	**in_IB**
From	**EU**			286.6		
	liq_AF	74.0			18.3	32.8
	liq_ME	7470.3				28.1
	liq_NA	298.4			227.9	73.8
	liq_RU	47.7			1.7	

Table 6-6: From – To table (low case scenario)

The expansion schedule of the Iberian interconnection with the EU by planning period and scenario is summarized in the table 6-7. To sum up, additional capacity to the initial 5 bcma is required regardless of the demand outlook.

	Initial 2015	**2020**	**2025**
High case. Northbound	5	34.8	4.9
Base case. Northbound			8.2
Low case. Southbound	5	4.8	

Table 6-7: Iberian interconnection investment calendar

6.2 Model validation

In order to gain confidence in the results, the range of accuracy of the model outputs is checked. Model variables must be consistent with the input parameters, and real data when available.

The three types of variables are evaluated below. The ranges of accuracy are acceptable, considering the model assumptions.

6.2.1 Regional demand

Firstly, the EU demand (including Iberia) obtained by the model is compared with the reference parameters. The corresponding deviations are shown in the tables 6-8 to 6-10.

	2015	2020	2025	2030	2035	2040	2045	2050
Model input	416.3	471.7	523.8	541.9	580.9	637.6	662.4	668.5
Model output	413.2	464.2	514.3	529.8	565	618.7	631.9	631.9
Delta	-3.1	-7.5	-9.5	-12.1	-15.9	-19	-30.6	-36.6
Delta (%)	-0.7%	-1.6%	-1.8%	-2.2%	-2.7%	-3.0%	-4.6%	-5.5%

Table 6-8: EU demand (high case)

	2015	2020	2025	2030	2035	2040	2045	2050
Model input	416.3	442.2	461.3	479.4	497.5	517.7	510.1	503.4
Model output	413.2	441.1	465	475.5	493.3	511.8	506.3	498.7
Delta	-3.1	-1.1	3.7	-3.9	-4.2	-5.9	-3.8	-4.7
Delta (%)	-0.7%	-0.2%	0.8%	-0.8%	-0.8%	-1.1%	-0.7%	-0.9%

Table 6-9: EU demand (base case)

	2015	2020	2025	2030	2035	2040	2045	2050
Model input	416.8	422.5	433.5	405.9	346.8	311.2	301.9	304.3
Model output	411.4	433.9	423.5	408	349.6	333.2	305.5	307.2
Delta	-5.4	11.4	-10	2.1	2.8	22	3.6	2.9
Delta (%)	-1.3%	2.7%	-2.3%	0.5%	0.8%	7.1%	1.2%	0.9%

Table 6-10: EU demand (low case)

Minor deviations are stated in each case, with the largest being observed in the high case scenario, based on the larger LNG supplies (more expensive) and the corresponding demand receding according to the price elasticity. Negative delta values are observed consequently. On the other hand, lower LNG supplies in the low case scenario results in a slight demand expansion (positive deltas). Finally, the best model response is shown in the base case.

6.2.2 Global flows in the year 2015

Since additional capacities are not considered until the year 2020, the previous planning years could be seen as independent static optimizations, whose results should be similar to the actual data. As a result, interregional flows in 2015 obtained by the model are compared with the natural gas trade in 2014 (BP, 2015), as shown in the tables 6-11 and 6-12.

Minor deviations of 47 bcm in the EU entry flows have been stated, with the main differences being observed in the Middle East supplies. Whereas the entire export capacity attends the higher- priced Asia Pacific market in the model (150 bcm), some 21.7 bcm were actually diverted to the European lower- priced market in 2014. Such an imperfect situation is caused by fixed destination clauses in some contracts. As a result, European LNG reloads have been shifted to other premium markets (Timera, 2013).

			To						
			EU	**IB**	**in_ATL**	**in_IB**	**in_MED**	**AP**	**Total**
From	Pipeline	**EU**		0.6					**0.6**
		IB							**0.0**
		NS	235.7						**235.7**
		RU	144.6						**144.6**
		AF		21.0					**21.0**
	LNG	**RU**						15.0	**15.0**
		AF			3.6	8.2	0.0	36.1	**47.9**
		ME			0.0	0.0	0.0	150.0	**150.0**
		NA							**0.0**
		Total	**380.3**	**21.6**	**3.6**	**8.2**	**0.0**	**201.1**	**614.8**

Table 6-11: Global flows (model output 2015)

			To						
			EU	**IB**	**in_ATL**	**in_IB**	**in_MED**	**AP**	**Total**
From	Pipeline	**EU**		4.3					**4.3**
		IB							**0.0**
		NS	235.7						**235.7**
		RU	134.0						**134.0**
		AF		11.1					**11.1**
	LNG	**RU**						14.5	**14.5**
		AF			3.3	7.6	2.9	21.1	**34.9**
		ME			13.3	4.1	4.3	101.1	**122.8**
		NA							**0.0**
	Total		**369.7**	**15.4**	**16.6**	**11.7**	**7.2**	**136.7**	**557.3**

Table 6-12: Global flows (real 2014)

6.2.3 Investment decisions 2000-2015

The most important objective in the present thesis is to support the investment decisions on the natural gas infrastructures over the period 2015-2050. Obviously, future flows and investments are not available to be compared. Instead, the model is simulated over the period 2000-30, considering as model inputs both the projections by the year 2000 and the real data. As a result, different investment planning intervals are defined for each infrastructure, which are finally compared with the real investments.

With the gas consumption worldwide having been doubled during the last 30 years up to 2,400 bcm per year by 2000, the global demand was projected to be doubled again over the following 30 years [IGU, 2003]. A little slighter growth was forecasted in the EU. However, while the global demand has met the projections until the year 2014, European consumption has dropped dramatically since 2006. As a result, EU demand by 2014 totaled 420 bcm, 200 bcm less than projected, even below the consumption in the year 2000.

Such a decrease in the EU has been offset by the Asia- Pacific demand. The price spread between both regions has subsequently increased (see figure 3-16). The demand projections 2000-2030, the real demand 2000-2014 and the demand scenarios 2015-30, are shown in the figures 6-2 and 6-3.

