UNIVERSIDADE ABERTA

SHIPPING AND SUSTAINABILITY
LIQUEFIED NATURAL GAS AS AN ALTERNATIVE FUEL:
EVIDENCE FROM PORTUGAL

Paulo Jorge Pires Moreira

Ph.D. Thesis in Social Sustainability and Development

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Ph.D. adviser Prof. Dr. Fernando José Pires Caetano
(Universidade Aberta)
Ph.D. co-adviser Dr. Vítor Manuel dos Ramos Caldeirinha (CEGE/ISEG)

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ABSTRACT

The objective of this Ph.D. thesis is to provide important inputs for the decarbonisation of marine transport and climate change mitigation policies concerning liquefied natural gas (LNG) as a substitute fuel. Real-world results show efficiency gains from LNG compared with traditional fossil fuels burned on-board vessel's engines even when equipped with mitigation technologies. Yet, this is a necessary but not a sufficient condition to LNG be elected as a substitute fuel. For a fuel switch of such order of magnitude to occur within a major end-use sector, other requirements are to be fulfilled: the government intervention in the public interest, and, to justify such policy intervention, the degree of social acceptability. This is accomplished by developing a social cost-benefit analysis (SCBA) performed at a regional basis after the assessment of the trade-off between the provision level of the good and Portuguese nationals' disposable income had been examined. SCBA attaches money prices - a metric of everything that everyone can recognise - to as many costs and benefits as possible in order to uniformly weigh the policy objectives. As a result, these prices reflect the value a society ascribe to the paradigm change enabling the decision maker to form an opinion about the net social welfare effects. Empirically, emissions from the Portuguese merchant fleet weighted by their contribution for the National Inventory were used to quantify and monetise externalities compared with benefits from LNG as a substitute marine fuel. Benefits from the policy implementation are those related with the reduction of negative externalities. Costs are those determined from the price nationals are hypothetically willing-to-pay for. Conclusions show that benefits are largely superior to the costs, so action must be taken instead of a doing nothing scenario. Apart from the social ex-ante evaluation, this thesis also imprints the first step for developing furthermore complete studies in this aspect and it can help fill policy makers' knowledge gap to what concerns to strategic energy options vis-à-vis sustainability stakeholders engagement. Although it addresses Portuguese particularities, this methodology should be applied elsewhere.

Keywords: Shipping and sustainability; Liquefied Natural Gas; Alternative Marine Fuels; Cost-benefit Analysis; Willingness-To-Pay

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RESUMEN

El objetivo de esta tesis es proporcionar insumos importantes para la descarbonización del transporte marítimo y políticas de mitigación del cambio climático abordando el gas natural licuado (GNL) como combustible sustituto. Los resultados en el mundo real muestran un aumento de la eficiencia del GNL en comparación con los combustibles fósiles tradicionales, incluso cuando los motores son equipados con tecnologías de mitigación. Sin embargo, esta es una condición necesaria pero no suficiente para que el GNL sea elegido como sustituto. Para que se produzca un cambio de combustible de tal orden de magnitud otros requisitos se deben cumplir: la intervención del gobierno en el interés público y, para justificar dicha intervención, el grado de aceptabilidad social. Esto se logra realizando un análisis de costo-beneficio social (SCBA) a nivel regional. La SCBA asigna los precios en dinero, una medida de todo y que todos reconocen, a tantos costos y beneficios posibles para sopesar de manera uniforme los efectos de las políticas. Como resultado, estos precios reflejan el valor que una sociedad atribuye al cambio de paradigma que permite al tomador de decisiones formarse una opinión sobre los efectos netos del bienestar social. Empíricamente, las emisiones de la flota mercante portuguesa ponderadas por su contribución al Inventario Nacional se utilizaron para cuantificar y monetizar las externalidades en comparación con los beneficios del GNL. Asimismo, los beneficios de la implementación de la política son aquellos relacionados con la reducción de las externalidades negativas. Los costos son aquellos determinados a partir del precio que los nacionales hipotéticamente están dispuestos a pagar. Las conclusiones muestran que los beneficios son en larga medida superiores a los costos, por lo que se deben tomar medidas en lugar de un escenario hacer nada. Además, esta tesis también imprime el primer paso para desarrollar estudios más completos y puede ayudar a llenar la brecha de conocimiento de los responsables de la formulación de políticas en lo que concierne a las opciones energéticas estratégicas con respecto al compromiso de las partes interesadas en materia de sostenibilidad. Aunque aborda las particularidades portuguesas, esta metodología puede aplicarse en otros lugares.

Palabras clave: Shipping y sostenibilidad; Gas natural licuado; Combustibles marinos alternativos; Análisis de costo-beneficio; Disposición a pagar

RESUMO

O transporte marítimo é um elo vital do comércio mundial graças à sua capacidade, confiabilidade e relação custo-eficácia no transporte de grande quantidade de bens; nenhum outro modo de transporte consegue alcançar tais economias de escala. Mas este argumento subestima os custos reais. A frota marítima internacional, excluindo barcos de pesca e navios militares, produziu em 2012 cerca de 796 milhões de toneladas (Mt) de dióxido de carbono (CO_2) e 816 Mt de dióxido de carbono equivalente (CO_2e) de gases de efeito de estufa (GEE) combinando dióxido de carbono (CO_2), metano (CH_4) e óxido nitroso (N_2O) correspondendo a cerca de 3,1% das emissões globais (IMO-International Maritime Organization, 2015; Rahman e Mashud, 2015) e é um dos setores de mais rápido crescimento em termos de emissões de GEE (Gilbert, Bows e Starkey, 2010; Bows-Larkin, 2014) previstas aumentar entre 102% a 193% em relação aos níveis de 2000 até 2050 (Bows-Larkin, 2014), crescendo a uma taxa mais elevada do que a taxa média de todos os outros sectores, com excepção da aviação. Como as emissões marítimas são produzidas, em grande parte, em mar aberto e por navios registados em países de bandeira de conveniência, foram excluídas dos compromissos nacionais no âmbito do Protocolo de Quioto de 1997, que cedeu o controlo à IMO o organismo da ONU responsável pelo sector[1]. De acordo com o *Maritime Knowledge Centre* da IMO, a frota mercante mundial de navios com pelo menos 100 *gross tonnage* (tonelagem bruta) era composta por 93.161 navios no final do ano de 2016. Espera-se que um número crescente de navios mercantes entre em operação nas próximas décadas, nomeadamente navios porta-contentores de grande capacidade, navios metaneiros e outros adstritos a actividades diversificadas como produção, armazenamento e descarga de gás natural e de petróleo (em inglês *Floating Production Storage and Offloading* - FPSOs). Os combustíveis marítimos tradicionais também produzem emissões de óxido de enxofre (SO_x), óxidos de azoto (NO_x) e micropartículas e o impacto sobre o ambiente dos poluentes primários e secundários resultantes da combustão do fuelóleo pesado (HFO) tem contribui para a acidificação, eutrofização e formação de ozono (O_3) fotoquímico (Bengtsson, 2011). Um efeito particularmente pernicioso na saúde das populações expostas é a mortalidade prematura

[1] Cerca de 60% da frota mundial de navios da marinha comercial estão registados e navegam sob Bandeiras de Conveniência sem qualquer vínculo entre registo nacional e proprietário o qual normalmente não é cidadão residente, o que imputaria ao país a responsabilidade pelas emissões excluindo o proprietário, o que pesou na decisão da sua exclusão de Quioto.

relacionada com micropartículas inaláveis associadas com o aumento do cancro de pulmão e problemas cardiorrespiratórios (Corbett et al., 2007) e, embora os efeitos nocivos mais graves sejam particularmente sentidos nas zonas costeiras e em áreas próximas das atividades portuárias, estes efeitos também ocorrem no interior dos países devido às condições predominantes dos ventos (Corbett, Fischbeck and Pandis, 1999) incluindo efeitos transfronteiriços (Nore, 2011).

Em Portugal e de acordo com o World Resources Institute, as emissões de CO_2 com origem nos combustíveis marítimos cresceram 24,5%, entre 2003 e 2012, em linha com o crescimento mundial (de 26,8%) no mesmo período de dez anos (World Resources Institute, 2015). Nesta tese, para efeitos de monetarização das emissões produzidas pela frota mercante nacional serão utilizados os dados do Inventário Nacional de Emissões, dados de 2014, os quais revelam que, embora o contributo do sector para o registo nacional seja mínimo – devido nomeadamente à exiguidade da frota – o potencial de danos causados não é de todo despiciente. Técnicas para aumentar a eficiência energética e tecnologias de mitigação dos efeitos nocivos - *scrubbers*, (depuradores) e dispositivos catalíticos - têm sido desenvolvidas e implementadas -, no entanto, embora o seu contributo para a descarbonização do sector deva ser levado em conta, estas tecnologias não correspondem à alteração pretendida do paradigma energético e podem constituir um incentivo ao *business-as-usual*. Por outro lado, o recurso a combustíveis com menor conteúdo de enxofre como o diesel marítimo é contraproducente uma vez que as emissões dos motores a diesel foram recentemente classificadas como cancerígenas pelo Centro Internacional de Investigação do Cancro (Oeder et al, 2015). O que isto significa é que embora o diesel corresponda ao exigido futuramente pelo Regulamento Tier III emitido pela IMO, na realidade não respeita suficientemente as preocupações com a saúde humana. De qualquer modo as refinarias não teriam provavelmente capacidade suficiente de fornecer todo o diesel necessário para abastecer a frota mundial. Por outro lado, as medidas de redução de poluentes emitidas pela IMO poderão ver seus efeitos reduzidos pelo crescimento esperado da atividade marítima nas próximas décadas e são destinadas a ser adoptadas lentamente ao longo de um largo período de tempo e mostram um progresso muito lento no contexto de evitar um aumento de temperatura superior a 2ºC acima dos níveis pré-industriais (Gilbert, 2013; Bows-Larkin, 2014), daí a necessidade urgente de investir em novas tecnologias e em novos tipos de combustíveis.

Benefícios directos do uso do gás natural liquefeito (GNL) resultam da redução em cerca de 20% das emissões de gases de efeito de estufa. Benefícios para a saúde das populações expostas, ecossistemas, culturas agrícolas e património edificado, resultam da menor emissão de poluentes como o NO_x ou da sua total ausência, como o SO_x e micropartículas. No entanto, para se proceder à descarbonização progressiva de um sector industrial é necessário um combustível abundante, barato e cuja tecnologia esteja provada. O GNL é, de momento, o único combustível de uso marítimo que reúne estas condições cumulativas além de ir ao encontro do recomendado pela Comissão Europeia e em linha com as metas para o Desenvolvimento Sustentável e mudanças climáticas da ONU. De qualquer modo, nesta tese, antevê-se o GNL como combustível de transição até que outros de origem renovável estejam disponíveis para serem largamente utilizados. Mas se o GNL parece, aparentemente, ser uma escolha óbvia, a prossecução de uma política de descarbonização como a preconizada exige a contribuição do Estado o que sugere ser necessário auscultar o contribuinte de modo a aferir a sua vontade de pagar pela mudança de paradigma e que mede o seu grau de aceitação/rejeição. Isto é feito com recurso à análise custo-benefício. Tendo-se identificado um notável gap de conhecimentos, nomeadamente a ausência de estudos baseados em análises de âmbito social, os objetivos a serem atingidos são: questionar as pessoas sobre a sua aceitabilidade, ou seja, auscultar a vontade de pagar da sociedade pela mudança na qualidade do ar; e, quantificar os benefícios ambientais, de saúde e outros através de uma análise custo-benefício social. Embora assumindo algumas incertezas no processo de quantificação, o resultado indica que os benefícios são quase 7,5 vezes superiores aos custos. Mesmo incorporando os impactos de outras externalidades não quantificadas, rácios benefício-custo de tal ordem de grandeza exigiriam grandes mas improváveis erros de cálculo para reverter os benefícios. Embora as estimativas presumam as particularidades portuguesas, os resultados são destinadas a ser reproduzidos e aplicados a outras realidades.

Palavras-chave: Transporte marítimo e sustentabilidade; Gás Natural Liquefeito; Combustíveis marítimos alternativos; Análise Custo-Benefício; Vontade de pagar;

AKNOWLEDGEMENT and DEDICATION

"*Je doûte; je pense donc je suis*"

Descartes
Discours de la Method

The difficult task, of giving birth this thesis has consumed more than four years of my life including time spending studying, collecting, researching and writing, revising and publishing it. Nonetheless, it was immeasurably gratifying to build something so defying from scratch while observing the subtle evolution week after week, month after month until the task being accomplished, and to look at it as a craft piece modelled by own hands.

The help from high discernment partners, as my advisors are, was precious to successfully accomplish such a challenging task. Therefore, I would first like to thank my thesis advisor Prof. Fernando Caetano who steered me in the right direction whenever he thought I needed it. Thanks also go to Vítor Caldeirinha for co-supervising my thesis, especially to matters relating to methodological guidance.

Furthermore, I want to give special thanks to Mário Esteves and Olga Dias for their collaboration as (non-profit) pre-test/pilot study interviewees as well as to all my proofreaders. In this sense I give thanks to all who anonymously had participated in the pretest/pilot survey and those who have responded to the research project questionnaire: without their collaboration and inputs the validation survey could not have been successfully conducted.

I also would like to express my gratitude to all direct and indirect participants, for ideas, help, interest and opinions throughout the evolution pathway that have led to the final results herein.

To my grandmother Julia in loving memory

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY, ABBREVIATIONS AND ACRONYMS

Bcf	Billion cubic feet
Boil-off	The effect of the heat input in warming cryogenic fluids (BOG)
Bunker fuel	Refers to all possible sorts of marine fuels
$CaCO_3$	Calcium carbonate
CaSO4	Calcium sulphate
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent; allows other greenhouse gas emissions to be expressed in terms of CO_2 based on their relative global warming potential (GWP)
cSt	Centistokes; measures the viscosity grade of a liquid
DWT	Deadweight tonnes
EC	European Commission
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EU	European Union
Flaring	Is the controlled and intentional burning of natural gas as part of production and processing
EGR	Exhaust Gas Recirculation
Gg	Gigagram (1 Gg equals one thousand millions of grams)
GHG	Greenhouse gases
g/mL	Grams per millilitres
GT	Gross tonnage
GWP	Global Warming Potential; the concept of global warming potential is used to compare the radiative forcing of different gases relative to CO_2 and represents the ratio of the cumulative radiative forcing *t* years after emission of a GHG to the cumulative radiative forcing from emission of an equivalent quantity of CO_2
HFO	Heavy fuel oil; pure or nearly pure residual oil, roughly equivalent to fuel oil table n. º 6 (high viscosity)

IGF Code	IMO's International Code of Safety for Gas-Fuelled Ships and other low flashpoint fuels
IMO	International Maritime Organization headquartered in London
IEA	OECD's International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
Kg/l	kilogram to litre
kPa	kilopascal
kt	Kilo tonnes (1 kt = 1000 tonnes)
KW	kilowatt
Lloyds	Lloyds Register Group (Classification Society)
LNG	Liquefied natural gas
MARPOL	International Convention on the Prevention of Pollution from Ships
MDO	Marine diesel oil; a mixture of heavy gas oil but which has a low viscosity (up to 12 cSt) and therefore do not need to be heated for use in internal combustion engines
MGO	Marine gas oil; produced by mixing light and medium fractions obtained by atmospheric distillation and by crude oil vacuum
MJ	Mega joule
mBtu	Million British Thermal Units
MMT	Million metric tones
Mt	Million tones
MW	Megawatt, corresponding unit of measurement to 10^6 watts
NaOH	caustic soda
NFR	Nomenclature For Reporting
NIR	National Inventory report (on greenhouse gases). The NIRs contain detailed descriptive and numerical information and the CRF tables contain all greenhouse gas (GHG) emissions and removals, implied emission factors and activity data
nm	Nautical mile
NO	Nitrogen monoxide
N_2O	Nitrous oxide
NO_2	Nitrogen dioxide

NO_x	Nitrogen oxide
O_3	Ozone
OECD	Organization for Economic Co-operation and Development
PM	Particulate matter
$PM_{2.5}$	Particulate matter with a diameter of 2.5 micrometres or less
PM_{10}	Particulate matter with a diameter of 10 micrometres or less
Ppb	Parts per billion
Reforming	(hydrogen reforming) or catalytic oxidation is a method to produce hydrogen from hydrocarbons or from methane
Retrofit	Fitting the existing fleet of shipping vessels with new technologies
rpm	Revolutions per minute (from ships engines)
SCR	Selective Catalytic Reduction. Is an advanced active emissions control technology system that injects a liquid-reductant agent through a special catalyst into the exhaust stream of a diesel engine
SEEMP	Ship Energy Efficiency Management Plan
Scrubber	Scrubber systems are a diverse group of air pollution control devices that can be used to remove some particulates and/or gases from industrial exhaust streams
SECA	Sulphur Emission Control Area
SO_2	Sulphur dioxide
SO_x	Sulphur oxide
Tonne	Unit of mass equal to 1,000 kilograms. The tonne is also known as "metric ton"
TJ	Terajoules
UNCLOS	United Nations Convention on the Law of the Sea
UNEP	United Nations Environment Programme
VOC	Volatile organic compounds
Venting	The discharge of vapours resulting from heat input in warming cryogenic fluids out of the storage container
Viscosity	(fuel's viscosity), expressed in square millimetres per second (mm^2/s) at a certain temperature (note: 1 mm^2/s = 1 cSt)
μm	Micrometre, that is, one millionth of a meter

INTRODUCTION

Paulo Jorge Pires Moreira
Ph.D. in Social Sustainability and Development

Human health and environmental hazards from shipping, a major industrial activity, are the concerns of this doctoral thesis aiming to discuss and evaluate liquefied natural gas (LNG) as an alternative fuel to ships' engines based on the rules and principles for progressive decarbonisation of maritime transport. In this sense, this thesis provides important inputs for the decarbonisation of marine transport and climate change mitigation policies addressing LNG as a substitute marine fuel as it lessens negative externalities compared with other fossil fuels. Therefore, LNG contribute for the phasing out of oil dependency - until feasible technically and economically renewable energy sources are available – comes under the spotlight taking into account socioeconomic costs and benefits. The CBA framework here developed as empirical analysis is important because available technical or economic-based studies showing that LNG offers real-world efficiency gains is a necessary but not a sufficient condition for LNG to be elected as a substitute fuel for shipping. In fact and equally important is to demonstrate the degree of social acceptability towards the energy paradigm change while concomitantly people's degree of awareness of such environmental decision is evaluated. These were the key elements that made this methodology chosen. Within the scope of social science knowledge the thesis' methodology combines both quantitative and qualitative research and aims to provide an interdisciplinary contribution for the field of research which is reflected in its comprehensive and theoretical linkages and novel connections while pushes the topic into new areas.