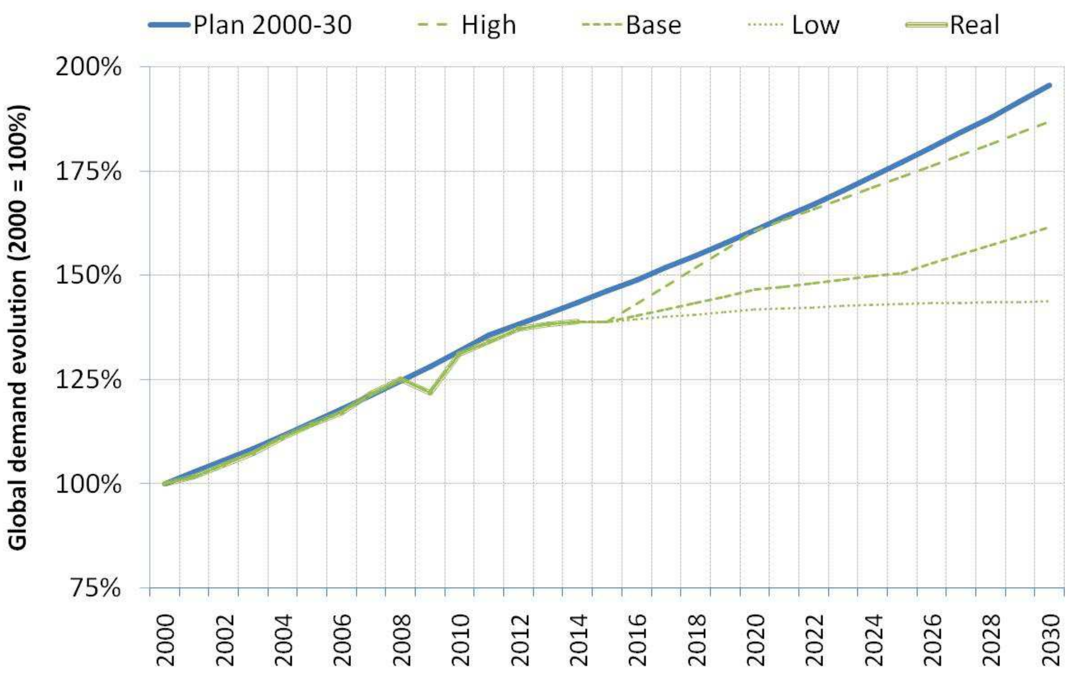


Figure 6-2: Global demand evolution and plans

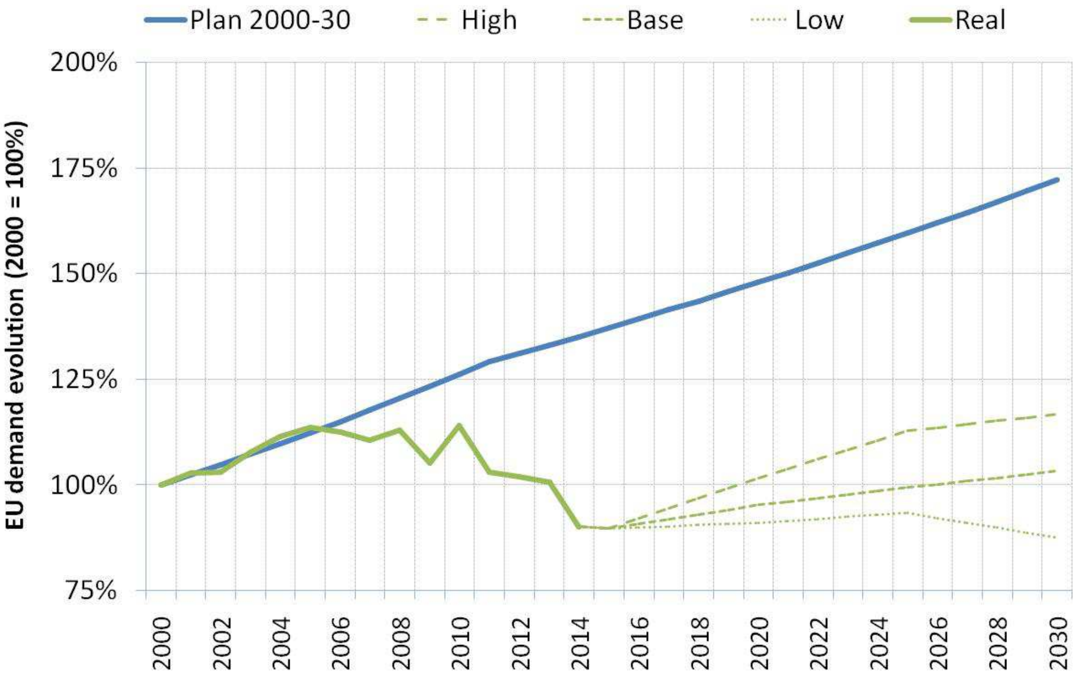


Figure 6-3: EU demand evolution and plans

As a result of the different demand inputs, the investments differ widely across the three alternatives:

1. Plan 2000-30 with demand as of 2000

2. Plan 2000-30 with real demand 2000-14 and base scenario 2015-30

3. Real 2000-14

The initial and final capacities as well as the corresponding investments over the period 2000-2015 are shown in the table 6-13 by scenario and gateway.

Plan 2000-30 (1)	**Initial 2000**	**Invest 2005**	**Invest 2010**	**Invest 2015**	**Final 2015**
IB Interconnect North	5.0	5.2	26.3	13.8	50.3
Russian gate	130.0	42.4	22.4	21.4	216.2
Regas IB	10.0		28.5	16.7	55.2
Regas ATL	15.0				15.0
Regas MED	7.0		6.5	22.6	36.1

Plan 2000-30 (2)	**Initial 2000**	**Invest 2005**	**Invest 2010**	**Invest 2015**	**Final 2015**
IB Interconnect North	5.0			6.8	11.8
Russian gate	130.0	47.1			177.1
Regas IB	10.0	6.4	5.8		22.2
Regas ATL	15.0		7.0		22.0
Regas MED	7.0				7.0

Real (3)	**Initial 2000**	**Invest 2005**	**Invest 2010**	**Invest 2015**	**Final 2015**
IB Interconnect North	5.0	0.0	0.0	0.0	5.0
Russian gate	130.0	0.0	0.0	55.0	185.0
Regas IB	10.0	21.0	30.0	19.0	80.0
Regas ATL	15.0	12.0	55.0	18.0	100.0
Regas MED	7.0	9.0	9.0	0.0	25.0

Table 6-13: Investment plan 2000-2015 by alternative

Since the penetration of regasification plants in Europe by the year 2000 was still limited, the infrastructure investment plan would consider the best option in terms of maritime- pipeline logistics. Thus, Iberian and Mediterranean plants would be expanded according to the lower shipping costs from Middle East and Africa.

Furthermore, investments in the Russian connection and the Iberian interconnection are selected in order to supply the EU.

However, different results are obtained when considering the actual demand 2000-14. In addition to the reduced EU demand, two new global market conditions have caused a regional redistribution of the natural gas trade. Firstly, Middle East and Africa supplies have been captured by the Asia-Pacific premium market, as a result of the faster economic growth in Asia- Pacific in this region and augmented by the Fukushima disaster. Secondly, shale gas boom in the US has diminished gas prices in North America, which can be diverted to the EU market. Moderate expansions in Atlantic (7 bcma) and Iberia (12.2 bcma) regasification plants as well as the Iberian interconnection (6.8 bcma) would have been projected accordingly. Thus, unpredicted events back in 2000 have a considerable impact on the investment decisions.

Finally, the real expansions during the period 2000-15 show an excessive expansion of regasification facilities, especially in Iberia (+70bcma) and the Atlantic (+85 bcma).

Planned capacity intervals as well as initial and final capacities for each gateway are summarized in the figure 6-4.

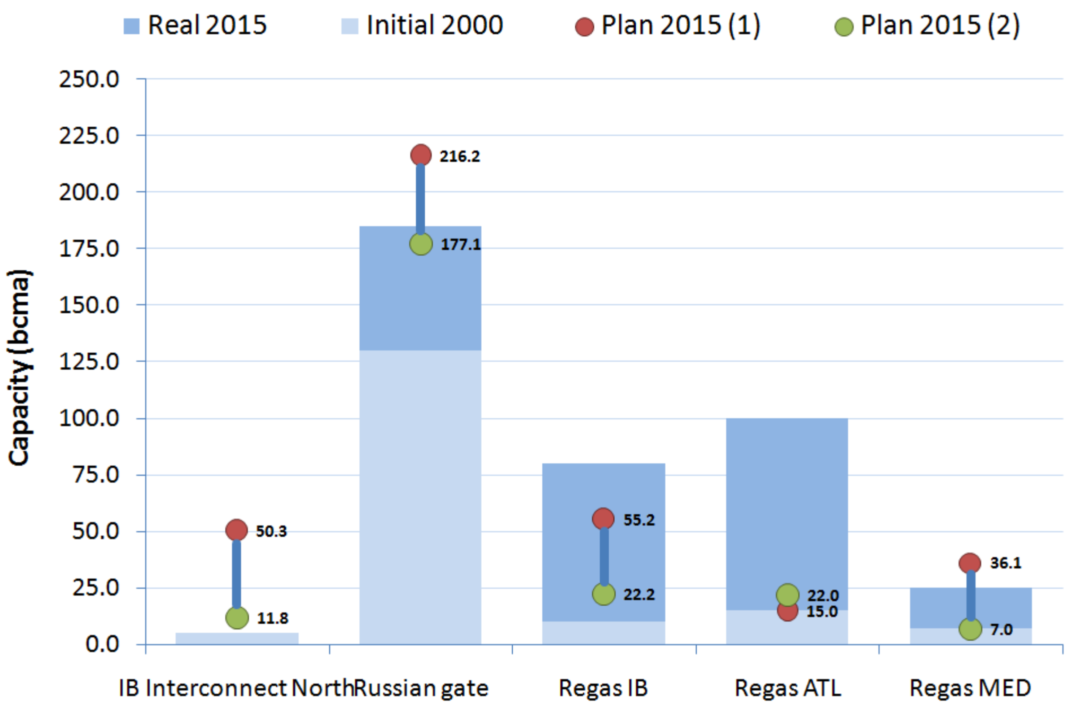


Figure 6-4: Initial and final capacities (in bcma) by alternative

To sum up, the following situations have been identified depending on the real investments and investment planning interval.

- Real investments adjusted interval: e.g. Russia- Central Europe connection, where the real investment until 2015 (55 bcma) is within the interval [47.1-86.2] bcma, validating the model.
- Non real investments adjusted interval: based on individual political factors at a country level beyond the welfare optimization considered by the model.
  - Oversized: e.g. Iberian and Atlantic regasification plants.
    - Real investment until 2015 in Iberia (70 bcma) is above the interval [12.2-45.2] bcma, and accordingly, above the real utilization of the Iberian plants, validating the model.
    - Real capacity by 2015 In the Atlantic (85 bcma) is above the interval [15.0-22.0] bcma, and accordingly, above the real utilization of the Atlantic plants, validating the model.

      Such an excessive capacity is primarily caused by an expansion of 52 bcma in the UK plants during the period 2005-2010.
  - Undersized: e.g. Northbound Iberian interconnection, where the negligible investment until 2015 is below the interval [6.8-45.3] bcma. The results are supported by the simulation over the period 2015-2050, with an expansion of 8.2 bcma.

6.3 Sensitivity analysis

A sensitivity analysis enhances the robustness of the results according to the existing uncertainty on the model parameters. As a result, a better understanding of the relationship between inputs and outputs is provided. Both parameters and variables were listed in the tables 5-2 and 5-3. The parameters selected in the sensitivity analysis are grouped by three following categories.

6.3.1 Market

As the main driver, the impact of the global demand was considered in the subchapter 6.1. The sum of investments in the Iberian interconnection over the period 2015-50 (x-axis, in bcma) and the European demand by 2050 (y-axis, in bcm) are illustrated in a scatter chart in the figure 6-5.