The thesis content is closely related with the EU's Energy Union and Climate goals, matches the Clean Power for Transport Package ambitions for a LNG market uptake and is aligned with the energy and climate-related targets under the United Nations' Sustainable Development Goals 7 - on energy - and 13 - on climate change - (UNCTAD, 2017)[2] thus in harmony with society's search for a better and more sustainable future for all. Thus, although the scope being at national level the root of the problem addresses collective concerns and actions since damages affect global commons.

The thesis is organized as follows:

Part I should start with an updated literature review of similar approaches supported in social studies concerning the introduction of LNG as an alternative fuel. However this is,

[2] See also: EC Directive 2012/33; EC Directive 2014/94; COM(2013) 17; COM(2013) 18.

so far as we know, non-existent, which invalidates the argument. The general information obtained is of little use to the methodology adopted, which represents an obstacle and a challenge. Thus, after describing the empirical method used and the way data are obtained that serve as input to create something new - the result of a cost-benefit analysis of social component, or output - a purely counterfactual analysis is initiated - an approach that can be found in the literature - on the advantages and disadvantages of using LNG in comparison with other traditional fuels, including the description of pre-treatment techniques on board. From this initial assessment some conclusions are obtained: LNG fuelled ships comply with all current and anticipated environmental legislation targets for nitrogen oxide (NO_x), sulphur oxide, (SO_x) particulate matter (PM) and carbon dioxide (CO_2) reduction (Chryssakis et al. 2014; Wurster et al. 2014) and is considered, at present time, one of the most promising alternative fuels in the maritime segment (Kolwzan and Narewski, 2012; Yaramenka et al. 2017; Liu et al. 2018; DNV GL, 2018; Moreira, 2018). Part I describes what is the concept of carbon footprint from shipping, to let know the emissions calculation methodologies and inherent complexity also encompassing the existing regulatory and legislative framework, policies and measures envisaged to mitigate emissions from ships. Part I also briefly analysis strengths and weaknesses of other potential substitute fuels and debate over the consequences of spills and sinks for different cases.

Part II introduces the problematic of pollutants emitted by ships. It starts by identifying global and annual CO_2 emissions and the danger CO_2 accumulation in the atmosphere poses, describes health and non-health hazards that come from the burning of traditional fuels and ends with an overview of the emissions from the Portuguese merchant fleet. After this introduction, it is demonstrated how was elicited the price people are willing-to-pay (WTP) for the change in the provision level in the quality of the good. This was achieved by means of Contingent Valuation method framed on individual preferences revealed through the results of a web survey. Prior to this, a pre-test/pilot study was used as a forerunner of the final survey whose main feature was to delimitate the upper and lower money bounds for the web survey. The respondents were meant to be able to comprehend the language, concepts and questions used in the survey; what they would get, how it would be provided and how they hypothetically have to pay for. The price people are willing-to-pay, a trade-off in which one benefit is given up in order to obtain another, provides the accuracy and relevance of an empirical study to fully assess the economic desirability of the change. To estimate society's WTP, the mean value obtained from the sample was multiplied by specific age groups of resident population to obtain the total amount Portuguese nationals are willing-to-pay.

Part III is dedicated to perform the (Social) CBA Analysis based on original methodology for data processing to estimate costs and benefits arising from the policy implementation and what is the net present value of such policy. Although there is plenty information and academic research about pollutant emissions from shipping and noxious effects over both people's health and the environment (e.g. Winnes and Fridell, 2010; Zhang et al. 2014; Chen et al. 2016) others who debate sector-specific pollution issues concerning mostly towards the adoption of mitigation techniques (e.g. Walsh and Bows, 2012; Ushakov et al. 2013; Ling-Chin and Roskilly, 2016) and others who provide knowledge about the role LNG can have to air emissions public policy targets (e.g. Thompson, Corbett and Winebrake, 2015), significant gaps in knowledge have been identified, namely a lack of studies anchored in social approaches to evaluate the true value the society has to bear from energy options and what is the level of social acceptability supporting those policies. This happens firstly, due to the novelty of the subject; for instance, LNG's viability entered too late in the EC's perceptions about substitute fuels for marine purposes. Secondly, the researchers have spent most of their efforts digging over the feasibility of the LNG based on ship-owners business case perspective of benefits and risks from a fuel switch rather than by doing a societal approach. On the contrary, the scientific innovativeness of this thesis is brought by a cost-benefit analysis based on people's willingness-to-pay to breathe a better air and to reduce environmental impacts produced by the national fleet after all costs and benefits have been quantified and monetised. Final results' for a three year reference period demonstrate beforehand that climate, health and non-health expected benefits to society are almost 7.5 times superior to the cost of the action. This means that the adoption of LNG as an alternative fuel is indeed a cost-effective solution in the context of "value for society" instead of "value for money" albeit is consistent with real-world efficiency gains. The view embodied in this particular study leads us to a reality that goes beyond mere expectation and shows that action is worth doing than choosing a "wait and see" policy. Furthermore and whilst focusing on the issues of one single country this thesis embodies sufficient contributions of knowledge to the international perspective of LNG as a substitute fuel assuming that the methodology and findings can be replicated to other countries (e.g. Baltic, Mediterranean, Black Sea countries), even though benefit-cost ratios will be dependent on people's WTP and country's particularities. Part III also includes a voyage-based model for estimating societal costs from energy use and emissions, proposed as a practical example of how this approach can be used and what is the essence of its outcomes.

Part IV presents the results from all the studies carried throughout this thesis casting a glance on the limitations and pointing out further research in need to explain less understandable issues. A discussion Section invites the reader to interpret and questioning himself about the significance of the findings, while it debates new understandings about the problematic. For example, a new insight brought by this Ph.D. thesis is the following: in order to change oil-based society's paradigm the transition needs support from main stakeholders, namely government agencies which mean public funding, but this is a very sensitive question: we are talking about taxpayers' money and direct state aid. Obviously this issue lacks support from citizens who should identify the purposes and recognise the importance of such policy, and is dependent upon the level of knowledge from decision makers who should implement it. By another hand, the idea of lowering carbon consumption by applying taxation on consumers can be obviously risky and no one should be surprised if the poorest of them begrudge paying for decarbonisation while they are struggling with stagnant wages, cuts to benefits and rising prices for food, transport and other essentials. As such, this is a delicate question that should be broadly discussed by experts, decision makers' and by ordinary people before policies are on place in order to avoid social discontentment. Lastly and even recognising that the trade-off dilemma is deemed as a simple monetary sum, one should remember that there is no simplicity when we talk about human lives and potentially irreversible environmental damages.

Finally, a prospective study for the introduction of LNG facilities and bunkering services in a Portuguese port was also conducted as part of the effort to disseminate the operational, technological and economic aspects of the LNG supply chain amongst port stakeholders, economic agents and population in general, another important gap that was found, in this case at both local institutional and industry levels.

PART I: LITERATURE REVIEW

1. LITERATURE SURVEY: OVERCOMING CONSTRAINTS

To clearly present the contribution of this thesis to the pool of existing knowledge, literature survey should present the most updated research status based on a thorough literature survey of papers published in a range of journals related to the topic addressed so as to fully appreciate the latest findings and key challenges. Yet, it happens that in this case the subject is really novel and few or no specific references are found mainly to what concerns to methodology and data resources, referring to social analysis based on people's willingness-to-pay and the contribution of national merchant fleet emissions to the national inventories, as inputs. The absence of specific literature is not only a disadvantage for the sake of comparing the results within the limits of the assumptions referred to herein; it is also a gap in knowledge (and in research) that needs to be fulfilled. However, some scientific evidence can be drawn from general work on environmental, health and non-health externalities related to the subject.

1.1 Methodology and assumptions

The theoretical assumptions of this thesis are rooted on a (Social) Cost-benefit Analysis. Historically, cost-benefit analysis were developed as an expansion of project analysis to incorporate the environmental effects of a project. Since then, "*corresponding assessment methods have evolved as evolved have been updated scientific evidence and improved modelling*" (Van der Kamp, 2017). CBA's assessment attaches money value to as many costs and benefits is possible – the most common and easy-to-understand metric. In the case of non-existing intervention, "business-as-usual" is considered to designate the counterfactual "do nothing scenario". Commonly CBA's uses two different perspectives with two different results: a normal financial cash-flow analysis to conclude on the funding need and, by adding the externalities and the correction of market prices to social values, the socioeconomic performance to conclude whether a projects is desirable or not. As such, CBA compares costs and benefits particularly in the public policy context of a particular intervention estimating the convenience for society as a whole, because a financial analysis by itself cannot properly capture societal benefits (Dubgaard, 2013)[3]. Despite its scientific foundations, CBA is applied social science and therefore it is not an exact discipline

[3] Both terms CBA and SCBA are used interchangeably. The mention "social" is applied only to stress CBA's social component.

largely because is based on approximations and hypotheses but also due to lack of verisimilar data or constraints in critical resources. Nevertheless, CBA methodology is widely used in regulatory context nowadays as means of foresee and cope with increasing environmental challenges including marine sources (e.g. Ofiara and Seneca, 2001; Caric, 2010; Brink et al. 2011) and to evaluate both health and non-health benefits from the policy intervention compared with the costs of a doing-nothing scenario (e.g. Kalli, Repka and Alhosalo, 2013; Ballini et al. 2015; Harris and Roach, 2016), yet few referring to fuel switch to LNG. Yaramenka et al. (2017) and Liu et al. (2018) are exceptions and they found that health and environmental benefits far outweigh the costs.

Estimates of costs and benefits may be based on market prices. However, there are no markets for the good in question (the atmospheric air, an extra-market good). As such marine airborne externalities can be valued through stated preference (SP) method and this needs to be measured empirically. SP methods are used to value non-market commodities and requires the use of hypothetical markets where a public good or service is transacted. Contingent valuation (CV) is a SP method which focus on the valuation of a non-market good and for the following it refers to the estimated value people are willing-to-pay (WTP) to obtain a given positive outcome (in this case environmental, health and non-health benefits) using the data collected being contingent on the features of the scenario (Carson and Louviere, 2010). While the concept of willingness-to-pay may depend on the ability "to pay", stated preferences also transmits to the analyst respondent' preferences for the good under evaluation. The price people (or, for this case, the random sample of Portuguese respondents to the survey) are willing-to-pay is a measure of present and future benefits and is closed to intergenerational equity - the concept or idea of fairness or justice between generations including environmental concerns, sustainable development, global warming and climate change. As we explicitly assume nationals considered as the "primary market" therefore their *collective* WTP is sufficient to measure the benefits of the project. In the possession of those elements we can carry on our specific analysis based on SCBA using damage values from the national merchant fleet emissions and the price people are willing-to-pay to reduce those damages by means of the introduction of LNG as ship's fuel, as inputs. The outputs are benefits gathered from that fuel switch. Part III of this thesis will better explain the concepts and methodology associated to our especially tailor-made CBA and how to use this tool to accrue and share scientific knowledge.

2. TRADITIONAL MARINE FUELS

Depending on their specific kinematic viscosity, a measure for the fluidity of the product at a certain temperature which depends on the intermolecular interactions, oil based fuels for propulsion or operations on-board a ship are commonly grouped into residual and distillate fuels. The first is also known as hard fuel oil (HFO) and the latter includes marine gas oil (MGO). For all ship types, the main engines (propulsion) are the dominant fuel consumers burning essentially HFO. Auxiliary engines and operation in ports require mainly the use of MGO. Distillate fuel is composed of petroleum fractions of crude oil that are separated in a refinery by a boiling process called distillation and they are considerably more expensive than residual marine fuels. Residual fuel is the fraction that does not boil, sometimes referred to as "tar" (Kolwzan and Narewski, 2012). Next subsections will introduce main aspects of residual and distillate fuels.

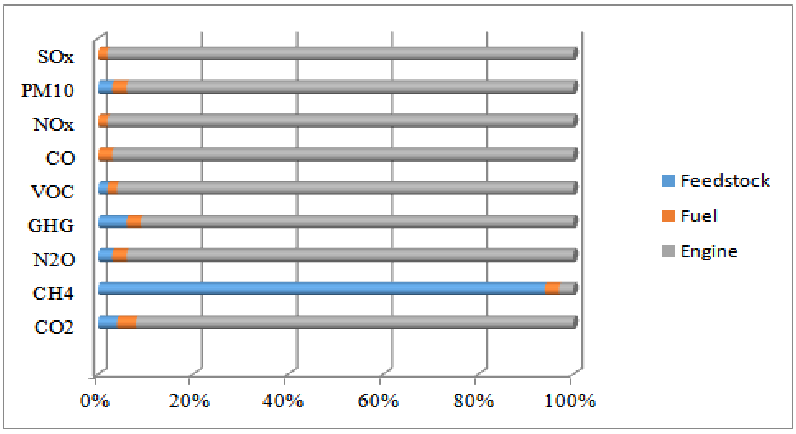
2.1 Residual marine fuels

Residual fuel oils are an unprocessed product made from the heavy fraction of the crude oil remaining after the most valuable products have been extracted, namely gasoline and distillate oil. It is a high viscosity grade fuel: at 50°C is within the range of 392/450 Cts[4] and a density between 0.869 and 0.892 grams per millilitres (g/mL) at 15°C (Environment Canada, 1999). Residual fuel oil is so viscous that it has to be heated with a special heating system before use[5]. When fuel oil is burned, an amount of heat is released, defined in the international units of energy Mega Joules per kilogram (MJ/kg) of the fuel (Vermeire, 2012). Residual fuel oil has a default carbon content of 21.1 kg per Gigajoule (kg/GJ) values that are also used for tar, peat and asphalt in contrast with 20.0 for crude oil and naphtha (Harmelen and Koch, 2002). HFOs may exceed 3% sulphur content which would yield about 0.06% sulphur in the exhaust gas (Goldthorpe, 2013) albeit according to ISO 8217 their maximum content must not exceed 3.5%. HFO burning presents problems such as: extreme smoke temperatures, unburned fuel oil waste in the smoke, black carbon and soot build-up in the combustion chamber, and fuel over-consumption increasing stack emissions. HFO's undesirable properties make it the cheapest liquid fuel available and the most widely used (80-90%) marine fuel at this time (Balon, Lowell and Curry, 2012;

[4] Centistokes (cSt) is the derived centimetre-gram-second (CGS) unit of kinematic viscosity.
[5] Heavier viscous products than HFO are asphalt for paving roads and bituminous residues that are used for roof waterproofing.

Chryssakis et al. 2014); virtually all medium and low-speed marine diesel engines are designed for heavy fuel oil. Total fuel consumption of shipping is dominated by three ship types: oil tankers, container ships and bulk carriers. Figure 2.1 depicts relative contribution from feedstock, fuel and engine sources to emissions from a tanker burning residual oil presenting exceptionally high emissions for CO_2, NO_x SO_x and PM_{10} among others.

Figure 2.1: Relative fuel consumption.



Source: Adapted from Thomson, Corbett and Winebrake (2015).

According to Thomson, Corbett, and Winebrake, (2015), although HFOs are the most energy efficient in terms of total fuel-cycle energy because they are a relatively low energy-intensive fuels to produce, referring to the extraction and processing stages also known as upstream stages, conversely and according to the aforementioned authors they are the most polluting with plus than 95% of the emissions coming from the vessel's operation stage (downstream stage).

When HFO is spilled into water only 5–10% is expected to evaporate in the first hours following the spill (Environment Canada, 1999; American Petroleum Institute, 2004; National Oceanic and Atmospheric Administration 2010 (from this point forward only NOAA)), primarily the lighter hydrocarbon fractions. The remainder will then often sink to the bottom of the water column where it stays for years. If it eventually burns, noxious fumes from oil will harm animals that can't avoid it, and others can be covered in it leading to suffocation and death. Birds that get enough oil on their feathers eventually lose their ability to fly, and oiled sea otters can suffer from hypothermia (NOOA, 2009). Taking into account the previous numbers designating the percentage of international shipping fuelled by residual fuel oil, this number translates a somewhat worrying global picture. This topic will be further analysed in subsection 7.1.4 where we will look to some LNG's advantageous considerations to what refer to accidents and spills.

2.2 Distillate marine fuels

Distillate fuel is obtained by crude oil in a refinery by a boiling process called distillation accounting for between 10-20% of fuel annually burnt by international shipping, to provide propulsion, heat, and electricity (Balon, Lowell and Curry, 2012; Chryssakis et al. 2014; DNV-GL, 2014). MGO and MDO (marine diesel oil) are low grade fuels which, given the 3.5% global maximum sulphur content requirement (0.5% from January 1st 2020; 0.1% in the sulphur Emission Control Areas since January 1st 2015), they can comply with IMO's directives for sulphur content. Yet, they are considerably more expensive than residual marine fuels and their availability is dependent on global refinery capacity. Indeed, meeting regulations through the use of low sulphur distillates and being able to provide an adequate global supply could increase the fuel cost for operators and can be considered to be too great a challenge since "*it assumes sufficient fuel is available for use, which, in reality is likely to put strain on refinery capacity and put the sector into direct competition with other end-users*" (Gilbert, 2013:377)[6].

Nevertheless, the scenario of a growing demand in the next decades for such fuels doesn't fit climate change concerns for reducing anthropogenic emissions, oil dependency or to restrain noxious health emissions from shipping. In reality, promotion of diesel fuels can entail a business-as-usual scenario (BAU) and may give wrong incentives to stakeholders. Besides that, if one looks over the full life-cycle perspective, CO_2 emissions will increase largely from a rise in the energy required for additional refining. On the other hand, diesel emissions were recently classified as carcinogenic by the International Agency for Research on Cancer. Saying so, and despite the almost somewhat inevitable contribution of marine diesel fuels for the energy-mix in the near future, it is very unlikely that a global diesel-only fleet correspond to the need of tackling down harmful emissions from shipping.

[6] Even assuming that capacity exists globally to produce sufficient 0.5% sulphur limit, refineries will not necessarily be geared towards the marine fuels market as it is stated by the International Bunker Industry Association (http://ibia.net/signals-hinting-at-2020-entry-into-force-of-0-50-global-sulphur-cap/). The IMO's global sulphur cap (0.1% max.) from 2020 onwards will launch some panic and scarcity within the industry.

3. ENERGY USE AND ENVIRONMENTAL PERFORMANCE

Although the empirical analysis applied later on in the case-study (Chapter 13) focus only on ship's end-use emissions the objective should be to capture complete noxious emissions from marine transport, i.e. the whole energy use consumption associated with each of the different fuels as a way to compare their environmental performance. In order to do so, overall life cycle global warming potential (GWP) of marine fuels - the carbon footprint originated from fuels - should be compared using a life-cycle approach (LCA)[7]. In such analysis, emissions are quantified along the entire fuel pathway from raw material acquisition, i.e. crude oil or natural gas, followed by fuel production, distribution and finally combustion in the marine engines as used by Winebrake, Corbett and Meyer (2007), taking into account consideration of energy use and criteria pollutant emissions. Such comprehensive approach is outside the scope of this thesis since it consumes not available time and resources. Notwithstanding, due to the importance LCA has for the interpretation and judgment of results when comparing energy options, some key aspects need to be mentioned.

3.1 The Carbon Footprint of the marine industry

Carbon footprint is an overall life cycle assessment considering the emissions of GHG of the source from "cradle-to-grave". The three most important GHG emitted from marine fuels are the CO_2, the CH_4 and the N_2O[8]. The carbon footprint is calculated by assessing global warming potential (GWP) at a 100 year time perspective (IPCC, 2007) considering emissions of those pollutants. GWP values are released by the IPCC for three time horizons, 20 years (GWP20), 100 years (GWP100) and 500 years (GWP500), although GWP100 is used almost universally in accounting methodologies and protocols. According to Wright, Kemp and Williams carbon footprint is defined as:

> "a [defined] population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest, calculated as CO_2 equivalents".
>
> (Wright, Kemp and Williams, 2011:61).

[7] LCA is recommended by the United Nations Environment Programme (UNEP) as a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle.
[8] Nitrous oxide (N_2O), a GHG, should not be confused with nitrogen oxide (NO_x) caused by the high temperatures and pressures in combustion engines.

It allows for a comprehensive assessment of human contribution to climate change which is consistent with standards of economic and environmental accounting. Although carbon footprint is a widespread used term, Wiedmann and Minx (2007) prefer the expression "*climate footprint*" because a comprehensive GHG indicator should include all the gases irrespectively of their carbon-base. When calculating a carbon footprint, GHG emissions are accounted by using a single meaningful unit: CO_2 equivalent, or CO_2e for short, which is based on a calculation of the GWP of 1 kg of a GHG over a certain number of years and expressed as the amount of CO_2 that would cause the same effect if emitted to the atmosphere (1 kg CH_4 = 25 kg CO_2e; 1kg N_2O = 298 kg CO_2e).

For what is of interest to us, shipping emissions GHG inventory should be reliably calculated in order to formulate and evaluate the implementation of relevant regulations (Psaraftis and Kontovas, 2009). This should entail the full completion of a climate footprint with the addition of a further measure of the total amount of emissions of a set of clearly defined and stated GHGs including aerosols, particulate matter, ozone and black carbon (Wright, Kemp and Williams, 2011). Baldi, Bengtsson and Andersson (2013) presented the following data for footprint calculations from different marine fuels. Well-to-tank refers to emissions from extraction, storage and distribution. Tank-to-propeller refers to downstream emissions (Table 3.1).

Table 3.1: Carbon footprint calculations for different fuels.

	HFO (1 MJ)	MGO (1 MJ)	LNG (1 MJ)
Well-to-tank			
Primary energy use (MJ)	1.09	1.16	1.1
Emissions of CO_2 (g)	6.68[a]	7.02[b]	6.97
Emissions of CH_4 (g)	0.073	0.078	0.046
Emissions of N_2O (g)	0.0002	0.0002	0.0036
Tank-to-propeller			
Urea consumption (2-stroke) (g)	1.19	1.10	1.06
Urea consumption (4-stroke) (g)	0.835	0.835	0
Emissions of CO_2 (g)	77.2	73.1	54.4
Emissions of CH_4 (2-stroke) (g)	0.000756	0.000744	0.04609
Emissions of CH_4 (4-stroke) (g)	0.000463	0.000465	0.816[c]
Emissions of N_2O (2-stroke) (g)	0.00388	0.0039	-
Emissions of N_2O (4-stroke) (g)	0.00352	0.00352	-
Totals (CO_2)	83.88	80.52	61.37

LNG to HFO (-26.83%) LNG to MGO (-23.78%)

Source: Adapted from Baldi, Bengtsson and Andersson, 2013.

According to this life-cycle assessment study LNG offers GHG savings from a well-to-propeller perspective, the same is to say from the extraction as a raw material until its final end-use as fuel to propeller: (LNG-to-HFO -26.8%; LNG-to-MGO - 23.8%). Yet, some other authors (e.g. Thomson, Corbett and Winebrake, 2015; Kollamthodi et al. 2016) point that this is true but depending from the intensity of fugitive methane emissions along the pathway. Methane emissions, better say, the methane slip, will be discussed in Section 7.3.

3.1.1 Emissions calculation methods

The Intergovernmental Panel on Climate Change (IPCC) categorize methods for calculating emission into three Tiers in increasing complexity. Tier 1 method (the default method) is the least accurate and specific but tends to be the easiest method to apply with the objective of calculating an accurate carbon footprint based on specific information. The Tier 1 method is actual emission estimation method although is often based on default activity data where better data is not available, i.e. CO_2 emissions are multiplied by estimated fuel sold with a default CO_2 emission factor (kg/Terajoules – TJ). This is equal to the carbon content of the fuel multiplied by 44/12 (Waldron et al. 2006). For marine emissions the following formula applies:

$$Emissions_a = \sum [Fuel_a * EF_a] \quad (3.1)$$

Where:
Emissions = Emissions of CO_2 (kg)
$Fuel_a$ = fuel sold (TJ)
EF_a = emission factor (kg/TJ)
a = type of fuel (e.g. HFO, diesel, natural gas)

The quantity of fuel used depends on many factors including vessel type, age, condition, distance travelled, engine load and speed. The calculations can be done for a single roundtrip voyage or from an engine over the duration of a year, for example, as used in our case-study calculations depicted further on Chapter 13.

The Tier of method used in calculating carbon emissions from shipping will be determined by the specificity of data available. It is usually possible to apply at least Tier 2 methods to the calculation of direct emissions, as most developed countries publish national emissions factors based on national average carbon contents of fuels, in conjunction with the manufacturer's published emissions factor per unit of distance travelled. This method would be specific to the type of engine and would use relatively accurate data to determine the specific distance travelled[9]. However, the mechanical condition of the engine and factors relating to engine use may cause actual emissions levels to be different from those predicted.

Tier 3 methods are the most accurate but also more time consuming and costly to apply. Notwithstanding, fuel inputs and emissions based on published national emissions factors for the fuel type can be measured with a high degree of accuracy and, therefore, there is little uncertainty in the result. Our voyage-based model follows Tier 3 assumptions.

Tiers 2 and 3 are technology-based methods and are also called "bottom-up" approach. The bottom-up approach is generally the most accurate for those countries whose energy consumption data are reasonably complete (Table 3.2). Both methodologies need to strive to capture the full life cycle impacts.

Table 3.2. The IPCC Tier methods for calculating emissions.

Tier	Description	Examples
1	Use of nonespecific data to estimate emissions	* National average fuel use per capita * IPCC default emissions factors * Assumption that technology meets minimum regulatory requirements
2	Use of country-specific data to calculate emissions	* Country-specific emissions factors * Engineereing estimates of system use and design * Technology modeled based on design specifications * Annual fuel use calculated from money spent multiplied by average fuel price for a year * Total distance travelled within a community, based on traffic counts and distances
3	Use of technology-specific data to calculate emissions	* Metered and submetered energy and fuel use * GHG emissions directly monitored using specialist equipment * Equipment modeled based on design specification, age of equipment and quality of maintenance

Source: Adapted from IPCC.

3.2 Life-cycle assessment methodologies

3.2.1 Top-down approach

Top-down approach is less labour and time intensive than bottom-up but also less accurate and subject-specific. Nevertheless, for international shipping data cost is a pivotal issue

[9] The Tier 2 IPCC approach requires only minor additional specificity. The *IPCC Guidelines* do not currently provide Tier 2 default emission factors by fuel type and engine type (Jun, Gillenwater and Barbour, 2001).

since it requires much more time and access to accurate data is expensive and statistics are mostly collected by Lloyd's Maritime Information System (LMIS) requiring annual updates and this circumstance makes top-down approaches be used instead of bottom-up methods.

Marine emissions top-down approach uses global fuel use data to calculate overall bunker fuel consumption, then uses national statistics compilations on fuel types and engine types to attribute emissions. For example, sulphur oxide emitted by ships will be derived by considering the total concentration of this pollutant at national level and by determining which part of the total concentration is imputable to transport sector and to the specific transport mode considered (Miola et al. 2008). We need to consider that this is not a completely reliable method and can produce underestimations reason why the IPCC recommends calculating GHG emissions based on fuel sales. That is the case of Portugal where the Portuguese Environment Agency (APA in its Portuguese initials) publishes fuel sales figures at a disaggregated level, bringing it closer to a micro system as we shall see later.

3.2.2 Bottom-up approach

As above explained, bottom-up approach uses fleet numbers and fuel consumption including auxiliary engines to estimate emissions taking into account assumed activity data and takes into account inaccuracies in bunker fuel records and reports. The calculation includes fuel consumptions and emissions not only at sea but also in ports during low-load and idling-modes of the engines and considers consumption rates and emissions of the auxiliary engine equipment (Eyring et al. 2005). Using actual vessel movement data rather than assumed movement the estimations are accuracy improved about geographical distribution. An example of a bottom-up calculation for the international ocean-going vessels can be seen in Eyring et al. (2005), Madsen and Olsson (2012) and Corbett and Khoeler (2003). For instance, Corbett and Khoeler (2003) have divided all world 89,063 ocean-going ships of the 2001 fleet inventory into 11 main ship classes. The corresponding 117,500 engines for the 11 classes were further divided into 132 engine sub-groups. For each engine sub-group the fuel consumption FC_i (in tonnes per year) is calculated by multiplying the accumulated installed engine power Pi (in MW) with the engines' average load based on duty cycle profiles F_{MCR} (in %), the average annual engine running hours τ_i

(in hours per year) and the power-based specific fuel-oil consumption rate $SFOC_i$ (in kg/kWh) defined by the following equation:

$$FC = \sum_{i=1}^{132} FC = \sum_{i=1}^{132} P_i * FMCR_{,i} * \gamma_i * SFOC_i \qquad (3.2)$$

Summing up over all 132 sub-groups gives the total fuel consumption (*FC*). A more detailed example is given by Klein et al. (2017) and is used to determine the emissions of vessels anchored in harbours, travelling and manoeuvring on Dutch territory and seagoing vessels on the national continental shelf. A distinction is made between main engines and auxiliary engines. Emissions of CH_4 and N_2O are more difficult to estimate accurately than those for CO_2 because emission factors depend on vehicle technology, fuel and operating characteristics.

Both two subsections above are intended to let know the methods and inherent complexity to quantify ships emissions. This is relevant to introduce to data quantification methodology to be used in Part III of this thesis partially gathered from the Portuguese National Inventory Report. These Reports issued by the Portuguese Environmental Agency, under the dependency of the Ministry for the Environment, are annually submitted to the UN Framework Convention on Climate Change (UNFCCC) under the Kyoto Protocol and to the European Commission. The present Report (2016) displays data from 2014 following a bottom-up approach in conjunction with a top-down approach for calibration. Similarly, disaggregated industrial sectors indicators from year 2014 used to obtain national quotas by pollutants were gathered from the NFR spreadsheet submitted to the EMEP[10] which reflects the results from the previous. In our particular case carbon dioxide, sulphur oxide, nitrogen oxide and particulate matter emitted by national navigation will be considered for calculations. Later, the case-study report also follow a bottom-up approach methodology as well based on vessel's specific fuel consumption adapted to a hypothetical voyage trip between two major Portuguese ports.

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[10] European Monitoring and Evaluation Programme under the Convention on Long-range Transboundary Air Pollution (CLRTAP).

4. GOVERNING POLICY AND LEGISLATIVE FRAMEWORK

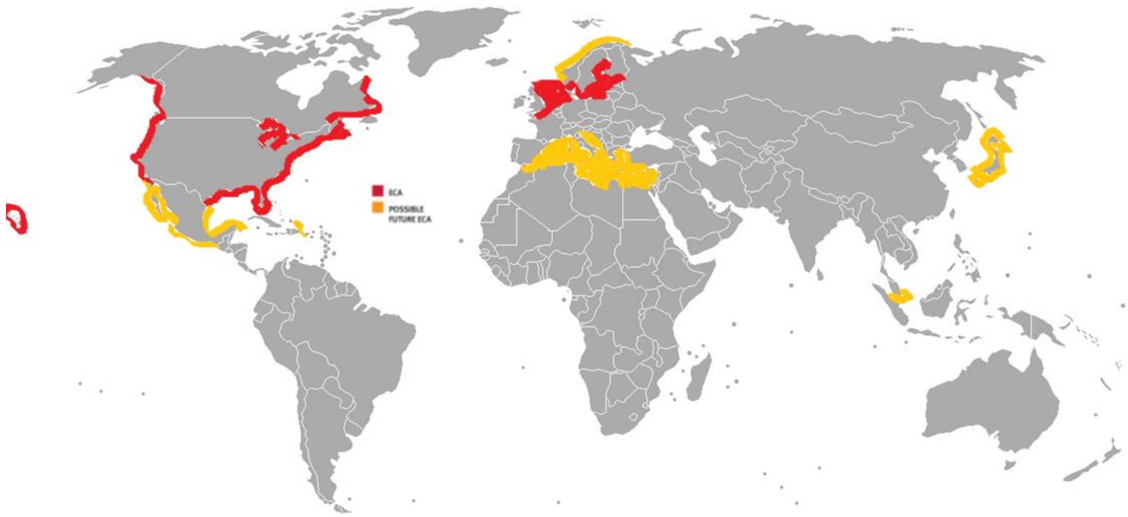
The Council of the European Union (EU) and the European Parliament issued in 1999 the Directive 1999/32/EC/ addressing concerns about the high level of sulphur content in marine fuels within the European Union. This Directive has been amended in 2012 and today is named Directive 2012/33/EC. Nevertheless, this effort on sulphur content burnt on-board made at a supranational level was not specifically addressed but instead the Directive refers to the corresponding revised International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI regulation issued by the International Maritime Organization (from now on referred to as IMO). Recently, the European Parliament addressed the EU governments urging them to include emissions reduction target in shipping and aviation, alleging that if these two sectors were a country, they would rank in the top 10 list of biggest polluting nations in the world. Shipping contributes approximately for 3.1% for global GHGs worldwide (IMO, 2014; Rahman and Karim, 2015), some 816 Mt carbon dioxide equivalent (CO_2e) for greenhouse gases (GHGs) combining CO_2, methane (CH_4) and nitrous oxide (N_2O) in year 2012. Moreover, future shipping CO_2 emissions are projected to increase significantly in the coming decades and, according to the IMO (2014) scenarios project an increase by 50% to 250% in the period to 2050. Under a business-as-usual scenario and if other sectors of the economy reduce emissions to keep global temperature increases below 2°C, shipping could represent a whopping 10% of global GHG emissions by 2050. This means that a delay in reducing shipping emissions will require steeper emission reductions from this sector in later years, presenting a far bigger challenge in costs for the industry and negatively impacting world trade (Transport and Environment, 2015).