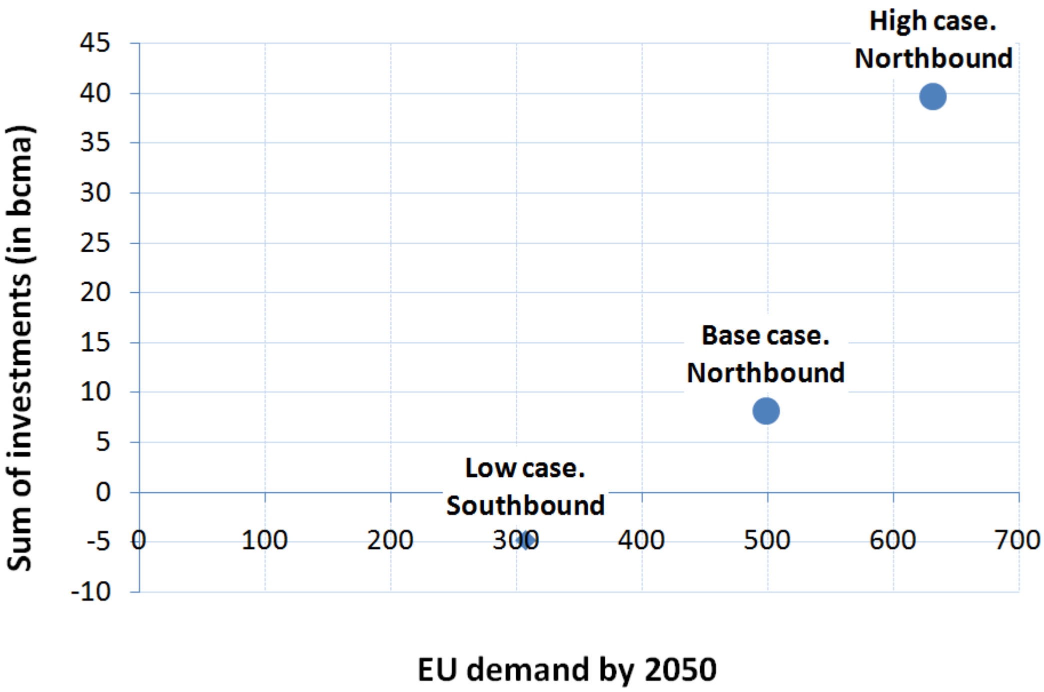


Figure 6-5: Scatter chart Iberian interconnection investments - EU demand

In addition to the regasification, LNG receiving plants are also used to meet LNG end user demand. Capacity restrictions and investment decisions are only considered by the model in the regasification activity (in bcma), while LNG supplies are assumed unlimited.

Even if these volumes are reduced today, such an option could post a considerable growth, provided that natural gas becomes an alternative fuel in the transport sector. Lower prices in the low case scenario could pave the way while increasing the utilization of the LNG plants, as shown in the table 6-14.

	2015	2020	2025	2030	2035	2040	2045	2050
Regas IB	6.8	9.4	10.0	1.8	2.1	3.3	4.9	6.4
Regas ATL	3.7	2.0	10.1	18.3	14.9	24.8	37.8	49.8
Regas MED	0.0	1.8	0.0	0.0	0.0	0.0	0.0	0.0

Table 6-14: Regasification plant volumes (low scenario with transport development)

With the entry infrastructure being covered by the regasification plants (56.2 bcm against 205 bcma), the LNG distribution will only require the development of other new businesses (storage, transshipment, bunkering, etc.)

As a global market, changes in the supply or demand conditions in any other region can influence the European infrastructure utilization. The impact of variations in the developing Asia- Pacific demand (±20%) on the EU gateways is presented in the table 6-15.

In case of a demand increase (+20%), the prices in this region grow. As a result, European prices also grow and its demand decrease from 498.7 bcm to 467.9 (about -6%) consequently. On the other hand, a demand reduction in Asia- Pacific region (-20%) result in a European demand increase up to 517.6 bcm (about +4%).

Both scenarios have a negative impact on the Iberian interconnection and LNG plants. In addition to the lower demand case, a substitution of African for Middle East supplies reduces the Iberian volumes even if the EU demand grows.

	AP demand +20%	Base case	AP demand -20%
Regas IB	26.3	37.3	30.8
Regas ATL	60.1	61.8	80.6
Regas MED	17.7	25	25.0
Russian gate	163.8	174.5	181.2
Regas total	104.1	124.1	136.4
EU demand	**467.9**	**498.7**	**517.6**
IB Interconnect. North	5.0	13.2	5.0

Table 6-15: Sensitivity analysis on Asia Pacific demand

6.3.2 Security of supply

Security of supply was incorporated into the model by limiting the Russian share up to a 35%. Variations in such a parameter have a direct impact on the LNG entry volumes and subsequently on the capacity investments, as stated in the table 6-16.

	Russian share 40%	Base case 35%	Russian share 30%
Regas IB	29.6	37.3	44.6
Regas ATL	60.1	61.8	73.9
Regas MED	13	25	25
Regas total	102.8	124.1	143.5
Russian gate	201.9	174.5	147.2
EU demand	**504.6**	**498.7**	**490.7**
IB Interconnect. North	5	13.2	21.2

Table 6-16: Sensitivity analysis on Russian supply share

Even though the previous share upper bound reduces the negative effects, political turmoil could cause a supply disruption. Assuming the base case scenario and a supply shock from Russia by 2035 corresponding results are shown in the table 6-17. As a result of the more expensive LNG supplies and the price inelasticity of demand in the short term, EU demand reduces by 5.8% (from 497.5 to 468.6 bcm). Additional capacity would be only required that year in the Mediterranean (40.7 bcma).

	2015	2020	2025	2030	2035	2040	2045	2050
Regas IB	21.9	22.0	30.7	52.6	71.8	75.0	74.5	73.8
Regas ATL	3.7	3.7	10.1	20.1	105.1	40.1	50.1	60.1
Regas MED	0.0	0.0	14.6	0.0	65.7	2.7	2.0	0.2
Regas total	25.6	25.7	55.5	72.7	242.6	117.8	126.6	134.1
Regas share (%)	5.5%	5.8%	12.0%	15.3%	51.8%	23.0%	25.0%	26.9%
Russian gate	163.5	154.4	162.4	166.8	0.0	179.1	177.2	174.5
EU demand	**467.1**	**441.1**	**464.0**	**476.5**	**468.6**	**511.8**	**506.3**	**498.7**
Interconnect North	0.0	0.0	0.0	20.7	39.7	39.7	39.7	39.7
Interconnect South	5.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6-17: Traffic by gateway (base case with disruption in 2035)

Extending the possibility of a Russian supply disruption to the years 2025 and 2030, and introducing the stochasticity dimension and a probability function equally distributed (2025, 2030, 2035) investments must be anticipated as shown in the table 6-18.

	2020	2025	2030	2035
Interconnect. North		15.7	19.0	**Shock**
Interconnect. North	34.5	**Shock**		

Table 6-18: Iberian interconnection investment calendar by disruption year

6.3.3 Transport

Finally, the influence of transport costs (CAPEX and OPEX) is considered.

As shown in the table 6-19, limited impact on interconnection expansion capacity have the regasification costs, since the three LNG entries would not be discriminated.