4.1 The MARPOL Annex VI new fuel requirements

Due to the international nature of the shipping industry it has been considered too complex for emissions to be regulated under the United Nations Convention on Climate Change (also known as The Kyoto Protocol) because emissions from shipping cannot be the responsibility of a specific country. As such, emissions caps and standards from shipping are responsibility of the IMO an agency of the United Nations (U.N.). IMO ship pollution rules are contained in the MARPOL 73/78 Convention. Subsequently, the MARPOL Convention has been amended by the “1997 Protocol” which includes Annex VI titled

"Regulations for the Prevention of Air Pollution from Ships". MARPOL Annex VI sets limits on NO_x and SO_x emissions from ship exhausts and prohibits deliberate emissions of atmospheric ozone depleting substances (e.g. chlorofluorocarbons) with the objective to minimize environmental and health risks related to air pollution from ships, in particular for people living in port cities and coastal communities. Although Annex VI requirement foresees a decline of those emissions through to 2050, CO_2 emissions are expected to continuously increase. NO_x increase in parallel with CO_2 albeit at a lower rate due to Tier III Regulation. The IMO emission standards are commonly referred to as Tier I, II and III standards. The Tier I standards were defined in the 1997 version of Annex VI, while the Tier II/III standards were introduced by Annex VI amendments. Two sets of emission and fuel quality requirements are defined by Annex VI: i) global requirements, and ii) more stringent requirements applicable to ships in Emission Control Areas (ECAs). An ECA can be designated for SO_x and/or NO_x, subject to a proposal from a Party to Annex VI.

Figure 4.1: Existing (red) and expected (yellow) Sulphur Emission Control Areas [11].



Source: Adapted from IMO.

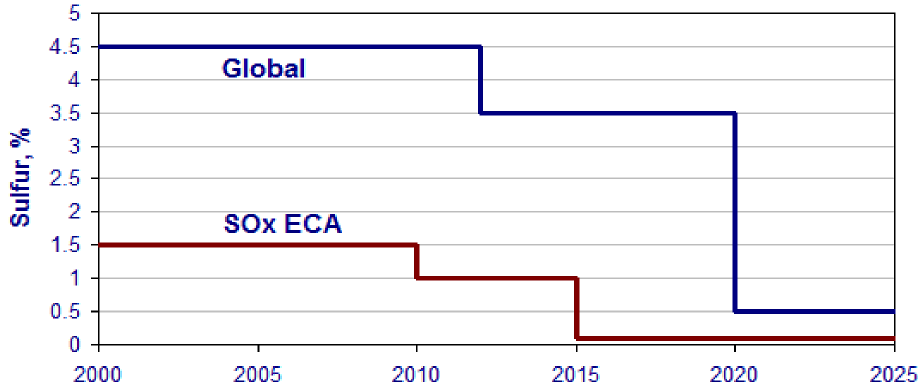
The MARPOL Annex VI has strengthened the standards relating to NO_x emissions, with NO_x emissions to be cut by 16-22% as from 2011 compared to 2000 levels, and by 80% in 2016. However, while sulphur limit values apply to the entire fleet, NO_x emission limits

[11] North America, including the Great Lakes and much of Northern Europe (in red) are currently ECA zones. Other areas (in yellow) are pending. Existing NECAs are only North American coast, Caribbean Sea, Puerto Rico and the U.S. Virgin Islands including most of U.S. and Canadian coast (for both NO_x and SO_x).

only apply to new ships sailing in designated areas; the NO_x Emission Control Areas (NECAs). A NECA for the English Channel, the Baltic Sea and the North Sea areas will be implemented on January 1st 2021 although it will only apply to new as-of-2021-built ships. In order to curb down emissions in an effective way, the criteria set forth in Annex VI for a full implementation of this legislation has to be put in place and should the IMO extend the SECAs to the Mediterranean Sea, the Black Sea, the Bay of Biscay and Iberian coast, and designate NECAs as soon as possible while monitoring compliance with the provisions of Annex VI.

In Sulphur ECAs (SECAs), requirements are more stringent. Beginning in July 2010, new and existing ships operating in ECAs were required to use fuels with maximum 1% sulphur content decreasing to 0.1% in 2015. Meanwhile the amendments provide for a progressive reduction of the global sulphur content of marine fuels as follows (Figure 4.2): from January 1st, 2012 the sulphur cap was reduced, from 4.5% to 3.5% and then progressively to 0.5% from 1 January 2020[12].

Figure 4.2: Global and ECA's sulphurous emissions reduction.



Source: IMO's MARPOL Annex VI Fuel Sulphur Limits.

4.2 Technical measures: Energy Efficiency Design Index (EEDI) for new ships

The Energy Efficiency Design Index (EEDI) for new ships is an important technical measure as it aims at promoting the use of more energy efficient and less polluting equipment and engines. The EEDI requires that from 2015 new ships should be 10% more

[12] Almost 70% of the world fleet is estimated to be entering ECA areas (Kolwzan and Narewski, 2012).

efficient, 20% more efficient by 2020 and 30% more efficient from 2025, aiming at to reduce annually up to 263 million tonnes of CO_2 by 2030 (ICCT, 2011).

In the 2050 horizon, the EEDI proposes a reduction of CO_2 emissions in the order of 50% per tonne/km. This regulation requires a minimum energy efficiency level per capacity/mile and it applies to new cargo ships greater than 400 GT varying with ship type, size and function. However, it has also raised concerns that some ship designers might choose to lower the installed power to achieve EEDI requirements instead of introducing innovative propulsion concepts (Papanikolaou et al. 2016). Future Energy Efficiency Design Index revisions may include additional ship and propulsion types by adjusting the calculated EEDI formula[13] based on design specifications and sea trials of new ships.

Table 4.1: EEDI implementation schedule.

2013	2014	2015	2020	2030	2050
EEDI, SEEMP regulations enter into force for 90% of existing fleet	EEDI required to meet energy efficiency targets	New ships must improve efficiency by 10%	New ships must improve efficiency by 20%	New ships must improve efficiency by 30%	50% CO_2 reduction per tonne/km

Source: Author's elaboration.

The EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry. However, and since ship efficiency can help to reduce the fuel bill, which represents the larger portion of operational costs, it is likely that it will result in more efficient ship designs and consequently in ships that have better operational efficiency. Improvements in efficiency will continue after 2030, although it is impossible to accurately predict because of the high uncertainty of technological development over such a timescale (IMO, 2014).

[13] The EEDI estimates ship CO_2 emissions per ton-mile of goods transported relative to a reference average of similar ships, using the following formula: EEDI = $P \cdot SFC \cdot C_f / DWT \cdot V_{ref}$, where P is 75% of the rated installed shaft power, SFC is the specific fuel consumption of the engines, Cf is CO_2 emission rate based on fuel type, DWT is the ship deadweight tonnage and $Vref$ is the vessel speed at design load.

4.3 The Ship Energy Efficiency Management Plan (SEEMP)

In addition to the EEDI, the new chapter 4 of MARPOL's Annex VI requires all ships or ship operating companies to develop and maintain a Ship Efficiency Management Plan (SEEMP) which provides a mechanism for monitoring efficiency performance over time. Conversely from EEDI, which applies to new cargo ships, the SEEMP applies to all ships taking into account operational measures to reduce fuel consumption, e.g. fuel efficient operations, optimized ship handling, hull and propulsion, machinery and equipment, energy conservation and awareness. The SEEMP establishes a mechanism for a shipping company and/or a ship to improve the energy efficiency of ship operations providing an approach for monitoring ship efficiency performance using, for example, the Energy Efficiency Operational Indicator (EEOI) as a monitoring and/or benchmark tool[14]. The SEEMP urges the ship-owner and operator at each stage of the operation of the ship to review and consider operational practices and technology upgrades to optimise the energy efficiency performance of a ship.

According to Bazari and Longva (2011), by 2020, an average of 151.5 million tonnes of annual CO_2 reductions are estimated from the introduction of the EEDI for new ships and the SEEMP for all ships in operation, a figure that by 2030, will increase to an average of 330 million tonnes annually. However, and according to the same Bazari and Longva, (2011), a great uncertainty surrounding the effects of the SEEMP is admitted since the results will be felt mostly at the long run. Following the same appreciation, Johnson et al. (2013) concludes that a number of factors that are considered to be crucial to be well succeeded are missing, such as requiring a company policy and a management representative, a baseline and setting goals, management commitment and accountability, and procedures for acting on non-conformities, concluding that these gaps are detrimental to the success of the SEEMP. Because the energy consumption monitoring practices are left to the industry itself to decide (Armstrong and Banks, 2015) and since improvements are driven by economics, compliance and customer requirements it is vital to take some steps particularly those to reduce the lack of reliable and robust information on ship performance, fuel consumption and hence predicted emissions.

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[14] Energy Efficiency Operational Index represents the mass of CO_2 emitted per unit of transport work to obtain a quantitative indicator of energy efficiency of a ship and/or fleet in operation. The EEOI enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation, e.g. improved voyage planning or more frequent propeller cleaning, or introduction of technical measures such as waste heat recovery systems or a new propeller.

5. EMISSIONS MITIGATION EFFORTS

According to the Hong Kong Environmental Protection Department (HKEPD), reduced emissions from power plants and road transport over the period 2007-2013 had made navigation the largest sectoral emission source in 2013 in that part of the world. In fact, in port cities pollution from ships, especially near port areas is becoming a matter of concern[15] in several port-cities, as it happens in Venice and Barcelona. Actually, the same concern is about to begin in Portugal's city capital – Lisbon, an increasingly tourism destination that is experiencing a major annual growth in cruise ships.

In the meanwhile and especially in some sea areas along busy shipping lanes, some mitigation techniques and abatement measures have been implemented aiming at reduce ship emissions by exhaust gases treatment techniques, and can be seen as incremental contributions of parts to a whole. Notwithstanding, as we intend to demonstrate, to meet ambitious reduction goals more profound changes will be needed, especially for the EU to achieve the climate goals up to 2020 and beyond established under the 2012 Revised Gothenburg Protocol[16].

5.1 Scrubber technology for the reduction of SO_x and PM emissions

Scrubbers are mechanical devices that can remove SO_x and PM from ship's engine exhaust. From January, 1st 2015 ships operating in a (sulphur) Emission Control Area (ECA) need to use distillate fuels or a technology that can reduce emissions to an equivalent level. One possibility for a ship owner to reduce the sulphur content is installing on-board scrubbers (also known as exhaust gas cleaning system). Scrubbers can be effective in complying with regulations that require the use of fuel with 1% or 0.5% sulphur content; however, the ability of certain scrubbers to provide equivalent 0.1% SO_x emissions to comply with ECA's requirements is more uncertain (ABS, 2013). On the other hand, the degree to which a typical scrubber provides NO_x emissions reduction is negligible and to meet future NO_x requirements an auxiliary catalytic reduction device must be installed.

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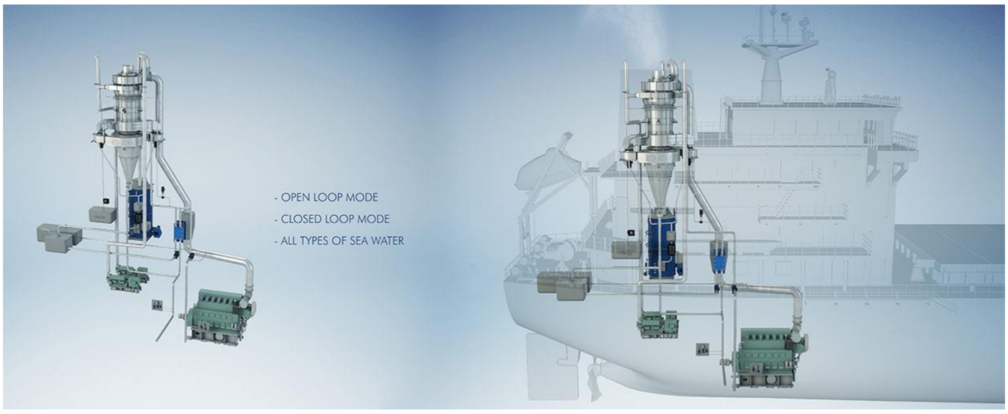
[15] It is worth to say that ship cruise segment including cruise ferries (e.g. the 2,800 pax Viking Grace) is one of the most suitable for the use of LNG as a substitute fuel.

[16] It refers to the overall commitments to reduce emissions by 59%, 42%, and 22% of, respectively, SO_2, NO_x and $PM_{2.5}$ below 2005 levels by 2020. Also it is not consistent with the decarbonisation target of 60% reduction goal by 2050, established under the EU's White Paper on Transport.

Figure 5.1: Scrubber installation on-board a ship.



Source: Clean Marine.

Available from: http://www.cleanmarine.no.technology. (Accessed February 15, 2015).

There are different types of scrubbers, notably two main types: wet and dry. For the former type, two kinds of technologies are used: open-loop scrubbers that use seawater as wash water, and closed-loop scrubbers that use freshwater treated with an alkaline substance like sodium hydroxide (caustic soda). In an open-loop scrubber, when sulphur oxide in the exhaust comes into contact with seawater, a fast and efficient reaction takes place between the SO_x in the exhaust and the calcium carbonate ($CaCO_3$) in the seawater, resulting in calcium sulphate ($CaSO_4$) and CO_2, thereby neutralizing the acidity of the SO_x. Because seawater has a slightly alkaline pH (close to 8), which means that contains an excess of base over acid, seawater scrubbing seems to be the most appropriate solution (CE Delft, 2006).Wash water is treated by removing solids and raising the pH before being discharged back to the sea. A freshwater scrubber operates in a similar way, but instead of using seawater, freshwater is boosted with an alkali, typically sodium hydroxide (NaOH) injected to neutralize SO_x in the exhaust (Tossio, 2009). Freshwater scrubbers, which allow direct control of wash water alkalinity, are typically used when high SO_x removal efficiency is needed, or in areas where low or variable alkalinity of seawater precludes the use of seawater scrubbers. As freshwater scrubbers can be operated under “zero discharge” mode, they are suited for vessels that operate in sensitive or vulnerable water bodies (like the North Sea and the Baltic Sea). Yet, this analysis does not include concerns on environmental impacts of wet scrubber discharges since wash water generated as a by-product (sludge) can contain contaminants from three sources (EPA, 2011a):

i) pollutants scavenged from the exhaust gas exiting the engine (combustion products, fuel and lubricants);
ii) the source of wash water used to clean the exhaust (seawater or freshwater); and,
iii) the scrubber itself (dissolution of materials, possible reaction products and/or chemical additives).

In fact, the acidity of the sludge discharged could become an environmental concern that hinders further adoption of open-loop scrubbers, the cheaper wet scrubber technology.
While the current IMO's standards requires the pH value of scrubber discharge wash water to be 6.5 or higher, wash water discharged from open-loop scrubbers typically has a pH of around 3.5 containing sulphur and other elements that are harmful to the marine environment. In line with these preoccupations, the Joint Group of Experts for Scientific Aspects of the Marine Environmental Protection (GESAMP) recommended the need for the IMO to consider the potential contribution to ocean acidification of the large scale application of SO_2 capture from ships and the discharge of effluents containing sulphurous/sulphuric acid (EMSA, 2010). Assuming the operation of an auxiliary engine with an output of 1 MW, running on fuel with 3% sulphur content and near 100% abatement through the use of a scrubber, 82 tonnes of seawater would be required per hour, producing 460 kg of calcium sulphate or similar salts per day (Fung, et al. 2014).
Dry scrubbers as opposed to using wash water to capture sulphur oxide in the exhaust, exposes hydrated lime-treated granulates to the exhaust gas to create a chemical reaction that removes the SO_x emission compounds, known as flue gas desulphurization process. The hydrated lime reacts with the hot exhaust gas and absorbs the SO_x components to form pellets of calcium sulfate dehydrate ($CaSO_4 \cdot 2H_2O$), or gypsum, a non-toxic harmless substance. Since the exhaust does not pass through water it is not cooled and therefore dry scrubbers can be used in conjunction with selective catalytic reduction (SCR) units, which typically require exhaust gas temperatures above 350°C to enable the catalysts to operate correctly, to reduce NO_x emissions (ABS, 2013). This solution requires significantly more storage and material handling capacity than wet scrubbers also requiring large material handling systems both on the ship and ashore, for transporting and loading the lime on-

board and for discharging the gypsum (ABS, 2013), turning them into the less desirable option for ship operators. The advantage of dry scrubbers is that pollutants are not transferred from air to water, as they are in wet scrubbers, but instead they form a by-product (EPA, 2011a), that can be reused for high-temperature desulphurisation at power plants, as a raw material for clinker, road construction or in fertilizer production (Dunster, 2007). There are also the costs of purchasing caustic soda or lime-treated granulates (Fung, et al. 2014).