	Regas CAPEX (+20%)	Regas OPEX (+20%)	Base case	Regas OPEX (-20%)	Regas CAPEX (-20%)
Regas IB	37.3	37.2	37.3	37.4	37.3
Regas ATL	61.8	61.8	61.8	61.8	61.8
Regas MED	25.0	25.0	25.0	25.0	25.0
Regas total	124.1	124.1	124.1	124.2	124.1
Russian gate	174.5	174.5	174.5	174.6	174.5
EU demand	**498.7**	**498.6**	**498.7**	**498.8**	**498.7**
IB Interconnect. North	13.2	13.1	13.2	13.3	13.2

Table 6-19: Sensitivity analysis on regasification CAPEX and OPEX

On the other hand, the zero impact of variations (±20%) of the Iberian interconnection CAPEX on the model results is stated in the table 6-20.

	Pipe CAPEX (+20%)	Base case	Pipe CAPEX (-20%)
Regas IB	37.3	37.3	37.3
Regas ATL	61.8	61.8	61.8
Regas MED	25.0	25.0	25.0
Regas total	124.1	124.1	124.1
Russian gate	174.5	174.5	174.5
EU demand	**498.7**	**498.7**	**498.7**
Interconnect. North	13.2	13.2	13.2

Table 6-20: Sensitivity analysis on pipeline CAPEX

6.4 Discussion

6.4.1 Proposed scenarios and results

Although a global binding agreement on climate is not in place yet, the EU is very likely to confirm the objective of cutting carbon emissions substantially, at least by 80%.

Two scenarios are proposed in the present thesis, as the most plausible:

1. BASE case, with the EU natural demand remaining at current levels of round **450-500 bcm per year**, supported by IEA (ETP4DS) and EUROGAS projections.
2. LOW case plus TRANSPORT with the EU natural gas demand being reduced to **300 bcm per year**, supported by IEA (ETP2DS) and several cases from the EC Roadmap 2050. Subsequent low prices and a supportive policy are the perfect context for LNG to be developed as a transport fuel, augmenting the EU demand in **56 bcm** (6 bcm in Iberia) at the expenses of the oil products.

In order to prevent the EU from the negative effects of a Russian supply disruption, regasification capacity should be increased in the Mediterranean (round 40 bcma). However, the EU has significantly increased the underground storage after the successive Ukraine – Russia crisis of 2006, 2009 and 2014, up to its equivalent winter consumption.

The ranges (±20%) of transport costs (regasification and pipeline) where results have been proved invariable are considered sufficient.

The EU demand and the LNG gateway traffics and capacities for both scenarios are represented in the figure 6-6.

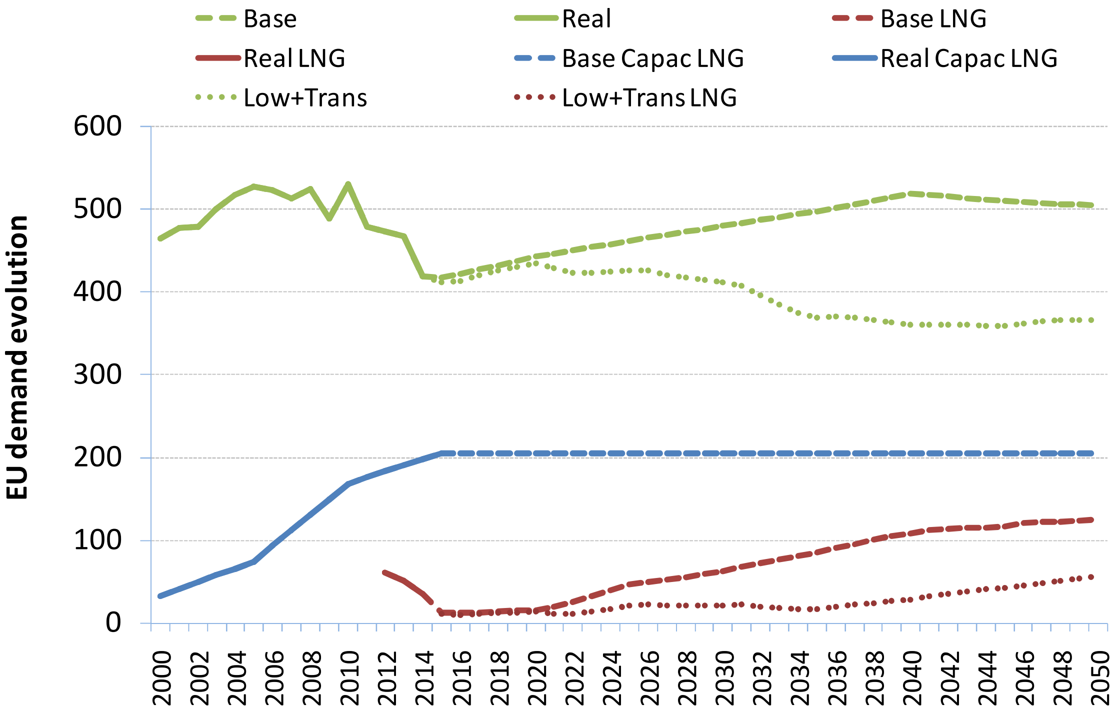


Figure 6-6: Demand and LNG gateway flows and capacities

Assuming the proposed scenarios as the model inputs, and an EU single planning objective that maximizes economic welfare in a perfectly competitive natural gas market, the corresponding results are finally declared.

Additional regasification plants are not required provided that the corresponding sub regions are properly interconnected. Although capital expenses per unit capacity for those interconnections are higher than the regasification ones, the additional charges can be offset by the lower shipping costs. Middle East supplies to the Iberian plants are up to 20€/tcm lower compared with the Atlantic plants, according to their geostrategic location. As a result, a capacity expansion of 8.2 bcma Northbound and 4.8 bcma Southbound are proposed in the Iberian interconnection.

After a slight expansion of the Spanish- French cross- border link by late 2015 up to 7 bcma, under discussion MIDCAT project would increase capacity in about 8 bcma Northbound and 2.5 bcma Southbound. Although the investment decision has not been taken yet, is expected by 2020, MIDCAT might be operational by 2020 (IEEE, 2014).

6.4.2 Impacts

Finally the impacts in terms of infrastructure deployment and reduction of GHG emissions according to the proposed scenarios above are further analyzed.