A technology based on a combination of the two type of technology is also available. This hybrid scrubber technology has the flexibility to operate in both open and closed loop using seawater. This provides a flexibility of operation in low alkaline waters, as well as the open ocean. When at sea the switch can be made to open loop using only seawater. The sulphur oxide in the exhaust react with the water to form sulphuric acid. When required to switch to closed loop, for instance whilst entering a port in a low alkalinity area, the natural alkalinity of seawater is boosted by an alkali which uses caustic soda as a buffer. Yet, this system can only be operated in zero discharge mode for a limited period (Wärtsilä, 2013), reason why no further attention is subsequently given[17].

From the operation costs perspective ship operators' have to worry with the additional consumption of fuel to operate the scrubber which can amount from 1% up to 3% of energy fuel consumption, plus costs for scrubber maintenance and crew training to operate with. The costs for purchasing and installing scrubbers vary from € 2.1M for an open-loop seawater scrubber to €2.6M million for a hybrid system, for new build cargo ship, though depending on the type and size of the ship and its trading area (EMSA, 2010). Further yard costs for the installation and land disposal of the residuals should also be added to the final bill[18].

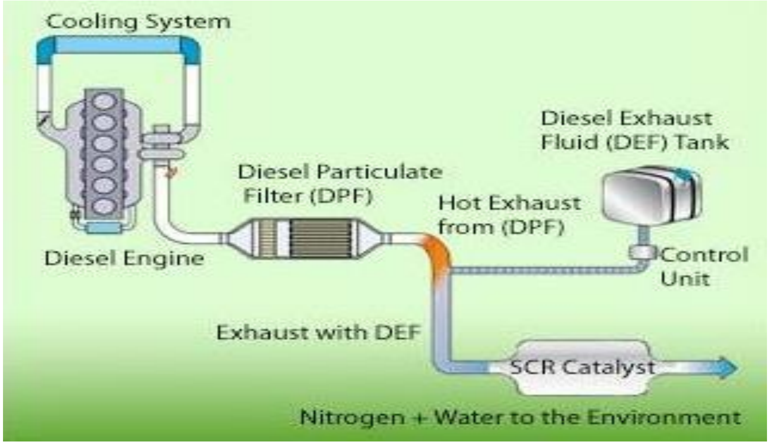
[17] Zero emission mode means that effluent water remains stored until discharged of in port waste facilities for further treatment. Otherwise, those effluent waters (sludge), even in small amounts and in a closed loop system, should be released to the sea.

[18] Yet, proposed new legislation intended to reduce emissions and discharges from ships sailing in Norway's world heritage fjords is now expected to be even stricter than first proposed earlier this year, including a ban on scrubber use (https://www.maritime-executive.com/article/norway-considers-scrubber-ban-in-heritage-fjords).

5.2 Selective Catalytic Reduction for the reduction of NO_x emissions

Tier III NO_x standard reduces NO_x emissions by 75% from the current Tier II[19]. To achieve this reduction, the use of NO_x emission control technologies is required. Two technologies for marine applications are Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR) depicted in Figure 5.2.

Figure 5.2: Selective Catalytic Reduction (SCR) on-board scheme.



Source: Interesting Energy Facts.
Available from: https://interestingenergyfacts.blogspot.com/2008/06/src-selective-catalytic-reduction.html. (Accessed January 27, 2016).

Selective catalytic reduction systems need high exhaust inlet temperatures to work, normally around 350°C, and must be deployed upstream of an engine for converting NO_x in the exhaust, with the aid of a catalyst (Fujita el al. 2010), into diatomic nitrogen, (N_2), and water, (H_2O). A reductant, typically anhydrous ammonia or urea, is added to the stream of flue and the hydrogen from the ammonia or urea reduces nitrogen oxide of up to 95%. As these SCR systems need high exhaust inlet temperatures to work this means they need to deal with the fuel sulphur content which may be a problem for some SCRs (ABS, 2013). If the exhaust gas temperature is lower they are less effective at low loads and for two-stroke engines (Bengtsson, Andersson and Fridell, 2011). Too low exhaust

[19] Ships constructed on or after 1st January 2016 will have limitations in the NOx emissions when operating in an ECA depending on engine speed, *n*, as it follows: 3.4 g/kWh when *n* is 130 rpm; 9 x $n^{(-0.2)}$ g/kWh when *n* is higher than 130 rpm and smaller than 2000 rpm; 2.0 g/kWh when *n* is 2000 rpm or higher.

temperatures can also originate ammonia slippage if the reaction between NO_x and urea are incomplete, which cause release of ammonia to the air. Most SCR manufacturers have catalyst technologies that can operate at a higher SO_x content while at a higher cost too. Also the use of an SCR in addition to a scrubber in the exhaust stream will increase exhaust back pressure, which has to be considered[20]. Another problematic issue with the use of post-combustion treatment techniques is that emissions of nitrous oxide (N_2O), a powerful GHG, may increase (Pozo et al. 2013).

5.3 Exhaust gas recirculation (EGR)

Like SCR, Exhaust Gas Recirculation (EGR) technology has been successfully adopted as a NO_x reduction strategy. EGR has been shown to achieve 75% NO_x reduction even with the use of high-sulphur bunker fuels and has been used as a sole control strategy for meeting the Tier III NO_x standard in some marine applications. EGR reduces NO_x emissions by routing (recirculate) a portion of the exhaust gas, typically 20% to 40%, back into the combustion chamber. The exhaust gas absorbs heat during the combustion process, lowering peak combustion temperature and reducing NO_x. Diluting the incoming air with the noncombustible exhaust also lowers the oxygen content of the combustion air, thus reducing the rate of NO_x formation (He et al. 2015).

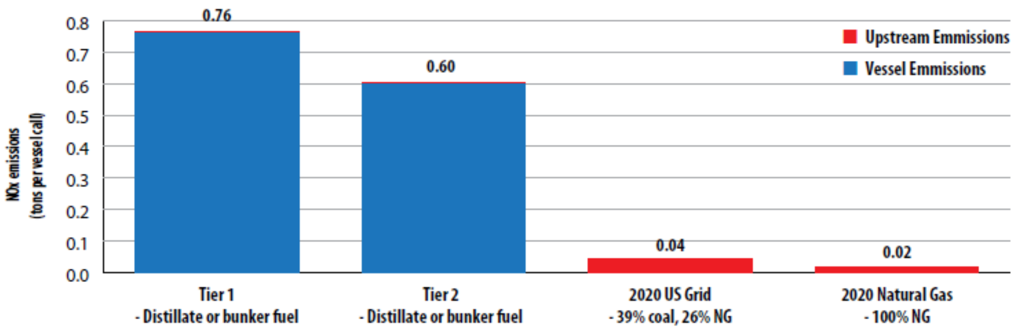
For high-sulphur, EGR-equipped engines can be fitted with an EGR scrubber to remove sulphate and particulate matter and to prevent engine fouling, corrosion and wear issues from the exhaust before it is recirculated back to the engine. Further, if the exhaust contains too much particles there will also be problems with the engine. For marine applications therefore, EGR usually requires that low sulphur fuel is used together with filters that take care of the particles in the exhaust that is recirculated; if the exhaust contains too much sulphur oxide this can lead to corrosion problems in the engine. The capital cost of an EGR system is typically around US$60 to $80 per kW, and the operating costs represent about 4% to 6% of the fuel costs when the ships operate in a NO_x ECA (Fung et al. 2014).

[20] Engine exhaust *back pressure* is defined as the exhaust gas pressure that is produced by the engine to overcome the hydraulic resistance of the exhaust system in order to discharge the gases into the atmosphere. Exhaust back pressure is usually measured in kilopascal (kPa).

5.4 Other small-scale abatement techniques: shore power

Shore power, also commonly called "*cold ironing*", allows ships to turn off main and auxiliary engines on-board and use shore side electricity to power refrigeration, lights, pumps, and other equipment being used while at berth, although very few ports around the world offer such in-service infrastructures (Alduino, Murillo and Ferrari, 2011). A relatively large share of ship emissions are emitted during manoeuvring operations, especially in those ports where ship engines are not equipped with scrubber's technology, and during hotelling[21], highlighting the importance of adopting measures to reduce emissions at port. Indeed cold ironing, due to the higher efficiency and to the limiting emissions facilities in lower plants, permits to save more than 30% of CO_2 emissions and more than 95% of NO_x and particulate (Alduino, Murillo and Ferrari, 2011) from the ship's auxiliary engines. Yet, a city's power grid should be able to bear the electrical load of cold ironing and from a life-cycle perspective, care is needed towards the increased demand for electricity as it may lead to higher emissions where the generating power plant is located, depending on how by what means electricity is generated. The source for land-based power may be also an external remote generator powered by renewable energy sources such as wind or solar. Table 5.1 depicts a life-cycle emissions comparison for a ship using different shore power at berth.

Table 5.1: NO_x life cycle emissions from different shore power at berth.



Source: Fung et al. (2014).

As Table 5.1 shows, the more shore power can be generated from clean energy sources, the higher the benefits of using shore power. By saying so and for the sake of the best

[21] Operations while stationary at dock.

assessment of the overall benefits of shore power every port should carefully examine the life cycle benefits analysis for this option, using its own specific assumptions, including the electricity grid mix and power plant emissions control performance (Fung et al. 2014).

5.5 Other related abatement strategies: vessel speed reduction (VSR)

Vessel Speed Reduction (VSR) refers to the practice of operating an ocean-going vessel at a speed significantly lower than its maximum speed. Such practice, also known as "*slow steaming"*, helps to save fuel and reduce emissions. Slower speed has been important for fuel saving as it is a key determinant for almost 50% of shipping costs in the container shipping sector (Fröberg and Brink, 2013), which represents 4% of all maritime vessels but generate 20% of emissions from international shipping (Cariou, 2010). Moreover, as emissions are directly proportional to fuel consumed, speed is also very much connected with the environmental performance, namely for a ship sailing in a SECA. Recent high oil prices and the rising amount of ships' available overcapacity on many trade lanes (Cariou, 2010), - which would be considerably worse if ships were steaming at faster speeds -, have drawn greater attention to the potential benefits of slow-steaming. Notwithstanding, while seeming a logical and wise option it also implies several challenges: first and for the ship-owner, how to avoid a trade-off between slower speed and ship frequency without adding new ships because when ships reduce their speed, the cycle time is obviously increased generating additional costs (Ronen, 2011); second, changes in ship speed may also induce modal shifts due to the time loss, especially if cargo choose road mode, increasing emissions in the entire loop. For a ship transiting a SECA, increasing speed at high seas as a mean to counteract the time lost can result in a global increase in CO_2 emissions.

While Corbett, Wang and Winebrake (2009) conclude that the speed reduction is able to significantly reduce CO_2 emissions, Doudnikoff and Lacoste (2013) findings, for example and for the container shipping industry, show that differentiating speed accordingly slightly decreases operating cost and increases CO_2 emissions in a similar way. In line with Cariou/Cheaitou's profit-maximisation model (Cariou and Cheaitou, 2012), it is demonstrated that "*a regional speed limit is counterproductive because it may generate more emissions [at sea] and incur a cost per tonne of CO_2 which is more than society is willing to pay*". Since a reduction in SECAs are partly compensated by additional HFOs consumption outside SECAs, the adoption of slow steaming to reduce shipping emissions may only result locally but not globally, even though this is not true for GHGs since for those it is of no importance where they are generated.

Further advanced technologies, like on-board carbon capture and storage (CCS), are in an early R&D phase and several technical and practical uncertainties have to be solved before commercialisation and large-scale production can be reality (Grahn et al. 2013). On-board CCS can be a reality in the future by taking an existing onshore carbon capture unit design and adapting it for maritime use, for example in a large crude carrier as the hypothetical host because of its size and relative abundance of deck space.

6. ALTERNATIVE MARINE FUELS

Existing technologies and associated fossil fuels used for transport systems have benefited from a long period of increasing returns. In fact, and according to Foxon (2002:3): "*industrial economies are in a state of carbon lock-in to current carbon intensive, fossil fuel based activities, resulting from a process of technological and institutional co-evolution, driven by path-dependent increasing returns to scale*". This *lock-in* effect is adverse for the development of new technologies, particularly more sustainable technologies which have high unit costs, meaning that firms will be reluctant to invest (Klitkou et al. 2015). The argument of lock-in is an important element of the general decarbonisation debate (Gilbert et al. 2015). For example, hydrogen-based systems, which some have promoted as the long-term alternative to carbon, face regulatory barriers in terms of perceived safety concerns, and lack of incentives for companies to create the large-scale infrastructure which would be needed. And the same happened until very recently with LNG technology for mobility.

Stakeholders and policy makers need to understand that innovation, in terms of the wider societal benefits that can accrue, can help to overcome lock-in to existing technologies or technological systems and/or *lock out* of emerging, more resource efficient technologies. Sustainable innovation to stimulate the development and take up of innovative technologies in helping to solve environmental problems and to provide a range of positive health and non-health externalities, either by creating options for substitution or enabling those problems to be solved by the adoption of alternative fuels and technologies, can be set in place if much more tight environmental and health policies are adopted. Significantly, the time of break-even, when an energy technology becomes competitive in the marketplace, depends on deployment rates, which the decision-maker can influence through policy, as the International Energy Agency (IEA) already have detail since back to the year 2000 in its report[22]. Thus, it is necessary to promote low carbon innovation technologies, alongside with health and environmental policy measures, to facilitate the path to low-carbon alternative fuels. But, before we went too far ahead with this introduction, let’s take a view about some of alternative fuels for shipping industry.

6.1 Hydrogen

Among the options of alternative fuels with different propulsion technologies, liquid hydrogen (H_2) with fuel cells is already used as fuel in submarines and some small passenger crafts (Kołwzan and Narewski, 2012) and is an example for a possible transition path for the use of hydrogen in shipping within the context of decarbonisation. For example, Raucci et al. (2014), in their study demonstrate that despite its higher price, hydrogen can be the fuel of choice for new ships from 2045 onward, suggesting that higher CO_2 emissions price could increase the competitiveness of hydrogen relative to other fuels. Hydrogen presents benefits for it is a fuel which generates no CO_2 or SO_x emissions to the atmosphere (only water vapour and heat) but on the other hand requires cryogenic storage at very low temperatures (-253ºC) and very well insulated fuel tanks (DNV-GL, 2014). Yet, large energy losses and liquefaction, transport and distribution of hydrogen costs much more energy compared to natural gas (Verbeek et al. 2013). If stored at 700 bar pressure the storage tanks would be at least six times bigger than for conventional fuels (Royal Academy of Engineering, 2013, hereinafter simply RAE). Grahn et al. (2013), suggests that costs for natural gas tank storage are around 110 USD/GJ, in comparison with a hydrogen storage tank cost of 250 USD/GJ, (plus a fuel cell system cost of 4,000 USD/kW). It also presents some disadvantages like the necessity of complex on-board pre-processing of electricity from fuel cells (FCs) resulting in a significantly more expensive way of generating electricity than conventional methods. Whilst liquid hydrogen benefits from a much higher specific heat per unit weight than conventional fuels, it requires a much greater volume for storage.

Since fuel cells are the most commonly used devices to convert the chemical energy of hydrogen into electricity a major issue is their fuels: oxygen can be obtained from air but

[22] Available at www.wenergy.se/pdf/curve2000.pdf

hydrogen is more of a challenge. Since currently all hydrogen used in industry is obtained from natural gas, a realistic choice for marine fuel cell power generation would be operation by natural gas, although the issue of effective CO_2 reduction should be taken into account to prevent GHG emissions are not transferred from a source on the sea to one on land, referring to the impact of the methane slip in a life-cycle perspective. A number of high temperature fuel cells are capable of operating directly on natural gas by converting methane into hydrogen, called termed internal reformation (RAE, 2013), even though the carbon in the methane is converted into CO_2. By another hand, fuel cells produce DC electrical output and, hence, are not so suited to ships with mechanical transmission systems. In the framework of a long-term de-carbonisation strategy (>50 ys.), hydrogen may enter the marine energy mix although further research is required for producing high capability batteries, dimensions and weight of FCs installations and their expected lifetime and hydrogen generation and storage to ensure safe operations on-board; high investment costs are thus expected. Finally, and as for LNG and other alternative fuels alike, a supply and distribution network infrastructure would be needed to liquid hydrogen become viable in a marine context. Notwithstanding, if ultimately hydrogen become a viable alternative fuel for the long run, the LNG presents itself as raw material for the hydrogen via "*natural gas reforming*" (Kalamaras and Efstathiou, 2013**)**, not belittling the fact that the LNG's flexible distribution and transportation structure is adaptable to other fluids[23].

6.2 Nuclear

Nuclear power generation is the fission of large, heavy nuclei into smaller fission products under controlled chain reactions. This releases a large amount of heat energy which is transferred to a coolant to generate useable power via an appropriate thermodynamic cycle (RAE, 2013). Nuclear ship propulsion has the advantage of enabling the vessel to run for long periods of time without the need to refuel[24], it has a high level of autonomy and there is a reduced level of local pollutants compared to other fuels. During operation it produces no CO_2, NO_x, SO_x, VOCs or PM emissions.

[23] Methane reforming is a production process to produce hydrogen with thermal processes, such as steam-methane reformation and partial oxidation that builds upon the existing natural gas pipeline delivery infrastructure. It is the cheapest process to produce hydrogen.

[24] For a merchant ship, because of the lower levels of fuel enrichment permitted, refuelling should be contemplated on about a five to seven year cycle depending on the actual level of enrichment deployed and the duty cycle of the ship (Carlton, Smart and Jenkins, 2011).

Although CO_2 emissions associated with operating the reactor are minimal, there are emissions associated with the extraction and re-processing of spent fuel (Gilbert et al. 2015). The use of nuclear-powered engines in commercial ships shows a regenerated interest and support from the part of some stakeholders[25]. This technology has been used since many years on-board navy ships; in Russian Arctic, for example, the power levels required for breaking ice up to 3 metres thick, coupled with refuelling difficulties for other different types of vessels to operate are key factors supporting this choice. But nuclear-powered ships have also been used for commercial purposes. The German cargo and research facility ship "Otto Hahn" operated successfully under nuclear power from 1968 until 1979 when it was proved to be too expensive to operate and was converted to diesel.

The most common reactor type is the uranium-fuelled pressurised water reactor (PWR). The heat derived from the water-cooled reactor in its primary circuit is transferred, through a heat exchanger, to produce steam which drives a conventional power plant (Carlton, Smart and Jenkins, 2011). It is expected at least a five-year refuelling cycle depending on the duty cycle of the ship and of the level of uranium enrichment which for commercial ships is lower than for military vessels. The refuelling process may take up to 30 days and during this period of time the ship remains out of duty. From the engineering viewpoint there is little problematic issues to be overcome in a ship propelled by nuclear energy (Carlton, Smart and Jenkins, 2011:52) although significant changes in ship design according to a goal base approach instead of the prescriptive rules defined by the IMO and classification societies are required (Gravina et al. 2011).

Indeed, significant safety standards in the ship building – namely reactor safety and integrity protection to prevent the risk of collision – operation, maintenance and decommissioning of the ship are of major worries (RAE, 2013:35), not despising concerns over accidents at sea and the disposal of nuclear waste (de-fuelling) operation. Storing used nuclear fuel on-board or either the disposal in shore-based facilities also reveals to be highly problematic: nuclear waste on-board disposal compartments is always risky in case of accident and trained crew is needed to overcome potential hazards arising from active and spent nuclear fuel on-board (Carlton, Smart and Jenkins, 2011), but the

[25] In 1981 the IMO adopted a Code of Safety for Nuclear Merchant Ships, Resolution A.491 (XII), and although it has not been implemented it is still extant. Also at the end of the last decade, Lloyd's Register reactivated its work on this type of propulsion for commercial ships.

aforementioned authors did not explain about the technical capability required for seafarers to operate in such a ticklish environment.

In fact, the de-fuelling process is of high risk deriving from unstable isotopes and gamma radiation that are present in the irradiated spent fuel and the compartments of the reactor need to be directly accessed since the use of cranes for the removal is not allowed. Given that ships frequently sail nearby coastal territorial waters visiting ports of different countries, trade routes upon which nuclear ships could be deployed and the countries that would be prepared to accept nuclear powered merchant ships are issues to take into careful consideration. Issues would also need to be addressed in terms of public perception and acceptability, insurance and nuclear emergency response plans for ports and surrounding areas. Another disadvantage is the possibility of sinking as a consequence of either accident or extensive damage. Plus, in the wake of an ongoing piracy threat that affects some crucial maritime areas, public awareness towards commercial nuclear ships that can be hijacked and the disastrous consequences from its use as weapons in terrorist attacks is more than ever present. For all those who do not accept decarbonisation at any price, nuclear propulsion in marine merchant is not worth it.

6.3 Biofuels

Biofuels can be defined broadly as any fuel derived from biomass including first generation biofuels like biodiesel and bioethanol and are sulphur-free fulfilling ECAs SO_x emission requirements. Biodiesel is produced from animal fats and vegetable oils such as coconut, palm, rape seed, soybean and tallow. For the upstream stage of the life-cycle, using biodiesel has a negative net sink of GHGs in the feedstock stages, referring to the carbon capture of plants as they grow (Winebrake, Corbett and Meyer, 2007). As for bioethanol, biodiesel is produced by fermenting renewable sources of sugar or starch, corn, sorghum, sugar beet, sugar cane, and wheat. The processes involved in biofuel production from sugar or vegetable oils are not particularly efficient and waste a significant quantity of the biomass or organic matter (RAE, 2013).

Second generation biofuels include: biomass to liquid (BtL), cellulosic ethanol, bio DME/Methanol, biosynthetic natural gas (BioSNG), Bio-oil/ Bio-crude, hydrocarbons from catalysis of plant sugars, bio-hydrogen, bioelectricity/CHP and bio-butanol. These types of biofuels are produced from residual non-food crops, parts of current crops (leaves, stems) and also industry waste such as wood chips, skins and pulp from the fruit pressing (Kołwzan and Narewski, 2012), although their mass production in an economically viable way is still in development.

Third generation biofuels include algal bio-fuels, but this technology is at an early stage of development and are subject to concerns of impacts on health, safety and environmental sustainability[26]. For the use of biofuels as marine fuel there are certain technical issues that should be addressed such as stability during the storage, acidity, lack of water-shedding, plugging of filters, formation of waxes and increased engine deposits. Care also must be taken to avoid contamination with water, since biofuels are particularly susceptible to biofouling[27]. Those practical challenges can impose harsh consequences (e.g. plugging of filters) provoking engine shutdown, which may be critical with respect to the safety of a ship.

First generation biofuels can be hydrogenated in refinery. In this case, the resulting fuel is of high quality and the aforementioned problems do not apply. But this upgrading adds energy costs, and hence results in additional emissions. These challenges are overshadowed for its limited availability that makes this option appear unlikely to be implemented on large scale in the near future (Kołwzan and Narewski, 2012). To power the current worldwide fleet of merchant ships using biofuels derived from natural sources such as vegetable oils it is estimated that it would a land area equivalent to that of about twice the size the United Kingdom, not to mention the question of whether it might be better to deploy such agricultural areas for world food production (RAE, 2013). Nevertheless, from a future marine fuel mix perspective, methanol, which can be produced from natural gas (the catalytic conversion of methane to methanol), can be seen as a potential substitute fuel.

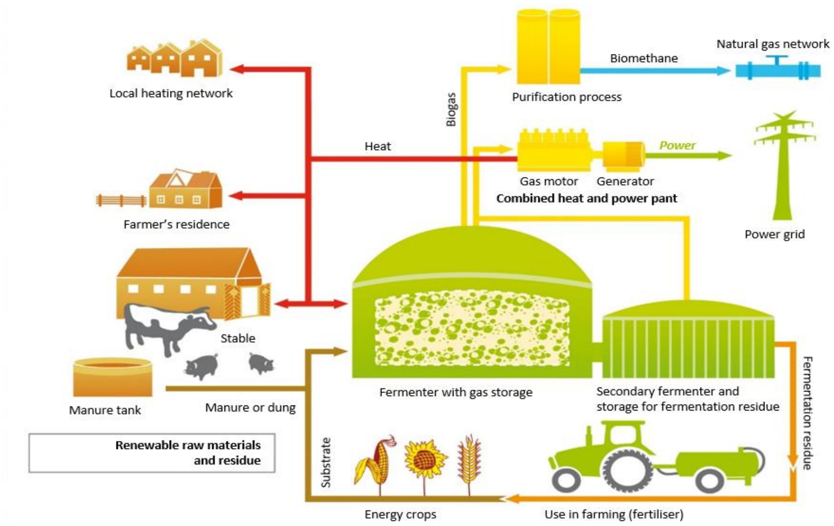
[26] A relevant group of micro algae are photosynthetic unicellular organisms with characteristic silica cell walls called "*diatoms*". These microorganisms are the main component of the phytoplankton and they produce oil drops that are stored intracellularly as a reserve material during the vegetative period of growth, with percentages that vary from 23% to 45% of dry cell weight, ending the potential of affording oil production by these microorganisms (d' Ippolito et al. 2015).

[27] Biofouling refers to the accumulation of microorganisms, plants, algae, or animals on wetted surfaces especially on ship's hulls. Biofouling has been identified as a major threat to the world's oceans because of marine species carried on ships' hulls may survive to establish a reproductive population in the host environment, becoming invasive, out-competing native species and multiplying into pest proportions (see more on: http://www.imo.org/en/OurWork/Environment/Biofouling/Pages/default.aspx).

6.4 Biomethane

Biogas, a mixture of gases fermented from organic materials in the absence of oxygen and anaerobic digestion is the raw material from which biomethane, a renewable fuel, is produced after removing the non-methane components. Biogas comprises CH_4, CO_2 and hydrogen sulphide and may also contain siloxanes[28] and moisture. After the removal of impurities biomethane is produced and can then be injected into the gas grid and subsequently used in the heat, power or transport sectors and can be used everywhere in the same way as natural gas itself including shipping (European Biogas Association, 2016). The majority of biogas and biomethane fuels in the EU are produced from crops. In addition to the anaerobic digestion from crops other sources of biomethane are organic waste-derived biomethane, domestic food waste, commercial and industrial waste, agricultural materials and sewage sludge digestion.

Figure 6.1: From biogas to biomethane.



Source: Clean Energy Wire.
Available from: https://www.cleanenergywire.org/dossiers/bioenergy-germany (Accessed October 2, 2016).

The use of biomethane has a number of benefits, for instance; there are significant well-to-propeller GHG emissions benefits (Kallamthodi et al. 2016). The CO_2 emissions released on combustion of biogas and biomethane produced from energy crops are not considered

[28] A siloxane is a functional group in organosilicon chemistry.

to contribute to climate change because they are part of the short-term carbon cycle (i.e. the CO_2 emitted on combustion was absorbed from the atmosphere up to around one year earlier). Conversely, if biomethane is produced from wood it could have net impacts on climate change in terms of CO_2 emissions released on combustion of the resulting biomethane, as forestry resources are not part of the short-term carbon cycle. By the other hand and similarly to biofuels, energy crops can potentially lead to undesirable environmental impacts such and indirect land use change, putting pressure on the amount of land available for growing food crops.

The EU currently relies heavily on imports of natural gas from third countries: 39% of imports are from Russia, and a further 29.5% of imports are from Norway (Kallamthodi et al. 2016). For Portugal, those numbers are, at the time this thesis is being written, 60% imports from Algeria (by pipeline) and 40% from Qatar and Nigeria mostly, although the port of Sines was the first in Europe receiving natural gas exports from the U.S in 2016. Albeit there is potential to increase production levels of biomethane to improve the EU's energy security by reducing the region's reliance on imports of natural gas, current resources of biomethane are limited and there is strong competition from the heat and power sectors for these limited resources. Legislative burdens together with the cost of producing biomethane - as it is significantly more expensive to produce than natural gas – are barriers to overcome. Nonetheless, by developing a more comprehensive understanding of the cost effectiveness of using biomethane in the maritime sector as a means of reducing GHG emissions could encourage the introduction of measures to support the use of biomethane in marine transport. Identical as for the LNG, for further development of biomethane industry and low carbon transport sector, public policies and true commitment at the national and European levels is needed. In order to achieve transport and GHG emission targets the right measures should be implemented and some financial support, as it happens already for on heat and power sectors, in the form of incentive schemes, would be necessary. For what it matters directly for shipping analysis, the biomethane could be seen as a possible way to reduce both national and EU's imports of natural gas and to promote the industry as a future marine LNG source even though the potential is limited. To what GHG savings respects, a local methane industry will shorten pipeline and shipping distance from extraction and processing sites reducing CH_4 fugitive emissions, requiring shorter LNG storage times and therefore producing less LNG boil-off gas from tanks.

6.5 Natural gas

Natural gas is defined as: "*a mixture of hydrocarbons and varying quantities of nonhydrocarbons that exist either in the gaseous phase or in solution with crude oil in natural underground reservoirs*" (Selley and Sonnenberg, 2015). Like oil, natural gas (NG) is a product of decomposed organic matter, typically from ancient marine micro-organisms, deposited over the past 550 million years. This organic material mixed with mud, silt, and sand, gradually become buried over time. Sealed off in an oxygen-free environment and exposed to increasing amounts of heat and pressure, the organic matter underwent a thermal breakdown process that converts it into hydrocarbons. In its pure form is a colourless, odourless gas commonly including a small percentage of carbon dioxide, nitrogen, and/or hydrogen sulfide also containing sometimes some heavy hydrocarbons (Devold, 2013) removed for commercial use prior to the methane being sold.

The NG withdrawn from a well is called wet natural gas because it usually contains liquid hydrocarbons and nonhydrocarbon gases. Useful gases are separated from the wet natural gas near the site of the well or at a natural gas processing plant. The processed gas is called *dry* or *consumer-grade* natural gas or "pipeline quality dry natural gas" (Devold, 2013). This natural gas is sent through pipelines to underground storage fields and/or to distribution companies, and then to consumers. While it produces about 29% less carbon dioxide per joule delivered than oil, in absolute terms it comprises a substantial percentage of carbon emissions, and this contribution is projected to grow. In the United States, the so-called "shale revolution" will continue to unfold, and fracking will continue to unlock the potential of the shale gas industry which will lead to a slump in gas prices (Troner, 2013), albeit this is an industry that remains very controversial as we will see further on. NG can be extracted by using conventional or unconventional methods.

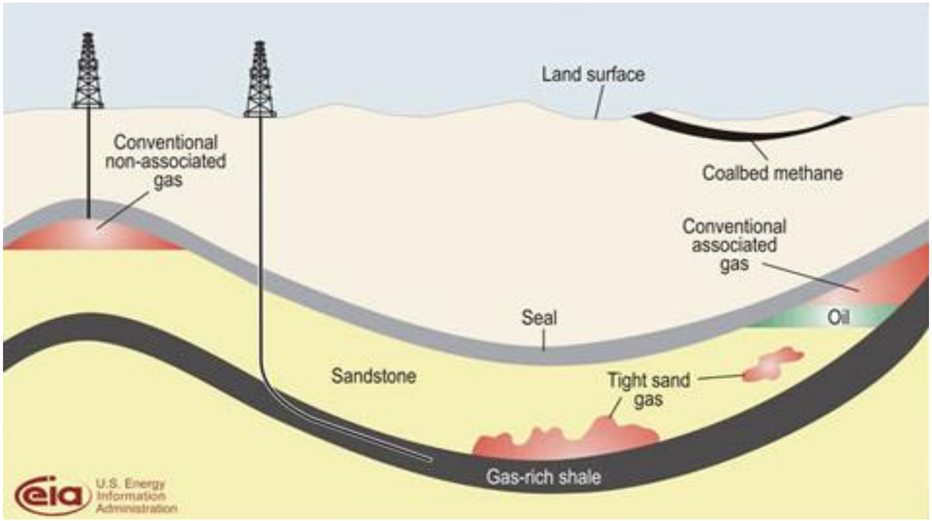
6.5.1 Conventional and unconventional extraction

Natural gas is found in deep underground rock formations or associated with other hydrocarbon reservoirs in coal beds and as methane clathrates[29] and it can be obtained through conventional reservoirs or from shale-gas extraction (unconventional). A

[29] A clathrate is a chemical substance consisting of a lattice that traps or contains molecules. Methane hydrate, hydro methane, methane ice, fire ice, natural gas hydrate, or gas hydrate, is a solid clathrate compound (more specifically, a clathrate hydrate) in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice.

conventional well is one which taps traditional sedimentary formations, sometimes also known as "traps." A conventional well typically is drilled using a vertical hole that employs layers of steel and cement to separate the well bore from the surrounding freshwater aquifers.

Figure 6.2: Schematic geology of gas extraction.



Source: U.S. Energy Information Administration.
Available from: https://www.eia.gov/todayinenergy/detail.php?id=110.
(Accessed October 2, 2016).