Infrastructures:

1. BASE case: the interconnection Iberia – EU (Northbound) should be increased by 8.2 bcma, resulting in an investment of 1,239 (2015 Mio. €), considering a unit CAPEX of 151.2 (2015 €/tcma and 1,000 kilometer).
2. LOW case plus TRANSPORT, the interconnection EU – Iberia (Southbound) should be increased by 4.8 bcma, resulting in an investment of 726 (2015 Mio. €).

   LNG refueling infrastructure must be deployed in order to ensure the development of the natural gas in the transport sector. As an example, publicly accessible refueling points for LNG shall be established within distances not exceeding 400 km along the roads and in all maritime ports of the TEN-T Core Network by 2020 (EC, 2013c).

   Priority projects can be considered of public interest and likely to receive funding under the EU's Connecting Europe Facility. Potential projects comprise LNG infrastructures such as barges, small scale terminals or refueling stations for vehicles.

Environmental:

1. BASE case: global EU reduction of carbon emissions would range between 41% (ETP4DS) and 82% (EUROGAS), considering the corresponding fuel mix.
2. LOW case plus TRANSPORT: in addition to the global reduction achieved by the LOW case (73%), carbon combustion emissions saved by the substitution of 52 bcm of natural gas for oil products (2,240 PJ) is estimated in 41.6 million tones of CO_2 in 2050, or a 3.3% additional reduction.

6.5 Limitations and further work

Assumptions have been taken along the modeling process at three different levels, in order to reduce the complexity during the problem formulation and optimization.

1. Framework: premises in each system dimension were discussed in the subchapter 5.1:
    - Commodity (one or various)
    - Market (perfectly or imperfectly competitive)
    - Transport (with or without intermediate storage)
    - Time (from a yearly to a daily basis)
    - Stochasticity (uncertain parameters)
2. Scalability: 20 nodes and 34 arcs have been selected at a regional level in the model. Obviously, a country or even a facility level would have provided a better representation, but also increased the solving complexity.
3. Parameterization: unpredictability is present in each model parameter when it comes to long run projections. Uncertainty is normally managed by simulation techniques. However, various scenarios can be optimized in a sensitivity analysis in order to gain confidence about the model results.

The model developed in this thesis could be further improved, relaxing the previous assumptions. Some would change the problem type (theory of games or simulation), while the others could be seen as extensions to the present thesis. Two options are finally proposed:

- Scalability of the model down to a country level (market) and a regasification plant level (transport).
- Time granularity down to a monthly basis, introducing the seasonal dimension and intermediate storage.

7

Conclusions

7 Conclusions

The conclusions extracted from the present thesis have been grouped in the following eight categories:

1. Model

According to the thesis objective, the model IBEUGAS is built in order to optimize the investment decisions on natural gas transport infrastructure in the EU over the period 2015-2050. IBEUGAS is a partial spatial equilibrium model with perfectly competitive markets, where the major regions and the main EU gateways (entry pipelines and regasification plants) are represented.

2. EU Demand

Once analyzed the outlooks from different organisations (AIE, CE, EUROGAS, etc.), three demand scenarios to 2050 are identified (HIGH, BASE y LOW).

Based on the EU objective of an 80% decarbonization, the abundant and widely dispersed natural gas resources and the highly technological development, two scenarios are proposed: BASE CASE with an annual demand at current levels of 450-500 bcm, and LOW CASE with a gradual reduction down to 300 bcm by 2050.

3. Sectoral demand

Corresponding lower prices in the LOW CASE scenario are the perfect context for natural gas as a transport fuel, envisaged as “The Great Gas Hope”. In the absence of feasible alternative fuels to oil products in two demand segments (maritime and heavy duty vehicles), an additional LNG demand up to 56 bcm by 2050 is proposed for the EU. With the entry infrastructure being covered by the regasification plants, the LNG distribution will only require the development of other new businesses (storage, transshipment, bunkering, etc.)

In a highly competitive power sector, envisaged as “The Battleground”, the gas-fired power plants are identified as the perfect partner to the intermittent non-dispatchable renewables, thanks to their lower emissions and higher efficiency and versatility.

4. Model validation (flows) and imperfect markets

The real interregional flows are compared with the model results in 2015 in order to validate the model. Minor deviations of 46 bcm are observed in the EU entry flows.

In the table 7-1, deviations in each connection as well as the corresponding error (see formula below) are represented. Such an error is introduced by the flows from Middle East (ME) to the EU, zero in the model and actually 21.7 bcm.

These deviations are basically derived from market imperfections, such as destination clauses present in some contracts that has enabled unloading operations (and subsequent reload to premium markets) in some Spanish regasification plants last years.

	from	to	model	real	deviation	|deviation|
Gateways	NS	EU	235,7	235,7	0	0,0
	RU	EU	144,6	134	-10,6	10,6
	AF	IB	21,0	11,1	-9,9	9,9
	AF	in_ATL	3,6	3,3	-0,3	0,3
	ME	in_ATL		13,3	13,3	13,3
	AF	in_IB	8,2	7,6	-0,6	0,6
	ME	in_IB		4,1	4,1	4,1
	AF	in_MED		2,9	2,9	2,9
	ME	in_MED		4,3	4,3	4,3
		Total	413,1	416,3	3,2	**46,0**
					Error	**11,0%**

Table 7-1: Deviations by connection and total error

$$Error = \frac{\sum_i |(R_i - M_i)|}{\sum_i R_i}$$

With an increasing demand in the non- OECD countries and an upturn in gas reserves worldwide, the market is getting more global and competitive, according to the model assumption of a perfect market.

5. Model validation (investments) and political factors

Investment decisions over the period 2000-2015 are also simulated, considering as model inputs, both the projections by the year 2000 and the real data. As a result, different investment intervals are defined for each infrastructure, which are finally compared with the real investments. The following conclusions are obtained:

- Real investments adjusted interval: e.g. Russia- Central Europe connection, where the real investment until 2015 (55 bcma) is within the interval [47.1-86.2] bcma, validating the model.
- Non real investments adjusted interval: based on individual political factors at a country level beyond the welfare optimization considered by the model.
    - Oversized: e.g. Iberian and Atlantic regasification plants.
        - Real investment until 2015 in Iberia (70 bcma) is above the interval [12.2-45.2] bcma. Real capacity by 2015 (80 bcma) is also above the real flow (11.7 bcm), validating the model.
        - Real investment until 2015 In the Atlantic (85 bcma) is above the interval [0.0-7.0] bcma. Real capacity by 2015 (100 bcma) is also above the real flow (16.6 bcm), validating the model.