Conventional NG deposits are commonly found in association with oil reservoirs, with the gas either mixed with the oil or buoyantly floating on top. An unconventional well is different in that it drills deeper to tap the organic rock that is the actual source of the oil and gas, in this case known as associated gas. An unconventional well usually employs sophisticated methodologies including horizontal drilling of deposits like shale gas, tight gas sandstone and coalbed. Although it is often more costly to produce, unconventional oil will almost certainly make an increasing contribution to future oil production (International Energy Agency, 2013).

Rock porosity and permeability play an important role in the formation of the NG. Highly porous rocks, such as sandstones, typically have porosities of 5 to 25%, giving them large amounts of space to store fluids such as oil, water, and gas. Permeability is a measure of the degree to which the pore spaces in a rock are interconnected. A highly permeable rock will permit gas and liquids to flow easily through the rock, while a low-permeability rock will not allow fluids to pass through. Most of the natural gas deposits we find today occur where the gas happened to migrate into a highly porous and permeable rock underneath an impervious cap rock layer, thus becoming trapped before it could reach the surface and escape into the atmosphere. In the United States, one of the leading producer countries in the world, conventional gas represents 46% of the total resource base, while the rest includes unconventional natural gas[30]. Both of methods produce methane leakages during its life time production and therefore it is of crucial importance to measure to what point those leakages can impact the final score of the NG over other conventional fuels, since one needs to give attention to the fuels source. It is widely assumed (Alvarez et al. 2011; Bradbury et al. 2013;   Brandt et al. 2014) that one reason that natural gas falls short of its full potential GHG benefit is upstream fugitive emissions and leaks, especially for those associated to shale gas using hydraulic fracturing techniques, even though until recently, robust and verified data on this topic was not available (Alvarez et al. 2012; Howarth, 2014), and information about the level of methane emissions were very poor.

6.5.2 Unconventional extraction (fracking)

Natural gas from unconventional sources is intrinsically more difficult to extract than from conventional reservoirs. However it is becoming increasingly commercially viable due to advances in drilling and well-site technology. Natural gas from hydraulic fracturing is an industry that has registered a booming growth in the past decade, in particular in the U.S. and in some Canadian Provinces; nonetheless it is expected to spread elsewhere[31]. For both conventional and shale gas, the GHG footprint is dominated by direct CO_2 emissions produced by end-users and by indirect emissions of CO_2 from fossil fuels used to extract, transform and deliver the gas, those released into the atmosphere by pipeline leaks and

[30] According to the U.S. Energy Information Administration (International Energy Statistics, Proved Reserves of Natural Gas), as of 2012, the largest known gas reserves in the world are found in Russia, which has five times the reserves of the United States. Iran and Qatar have four and three times as much gas as the U.S. respectively, and significant reserves are also present in Saudi Arabia, Turkmenistan, UAE, Nigeria, and Venezuela. Europe has no shale gas production as yet, despite strong lobbying efforts, but major onshore shale gas basins can be found across the entire continent.

[31] Hydraulic fracturing technique consists in extracting the shale-gas by forcing large volumes of under pressure water into the shale to fracture and re-fracture the rock to boost gas flow. This technique is not absent of high criticism because "hydraulic fracturing" literally involves the smashing of rock with millions of gallons of drinking water along with sand and a undisclosed assortment of chemicals in order to bring gas to the surface.

venting and those from heavy machinery, generators, equipment and lorries[32] (Howarth, Santoro and Ingraffea, 2011), although emissions from flaring also have to be taken into account[33].

Therefore the GHG footprint for natural gas is equal to[34]:

$$[CO_2 emissions + (GWP * \ methane\ emissions)]\ /efficiency \tag{6.1}$$

Notwithstanding higher emissions being those coming from the hydraulic fracturing and from the drilling process, the *U.S. Inventory of Greenhouse Gas Emissions and Sinks 1990 – 2009* estimates that 68 billion cubic feet (Bcf) of methane are vented or flared annually from unconventional completions and work overs (EPA, 2011a) and globally, flaring represents 400 million metric tonnes (Mt) of carbon dioxide equivalent (CO_2e) emissions every year (Malins et al. 2014). Following data presented by the U.S. EPA (*apud*, Moore et al. 2014), leak rates from natural gas production ranged from as high as 2.8%, to as low as 1.65%[35] but some scientific studies (e.g. Miller et al. 2013), found that U.S. total CH_4 emissions were underestimated by ~50% in their inventories. More recently, EPA's 2013 inventory estimate made a large adjustment that reduced the estimate to 1.5% (Larson, 2013).
Howarth, Santoro and Ingraffea, (2011), were large less conservative and calculated in 2011 that some 3.6% to 7.9% of the total methane from shale-gas production escapes to the atmosphere over the life-time of a well and venting and leaks are major contributors. Howarth, Santoro and Ingraffea, (2011) proclaims that shale gas would cause more climate damage than coal per unit of energy produced for electrical power generation. The aforementioned study has provoked large discussion. It compares methane emissions on the basis of gCO_2/ unit energy equivalent to CO_2, focusing on the use of natural gas for

[32] For example, when hydraulic fracturing operations are under way, large diesel engines run at near full capacity almost 24 hours a day (Zoback and Arent, 2014).
[33] Flaring is the controlled and intentional burning of natural gas as part of production and processing. Venting is the word used to describe natural gas that is released to the atmosphere, as a part of regular operations.
[34] In the context of transport, fuel economy is the energy efficiency of a particular vehicle, given as a ratio of distance travelled per unit of fuel consumed.
[35] This rate is important because for instance, leakages of 3.2% or less would provide immediate net climate benefits for electricity production from natural gas compared to coal (Alvarez et al. 2012).

power generation and thus reporting gCO_2e/MWh (grams of CO_2 equivalent per megawatt hour of generation). It was widely criticized because it did not do a life cycle assessment: for example, it did not include the significant CO_2 emission reductions that result from the efficiency of natural gas combustion compared to coal (Zoback and Arent, 2014). Recent estimates contain significant uncertainty and lacks sufficient real-world measurements, ranging from 1% to 4.5% for shale gas (Larson, 2013). While some studies show that fugitive emissions from unconventional gas are very likely not substantially higher than for conventional gas (Hultman et al. 2011; Cathles et al. 2012), some others studies suggest that shale gas life-cycle from fugitive emissions are 6% lower than conventional natural gas (e.g. Burnham et al. 2012).

For what it matters for us, one need to be aware that natural gas to be used as a fuel for marine transport purposes cannot afford any doubts that NG from unconventional extraction have no superior efficiencies against diesel oil, and that may aggravate rather than mitigate global warming. As such, methane slip from fracturing methods deserves far greater study. Saying so, new technologies to reduce gas-industry methane emissions by use of smart-automated plunger lifts, venting reduction and use of flash-tank separators or vapour recovery units to reduce dehydrator emissions (EPA, 2015) are welcome if one consider that unconventional gas would be used as a source for liquefied natural gas.

6.5.3 Conventional extraction

In contrast with shale gas, conventional gas is often contained within sharply defined geological formations, which can be accessed only from a relatively small area using deeper wells, and they have been the most practical and easiest deposits to mine. Emissions are far lower for conventional natural gas wells during completion, since conventional wells have no flow-back[36] and no drill out during well completion (Table 6.1).

[36] Flow-back is the term used in the industry to refer to the process of allowing fluids to flow from the well following a treatment, either in preparation for a subsequent phase of treatment or in preparation for clean-up and returning the well to production.

Table 6.1: Emissions from NG from conventional wells and from shale formations.

	Conventional gas	Shale gas
Emissions during well completion	0.01%	1.9%
Routine venting and equipment leaks at well site	0.3 to 1.9%	0.3 to 1.9%
Emissions during liquid unloading	0 to 0.26%	0 to 0.26%
Emissions during gas processing	0 to 0.19%	0 to 0.19%
Emissions during transport, storage, and distribution	1.4 to 3.6%	1.4 to 3.6%
Total emissions	1.7 to 6.0%	3.6 to 7.9%

Source: Howarth, Santoro and Ingraffea (2011).

Once a well is completed and connected to a pipeline, the same technologies are used for both conventional and fracturing which means that from this point onward leaking emissions are the same for the two techniques[37].

Howarth, Santoro and Ingraffea (2011) estimate the average fugitive emissions at well completion for conventional gas as 0.01% of the life-time production of a well in comparison with 1.9% to unconventional extraction, as depicted in Table 6.1. Life-cycle methane emissions for conventional gas are less than half for those from unconventional gas and, according to Howarth, Santoro and Ingraffea (2011), the GHG footprint for shale gas in a 20-year time span is 22% to 43% greater than that for conventional gas. As to venting and flaring respects, the exact percentage is not known. Yet, available methodologies to estimate source emissions generally occur in three steps (EPA, 2015):

i) Calculate Potential Methane by collecting activity data on production and equipment in use and apply emission factors;
ii) Compile Reductions Data to calculate the amount of the methane that is not emitted, using data on voluntary action and regulations and,
iii) Calculate Net Emissions to deduct methane that is not emitted from the total methane potential estimates to develop net CH_4 emissions, and calculate CO_2 emissions.

[37] Most of cited authors include processing, transport, storage and distribution of NG as downstream emissions. Inversely and for the sake of this study, those are considered as midstream emissions but, since the revised papers are based only in gas and coal for the electric generation standpoint of view, excluding transport use purposes, authors' original partition is maintained. Since the achieving goal is to summing up of all leakages along LNG supply chain, this partition does not affect the final results: the accounting of all the emissions.

In practice, such emissions can be captured and sold rather than being flared or vented to the atmosphere if the necessary pipeline and other infrastructure are available to take the gas to market. Mitigation techniques like REC[38] not only reduces emissions but delivers natural gas product to the sales meter using specially designed equipment at the well site to capture and treat gas so it can be directed to the sales line. This process prevents some natural gas from venting and results in additional economic benefit from the sale of captured gas and, if present, gas condensate.

Equipment required to conduct a REC may include additional tankage, special gas-liquid-sand separator traps and a gas dehydrator. In many cases, portable equipment used for RECs operates in tandem with the permanent equipment that will remain after well drilling is completed. In other instances, permanent equipment is designed (e.g. oversized) to specifically accommodate initial flow-back[39].

Another mitigation technique is the so-called completion combustion which destroys the organic compounds. Completion combustion is a high-temperature oxidation process used to burn combustible components, mostly hydrocarbons, found in gas streams. These devices can be as simple as a pipe with a basic ignition mechanism and discharge over a pit near the wellhead. Completion combustion devices provide a means of minimizing vented gas during a well completion and are generally preferable to venting, due to reduced air emissions. Operational procedures to manage flaring include re-injecting the gas back into the oil reservoir to raise the pressure in the reservoir so the oil flows to the well more easily, leading to greater oil recovery. The gas can also be recovered and injected back into the reservoir to maintain pressure and sustain production levels. In this case, the natural gas can later be produced and sold when crude oil production ceases (Bott, 2007).

7. LIQUEFIED NATURAL GAS

According to the Eurostat (2015:247), emissions from shipping have to be cut at least in 40% by 2050. To achieve this goal reducing pollutant emissions produced by sea and inland waterways through the use of mitigation technologies together with lower carbon

[38] Reduced emissions completions (REC) are used to capture natural gas during the completion stage. Completion is the process of making a well ready for continuous production. REC equipment is brought to the well to separate the gas and send it to the sales line where it can be sent to market. A study from Allen et al. (2013) showed that using RECs can reduce emissions from completions by 99%. Under the New Source Performance Standards issued by the U.S. EPA, RECs are required for new gas wells.

[39] For more technical and usage specifications see EPA, 2014.

propulsion fuels is imperative (Turner et al. 2017). The underlying potential of the first action is based on the adoption of on-board cleaning techniques, but this is not, by itself, a sufficient condition to long-term shipping contribution to sustainability. Technical limitations (sufficient space for the scrubber, tanks and peripherals, the stability and longitudinal strength of the ship) also limit or hinder the installation of an exhaust gas cleaning system in most of ships (Bachér and Albrecht, 2013).

Moreover, as previously seen, scrubber and selective catalytic reduction devices require additional energy consumption on-board to operate further increasing CO_2 consumption (Kjølholt et al. 2012), and cannot be considered as a step-change for long-term low-carbon perspective, rather they should be seen as operational mitigation measures instead of drivers of change[40]. The latter refers to an end-use fuel capable to reduce noxious emissions – liquefied natural gas - that can also contribute to reduce sunk costs from investments in land facilities coupled with the rebirth of marine industries (e.g. LNG tanks, new buildings and ship retrofitting) or to boost investment in biomethane plants to diminish natural gas dependency from abroad. LNG may present economic advantages (Adamchak and Adede, 2015) especially for a country like Portugal with large tradition in shipbuilding and ship repair. Indeed, operations of retrofitting, newer ships and the establishment of a supply chain and port operations for fuelling ships and harbour vehicles, can promote the industry and become interesting both to increase port diversity and hence port throughput and attractiveness, as well as for the national economy as a whole.

Liquefied Natural Gas (LNG) is natural gas that has been cooled down to its liquid state at atmospheric pressure. Its average methane composition, in percentage, range from 82.57 LNG from Libyan origin to 99.71 from Alaska origin. The gas is first extracted and transported to a processing plant where it is purified by removing any condensates such as water, oil, mud, as well as other gases and to remove trace amounts of mercury from the gas stream to prevent mercury amalgam zinc with aluminium in the cryogenic heat exchangers. The gas is then cooled down in stages until it is liquefied. LNG is finally stored in storage tanks and can be loaded and shipped (due to the low temperature, the LNG has to be stored in cryogenic tanks). LNG achieves a higher reduction in volume than

[40] It seems obvious that these technologies are important to counteract the effects of cumulative CO_2 emissions; but they can also promote business-as-usual for the industry. Yet, care is need when addressing these technologies due to the absent of mandatory regulations about effluents from scrubbers (e.g. oceanic wash water discharges).

compressed natural gas (CNG)[41] so that the volumetric energy density of LNG is 2.4 times greater than that of CNG or 60 percent of that of diesel fuel. When natural gas is cooled down to minus 162 degrees Celsius, 600 cubic metres are condensed to 1 cubic metre of the volume needed for methane vapour and this physical property makes LNG suitable for storage, distribution and bunkering. This advantage improves the energy density significantly for LNG. As a result, when compared to diesel fuel, LNG has about 2/3 as much energy on a volume basis and almost 90% as much energy on a weight basis. LNG has roughly half of the density of traditional heavy fuel oil, but its calorific value is roughly 20% higher. The density of LNG is less than half of water and is sparingly soluble in water (Selley and Sonnenberg, 2015), which means, LNG if released will hover close to the water surface. When the vapour warms to above about -100°C, it will be lighter than air and begin to further dissipate. Although it's colourless, cold methane vapours cause the moisture in air to condense resulting in a white cloud. Within the visible cloud, the methane concentration is still within the flammable range so it is critical that equipment and procedures are in place to prevent a flammable mixture from occurring, and that sources of ignition are non-existent in and around areas where a flammable mixture is likely to occur (Figure 7.1).

Figure 7.1: Vapour cloud resulting from condensing LNG.

Source: SFPE. Available from:
https://www.sfpe.org/page/2013_Q4_1?&hhsearchterms=%22lng+and+cloud%22.
(Accessed March 3, 2017).

[41] Natural gas can also be compressed (CNG), but so far it has been only of interest for road vehicles.

LNG poses little danger as long as it is contained within storage tanks, piping, and equipment designed for use at LNG cryogenic conditions. Yet, at -162°C the LNG provokes severe frostbites. Direct contact with the liquid, vapour or non-insulated parts of equipment used to transfer cryogens will immediately freeze body tissue and cause frostbite and effects on the skin similar to a thermal burn (Yale Environmental Health & Safety, 2016). Materials that are normally structurally sound, can become brittle and fail due to thermal stress fracturing and structural failure can pose a severe physical hazard; as such, special equipment and procedures are required. In addition, unprotected skin can adhere to cryogen cooled metal surfaces and then tear when pulled away.

Considering both its lower density and higher heating value, on a volumetric basis (m^3) roughly 1.8 times more LNG needs to be bunkered to achieve the same range compared to bunkering heavy fuel oil (ABS, 2015). LNG has a high ignition temperature (540°C) and therefore needs an additional source of ignition, i.e. a pilot flame for igniting fuel in two or four stroke engines. The gas has a very narrow range of flammability. The upper flammability limit and lower flammability limit of LNG vapour are 5% and 15% by volume, respectively. When fuel concentration exceeds its upper flammability limit, it cannot burn because too little oxygen is present.

Table 7.1: LNG properties.

Properties	LNG
Toxic	No
Carcinogenic	No
Flammable Vapor	Yes
Forms Vapor Clouds	Yes
Asphyxiant	Yes
Extreme Cold Temperature	Yes
Flash point (°C)	-188
Boiling point (°C)	-160
Flammability Range in Air, %	LEL = 5.5% and UEL 14% (at 25°C)
Auto ignition Temperature ^{0}C	540
Behavior if Spilled	Evaporates, forming a partly visible clouds

Source: Basha (2012)[42].