          Such an excessive capacity is primarily caused by an expansion of 52 bcma in the UK plants during the period 2005-2010.

	model	**real**	**Deviation**	**Capac**	**load**
In	11,8	35,3	23,5	205	17,2%
in_ATL	3,6	16,6	13	100	16,6%
in_IB	8,2	11,7	3,5	80	14,6%
in_MED	0	7	7	25	28,0%

	Real	**Capac**	**load**
Belgium	2,88	9,0	32,0%
France	6,67	37,0	18,2%
UK	10,90	52,0	20,7%
Italy	4,36	11,0	39,6%
Iberia	11,70	80,0	14,6%

Table 7-2: Real flows and load factors in EU regasification plants

- Undersized: e.g. Northbound Iberian interconnection, where the negligible investment until 2015 is below the interval [6.8-45.3] bcma. The results are supported by the simulation over the period 2015-2050, with an expansion of 8.2 bcma.

6. Sensitivity analysis

As a global market, changes in other regions influence the model results. As an example, an increase of 20% in the Asia- Pacific demand would result in a reduction of 6% in the EU demand.

The negligible impact of variations (±20%) in the transport costs (OPEX and CAPEX) of the regasification plants and Iberian interconnection on the model results is also stated.

7. Security of supply

In addition to limiting the volumes through the Russia- Central Europe connection up to a 35% of the EU demand, Russian supply disruptions at different years (2025, 2030 y 2035) are simulated. As a result, Mediterranean regasification capacity and Northbound Iberian interconnection should be increased by 40.7 bcma and 34.7 bcma respectively, in order to deal with the peak load by the disruption year, once the regasification capacity had been reached in the Mediterranean and Atlantic.

However, underground storage expansion is considered a better option, in line with those completed as a result of the successive Russia- Ukraine conflicts.

8. Transport infrastructures

Additional investments on regasification plants are not required in the EU, provided that the corresponding gateways are properly interconnected. Therefore, the geostrategic location of each plant is benefited, what in the case of the Middle East supplies result in a cost saving of 20€/tcm in the shipments to Iberia compared with those to the Atlantic.

Capacity expansions are proposed in the Iberian interconnection, both Northbound (8.2 bcma by 2025) and Southbound (4.8 bcma by 2020). The model results are in line with real and projected investments, highlighting the expansion of 2 bcma (both ways) coming online by late 2015, and urging the Spanish and French governments to take the final investment decision for the MIDCAT. This project would increase the Northbound (8 bcma) and Southbound (2.5 bcma) capacities.

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Appendixes

Appendixes

Appendix I: Units

	TJ	GWh	Mbtu	Mtoe	bcm	Mio m3 LNG	Mio tonne LNG
TJ	1	0.2778	9.478E+02	2.388E-05	2.37E-05	4.09E-05	1.76E-05
GWh	3.6	1	3412.1416	8.60E-05	8.55E-05	1.47E-04	6.35E-05
Mbtu	1.055E-03	2.93E-04	1	2.52E-08	2.50E-05	4.35E-08	1.86E-08
Mtoe	4.187E+04	1.16E+04	3.97E+07	1	0.994	1.7134	0.7385
bcm	4.21E+04	1.17E+04	3.99E+07	1.006	1	1.7237	0.743
Mio m3 LNG	2.44E+04	6.79E+03	2.32E+07	0.5836	0.5801	1	0.431
Mio tonne LNG	5.67E+07	1.57E+07	5.37E+07	1.354	1.36	2.32	1

Appendix II: GAMS code

```
$Title IbEuGas55 Model. Thesis (Pablo Fernandez Fernandez)

$Ontext

A spatial equilibrium model used to represent global natural gas market and European infrastructure emphasizing the Iberian subregion

$Offtext

Sets  n     nodes

/

$call =xls2gms r=Transport!c3:v3 s="," i=IbEuGas55.xlsx o=setn.inc

$include setn.inc

/

     dr(n)  demand regions

/

$call =xls2gms r=Transport!c3:k3 s="," i=IbEuGas55.xlsx o=setd.inc

$include setd.inc

/

     sr(n)  supply regions

/

$call =xls2gms r=Transport!g3:l3 s="," i=IbEuGas55.xlsx o=setr.inc

$include setr.inc

/

t  periods /2015*2050/

p  ranges /2020, 2025, 2030, 2035, 2040, 2045, 2050/
```

```
sc scenarios /normal, 2020_, 2025_, 2030_, 2035_, 2040_, 2045_, 2050_/

Alias (n,np), (t,tt)

Parameter
previous(t,tt)
range(t,p);
previous(t,tt)$(ord(t)<ord(tt))=1;
range(t,p)$(((ord(t))-1>5*(ord(p))))=1;

Parameter
Table QrefS(sr,t)  supply reference
$call =xls2gms r=Market!b23:al29 i=IbEuGas55.xlsx o=parc.inc
$include parc.inc
Table QrefD(dr,t)  demand price reference
$call =xls2gms r=Market!b12:al21 i=IbEuGas55.xlsx o=parc.inc
$include parc.inc
Table PrefS(sr,t)  supply price reference
$call =xls2gms r=Market!b1:al1,Market!b6:al11 i=IbEuGas55.xlsx o=parc.inc
$include parc.inc
Table PrefD(dr,t)  demand price reference
$call =xls2gms r=Market!b1:al10 i=IbEuGas55.xlsx o=parc.inc
$include parc.inc
Table opex(n,np)   operating transport cost
```

```
$call =xls2gms r=Transport!b3:v23 i=IbEuGas55.xlsx o=part.inc
$include part.inc
Table capa_init(n,np)    initial capacity
$call =xls2gms r=Transport!b3:v3,Transport!b24:v43 i=IbEuGas55.xlsx o=part.inc
$include part.inc
Table capa_inv(n,np)     investment capacity
$call =xls2gms r=Transport!x3:ar3,Transport!x24:ar43 i=IbEuGas55.xlsx o=part.inc
$include part.inc
Table capex(n,np)     capital investment cost
$call =xls2gms r=Transport!x3:ar23 i=IbEuGas55.xlsx o=part.inc
$include part.inc
Table gate(n,np)      EU gateways
$call =xls2gms r=Transport!at3:ay10 i=IbEuGas55.xlsx o=part.inc
$include part.inc

Scalar elastS_         price elasticity of supply /.5/
Scalar elastD_         price elasticity of demand /-.4/
Scalar k               capital cost /0/
Scalar MinInv          minimum capacity investment /10/
Scalar shareRU         Russian share in EU consumption /.35/

Set arc(n,np) active arcs; arc(n,np) = opex(n,np);
Set IbEu(n,np) IbEu arcs; IbEu(n,np) = capex(n,np);
Set bounded(n,np) limited arcs; bounded(n,np) = capa_init(n,np);
```

```
Set NS_EU(n,np) /NS.EU/;
Set RU_EU(n,np) /RU.EU/;

Parameter elastS(sr,t,sc)       elasticity of supply;
elastS(sr,t,sc)=elastS_
Parameter elastD(dr,t,sc)       elasticity of demand;
elastD(dr,t,sc)=elastD_
Parameter a(dr,t,sc) intercept demand curve;
a(dr,t,sc)=PrefD(dr,t)*(1-1/elastD(dr,t,sc))
Parameter b(dr,t,sc) slope demand curve;
b(dr,t,sc)=(PrefD(dr,t)/QrefD(dr,t))*(1/elastD(dr,t,sc))

Parameter c(sr,t,sc) intercept supply curve;
c(sr,t,sc)=PrefS(sr,t)*(1-1/elastS(sr,t,sc))
Parameter e(sr,t,sc) slope supply curve;
e(sr,t,sc)=(PrefS(sr,t)/QrefS(sr,t))*(1/elastS(sr,t,sc));
Set scenario(sc,t) disruption scenarios
/2025_.2025,2030_.2030,2035_.2035/;
Parameter psc(sc) scenario probability
/normal 0.7, 2025_ 0.1, 2030_ 0.1, 2035_ 0.1/;

elastD("EU",t,sc)$scenario(sc,t)=-0.1;
elastD("IB",t,sc)$scenario(sc,t)=-0.1;
```

```
Positive Variables

x(n,np,t,sc)     arc volume

d(n,t,sc)        node demand

s(n,t,sc)        node supply

capa(n,np,t)     arc capacity

inv(n,np,p)      investment in fraction of x bcm

Variables

obj              objective value


Equations

    bal(t,sc)          supply demand balance

    nbal(n,t,sc)       node balance

    capac(n,np,t,sc)   arc capacity upper bound

    invest(n,np,t) arc capacity update

    capainv(n,np,p)  arc investment capacity upper bound

    share_RU(np,n,t,sc) security of supply RU > EU

    x_NS(np,n,t,sc)    supply from North Sea

    shock(n,np,t,sc)   supply shock from Russia

    objdef             objective function definition

    objsupdef          objective supply europe

    objdemdef          objective demand europe

    objctdef           objective transport europe

    objinvdef          objective investment europe;
```

```
bal(t,sc)..        sum(dr,d(dr,t,sc))=e=sum(sr,s(sr,t,sc));

nbal(n,t,sc)..     s(n,t,sc)$sr(n)+sum(arc(np,n),x(arc,t,sc)) =e=

                   d(n,t,sc)$dr(n)+sum(arc(n,np),x(arc,t,sc));

capac(arc,t,sc)$bounded(arc)..

                   x(arc,t,sc)=l=capa(arc,t);

capainv(arc,p)$bounded(arc)..

                   MinInv*inv(arc,p)=l=capa_inv(arc);

invest(n,np,t)$bounded(n,np)..

                   capa(n,np,t)=e=sum(p$range(t,p),MinInv*inv(n,np,p))+capa_init(n,np);

share_RU(n,np,t,sc)..

                   x("RU","EU",t,sc)+x("liq_RU","in_ATL",t,sc)+x("liq_RU","in_MED",t,sc)+x("liq_RU","in_IB",t,sc)

=l= shareRU * (d("EU",t,sc)+d("IB",t,sc)+d("L_EU",t,sc)+d("L_IB",t,sc));

shock(n,np,t,sc)$(RU_EU(n,np) and scenario(sc,t))..

                   x(n,np,t,sc)=e=0;

x_NS(n,np,t,sc)$NS_EU(n,np)..

                   x(n,np,t,sc)=l= QrefS("NS",t);

objdef..

   obj =e= sum(sc,(sum(dr,sum(t,a(dr,t,sc)*d(dr,t,sc)+.5*b(dr,t,sc)*sqr(d(dr,t,sc))))

     - sum(sr,sum(t,c(sr,t,sc)*s(sr,t,sc)+.5*e(sr,t,sc)*sqr(s(sr,t,sc))))

     - sum(arc,sum(t,opex(arc)*x(arc,t,sc) ))

     - sum(arc$IbEu(arc),sum(p,MinInv*inv(arc,p)*capex(arc)*life(p)))) * psc(sc));


Model IbEuGas55 /bal,nbal,capac,invest,capainv,objdef,objsupdef,objdemdef,

              objctdef,objinvdef,share_RU,x_NS,shock/;
```

```
Solve IbEuGas55 maximizing obj using nlp;


*Specification of the reports

Parameters

          rep1(sc,n,np,t) flow summary

          rep2(n,np,t) capacity summary

          rep3(n,np,p) investment summary

          rep4 supply demand and price summary;

rep1(sc,n,np,t)$gate(n,np) = x.l(n,np,t,sc);

rep2(n,np,t)$gate(n,np) = capa.l(n,np,t);

rep3(n,np,p)$gate(n,np) = MinInv*inv.l(n,np,p);

rep4(sr,t,sc,"Qs") = s.l(sr,t,sc);

rep4(sr,t,sc,"Ps") = c(sr,t,sc) + e(sr,t,sc)*s.l(sr,t,sc);

rep4(dr,t,sc,"Qd") = d.l(dr,t,sc);

   rep4(dr,t,sc,"Pd") = a(dr,t,sc) + b(dr,t,sc)*d.l(dr,t,sc);

display range,rep1,rep2,rep3,rep4,rep5,rep6,rep7,rep10,obj.l,objsup.l,objdem.l,objct.l,objinv.l


*Unload to GDX file

   execute_unload "IbEuGas55.gdx" x.l capa.l rep3 rep4 rep5 rep6 rep7 rep10

*Write in Excel file from GDX

   execute '          IbEuGas55.gdx var=x.l rng=_flow!b1:et534'

   execute 'gdxxrw.exe IbEuGas55.gdx var=capa.l rng=_capa!b1:as34'

   execute 'gdxxrw.exe IbEuGas55.gdx par=rep3 rng=_inv!b1:as34'

   execute 'gdxxrw.exe IbEuGas55.gdx par=rep4 rng=_equ!a1:g800'
```