When fuel concentration is below the lower flammability limit, it cannot burn because too little methane is present. LNG's SO_x and particulate matter emissions are minimal and the

[42] LEL: Lower Explosive Limit; UEL: Upper Explosive Limit.

NO_x emissions are around 90% lower due to reduced peak temperatures in the combustion process (EMSA, 2010; Kolwzan and Narewski, 2012). Furthermore, as LNG produces no sludge there is any visible smoke. Moreover, LNG also reduces the noise level on board.
Operating on LNG does not affect the speed or otherwise the operational qualities of the ship, though it does involve some additional technical and operational complexities which requires special training for crew members. During bunkering operations safety and security zones need to be set up around to reduce the risk of damage to property and personnel. General safety standards for bunkering while passengers are on-board or fuelling simultaneously while cargo is transferred is something that needs institutional intervention. As such, IMO's new International Code of Safety for Gas-fuelled Ships (IGF Code) adopted June 2015 entered into force on 1 January 2017 and applies to new cargo ships ≥ 500GT and passenger ships using low-flashpoint fuels, focusing initially on LNG**.** The IGF Code addresses safety for gas-fuelled installations in ships and aims to minimize the risk to the ship, its crew and the environment, having regard to the nature of the fuels involved. The intention is to make the Code mandatory through its inclusion in the International Convention for the Safety of Life at Sea (SOLAS).
The LNG have lower acidification and eutrophication potential and less human health impact than diesel fuels, has a low life-cycle CO_2 emissions and higher hydrogen-to-carbon ratio (Ryste, 2012) which results in lower specific CO_2 emissions (kg of CO_2/kg of fuel). Prior we have seen that LNG is one of the choices amongst a whole range of other alternative energy sources for marine propulsion, namely: nuclear, hydrogen and bio-fuels. Yet, some disadvantages from those fuels act against their adoption: Nuclear involves additional technical complexities and a too high perceived risk for safe use on-board merchant vessels (Gu and Zhang, 2014) and is not a viable option. The second, hydrogen, still has a long pathway ahead to become a fierce alternative, for it would need a supply infrastructure to be viable and because fuel cells produce direct current (DC) electrical output and, hence, are not so suited to ships with mechanical transmission systems (RAE, 2013). To what refers to the latter, bio-fuels, it implies other critical effects such as land and water usage and lacks efficient large scale production. Concerns related to long-term storage stability of bio-fuels on-board ships and issues with corrosion also need to be addressed (Chryssakis, et al. 2014).

The exclusions pointed above let us with LNG as the sole prospect of reasonability. Unfortunately, the use of LNG presents a downside: fugitive emissions of methane along the life cycle pathway hence reducing the net global warming benefit (Winebrake, Corbett, and Meyer, 2007; Bengtsson, Andersson and Fridell, 2011; Kołwzan, and Narewski, 2012; Bows-Larkin, 2014) referring to the significant methane impacts to global atmosphere (Howarth, 2014). Methane is the primary component of natural gas and a potent greenhouse gas some 20-25 times more powerful than CO_2 during a 100 year time span and 72 times in a 20 year perspective (Winnes, Styhre and Fridell, 2015). If it is allowed to leak into the air before being used it absorbs the sun's heat warming the atmosphere offsetting benefits from fuel-switching because of greater radiative forcing[43] to CO_2. Further reading on this topic on Section 7.3.

Undoubtedly and for sure, LNG offers end-of-pipe environmental benefits such as:

- Practically 100% elimination of SO_x emissions and particulate matter (Deal, 2013; Jónsdóttir, 2013; DNV-GL, 2015a);
- Between 85-90% reductions of NO_x due to lower peak temperatures in the combustion process (Herdzik, 2011; Jónsdóttir, 2013; Laugen, 2013);
- Nearly 100% of VOCs (Deal, 2013; Laugen, 2013), and;
- A reduction in CO_2 emissions of 25% (Winnes, Styhre and Fridell, 2015) or between 12-27% (Lowell, Wang and Lutsey, 2013).

While natural gas has the unique capability to help bridge the gap between fossil fuels and renewable energy, something that should be let clear is that LNG as a marine substitute fuel is to be seen as such: an immediate alternative, not as a final solution by itself. Hence, for what follows, the LNG should be perceived as a solution for buying us time to develop new clean, affordable and renewable trustfully technologies.

7.1 The advent of the LNG as a marine fuel

The era of passenger gas-fuelled ships have started a new epoch. The starting gun began in the year 2000 with the Norwegian ferry "*Glutra*" the world's first ship fuelled with LNG.

[43] Radiative forcing is defined as the difference of insolation (sunlight) absorbed by the Earth and energy radiated back to space.

Norwegian national draft regulations and details from the rules for gas carriers. Norway has been traditionally a driving force behind the development of LNG as a marine fuel and the Norwegian NO_x Fund has stimulated interest in this technology and also co-funded many of the installations[44]. Following what was set by the Norwegian NO_x Fund, the European Commission have started studying the ways to implement a similar approach in which the operators will be charged by their emissions and then using the available funds for abatement technology, research, etc. (EC, 2011). After the *Glutra*, the LNG has been used in LNG carriers and cruise ships and, more recently, in on-board platform supply vessels (PSV), Ro-Pax ferries and tugs; several containerships are already on duty with several others under construction, including the new CMA-CGM's 22,000TEU ULCVs as well as oil and ore carriers[45].

European based marine engines manufacturers firms like Wärtsilä (Finland), Rolls Royce Marine (UK) and MAN (Germany), are the most relevant leading pioneers in technology development, and equipment manufacturers related to LNG propelled ships. As for the LNG supply chain, several North Sea and Baltic Sea countries are in the move to establish LNG storage and bunkering operations in ports such as Antwerp (Belgium), Rotterdam (Netherlands), Oxelösund and Gävle (Sweden), Turku/Naantali (Finland). LNG hubs in Estonia, Lithuania, Poland and Germany are also planned or already established (Klàipeda in Lithuania, for instance). Classification Societies (Lloyds, 2012; DNV-GL, 2014; ABS, 2015) anticipates LNG to become the fuel of choice for all shipping segments in contrast to what was thought before: best fuel choice for short sea shipping due to the small number of existing facilities to provide LNG as bunker fuel (Bengtsson, 2011; Verbeek et al. 2011, Wurster et al. 2014). In fact, work-in-progress LNG technology is rapidly increasing improvements both in engine fuel optimisation together with the ongoing investment in LNG infrastructure and bunkering facilities across busy shipping lanes especially in Southeast Asia and Northern Europe. This because 9 of the 10 largest bunker ports in the world already have LNG supply facilities for ships or have plans to do so by 2020 (SEA / LNG, 2019).

[44] The NOx Fund is operated in accordance with the non-profit principle and has the purpose of supporting the business organizations and the State. Both are committed to working together to survey, develop and provide information on possible emission reducing measures for the implementation of the NOx Agreement (Nore, 2011).

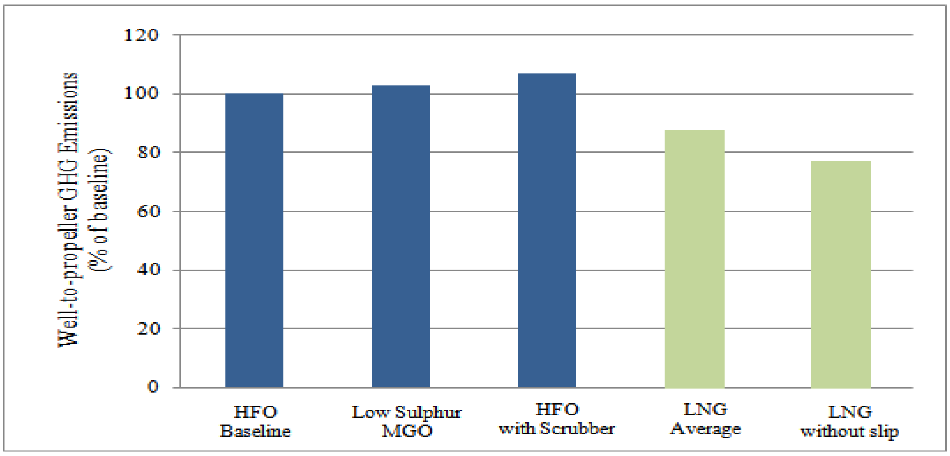
[45] Switzerland-based Winterthur Gas & Diesel Ltd (WinGD) revealed it has been chosen to supply the 12-cylinder, 92cm bore, dual-fuel low-speed main engines (12X92DF) that will power the CMA-CGM's new mega-containerships.

From literature review and state-of-the-art technique one can perceive that the driving forces behind the LNG as an alternative fuel are health, environmental and economic considerations relative to residual and distillate fuels. Holding back are fuelling infrastructure (though already operational in several northern European seaports hubs), but mostly the methane leakage problem. Apart from its environmental and societal benefits LNG, due to its characteristics as a cleaner fuel together with pressure to decrease carbon emissions through the adoption of more stringent regulations along with the limited available capacity of low-sulphur fuels, ship-owners will be forced to look at LNG as an alternative. Though not without costs and some technical hurdles, a fuel switch to LNG could effectively allow ships to sidestep the need for low-sulphur marine fuel and after-treatment devices. However, when considering a new technology, it is important to have a clear understanding of not only the benefits, but the burdens that may be involved. Next subsections will identify the pros and cons of the adoption of such a fuel by means of weighing advantages and disadvantages.

7.1.1 The pros: environmental benefits

LNG's first advantage to become an attractive fuel for shipping is because it not only complies as it over-accomplishes all current and anticipated environmental legislation targets for NO_x, SO_x, PM and CO_2 reduction (Wurster et al. 2014).

Table 7.2: Well-to-Propeller assessment of GHG for conventional marine fuels and LNG.



Source: Adapted from Chryssakis, Brinks and King (2015).

Emissions mitigation from ships can significantly reduce ocean acidification, hipertrophication and ecosystem injuries[46] improve water quality in lakes and streams and the health of forests. Table 7.2 depicts well-to-propeller assessment of GHG for conventional marine fuels and LNG under various scenarios.

Since its environmental properties are superior to conventional fuel oils, LNG is considered the most promising alternative fuel in the maritime segment today (Kolwzan and Narewski, 2012; Chryssakis et al. 2014; DNV GL, 2018). In China, a country that is paying a high price for pollution associated with shipping, because of its lower air pollution impacts LNG gradually gains traction in the marine sector (Fung et al. 2014).

LNG has a higher hydrogen-to-carbon ratio compared to oil-based fuels, which results in lower specific CO_2 emissions (kg of CO_2/kg of fuel). Depending on the source of the natural gas, the potential exists for lower GHG emissions across its life cycle to strongly reduce methane leakage in the production and combustion phases. In practice, zero methane leakages are very unlikely to reach and some leaks should be expected, thus best practices and appropriate technologies for minimizing them should be utilized. This can lead to realistic reductions of GHG by 20% with a potential for up to 25% compared with conventional oil-based fuels (Chryssakis, Brinks and King, 2015) including the emissions of non-burnt methane (EMSA, 2010). More substantial greenhouse gas reductions are possible if fossil LNG is substituted with biomethane resulting in a reduction of 14% to 27% in GHGs in both well-to-tank and tank-to-propeller emissions (Wurster et al. 2014). Although climate change net effect on emissions still is a controversial question, there is a good chance to reduce those emissions both through the adoption of best practices and from new technologies (pipeline slippage reduction, boil-off gas (BOG) reduction, carbon capture and storage, for instance) which will further yield benefits. Hence, environmental benefits are expected to increase with the widespread adoption of LNG as a marine fuel.

7.1.2 The pros: health and non-health benefits

The combustion of fossil fuels on-board, even though the large of emissions occur far from shore, due to prevailing winds pollutants can spread for over hundreds of kilometres with implications for the air quality in regions far away from coastline (Evtyugina et al, 2007)

[46] Ocean acidification is the ongoing decrease in the pH of the Earth's oceans, caused by the uptake of carbon dioxide from the atmosphere. Eutrophication is when the environment becomes enriched with nutrients which induce explosive growth of plants and algae.

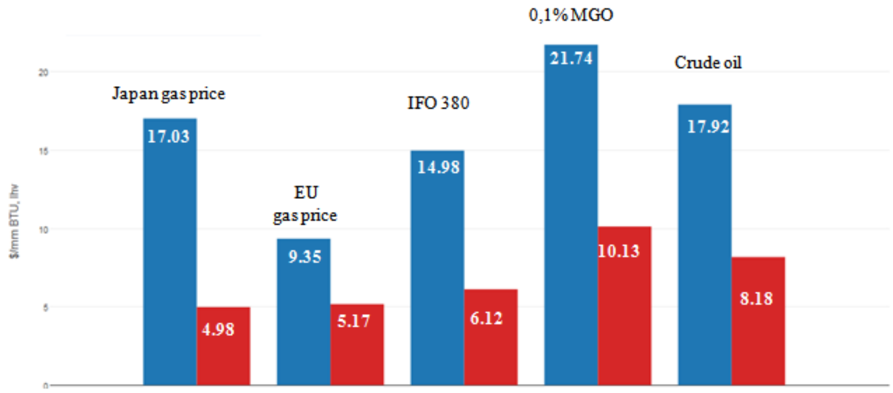
causing human health damage and premature deaths and impacts negatively over land use and biodiversity (Eyring et al, 2005). Since most of ship emissions occur on high seas people are not well aware of the danger imposed neither to their health nor about the impacts of air pollution from shipping or its contribution for global climate change.

LNG's benefits also include avoided non-health receptors reducing damages and costs over crops and materials, comprising infrastructures, buildings and cultural monuments. As it results from health and non-health assessment performed in Part III of this thesis, human health risk to air pollution and noxious effects over crops and materials will fall to lower ranges with the adoption of LNG as a marine fuel.

7.1.3 The pros: World reserves and spot prices

For an alternative fuel to be adopted it has to fall into three categories: be abundant, cheap and technologically tested. A critical determinant of the prospects for natural gas as a transport fuel is its long-term price relative to conventional fuels (Lowell, Wang and Lutsey, 2013) and this has been the case in the U.S. in the past years (Table 7.3).

Table 7.3: Gas and oil prices begin of Oct. 2014 (blue) ending July 2016 (red).[47]



Source: Adapted from DNV-GL.
Available from: https://www.dnvgl.com/maritime/lng/current-price-development-oil-and-gas.html. (Accessed March 11, 2016).

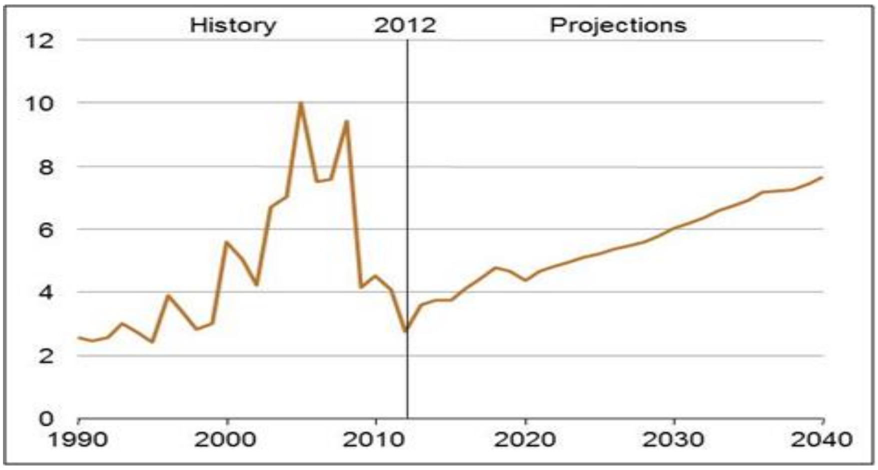
Projections of natural gas prices are influenced by resource availability and natural gas demand (EIA, 2015: 10). Notwithstanding low prices scenario for oil given to both growing energy efficiency in the transport sector and a lull in demand associated with slow

[47] Gas: no liquefaction and distribution included.

economic growth this downward trend will not last long. Crude prices reached over $80/barrel in mid-2018 and although projections of the events that shape energy markets are random and cannot be anticipated simply because future developments in technologies, demographics and resources cannot be foreseen with certainty, it is expected that world petroleum consumption will rise by an annual average of 1.1 million barrels/day (b/d), increasing from 100 million b/d in 2020 to 121 million b/d in 2040. Future growth in demand from non-OECD countries can result in a return to higher world oil prices, and the Brent price is expected to rise to $141/b in 2040 (U.S. International Energy Outlook, 2016).

Notwithstanding, since there is not such a thing as an international natural gas market (it is regionally segmented) the projections for natural gas prices are influenced by assumptions about oil prices. Indeed NG supplied to international markets priced on the basis of world oil prices is the reason for the differences between international and U.S. natural gas prices, resulting in significantly higher prices for global NG than for U.S. natural gas supply, particularly in the near term. Table 7.4 forecasts the prices for NG in the horizon 2040 (in 2012 US$/mBtu).

Table 7.4: Annual average Henry Hub spot NG prices 1990-2040.[48]



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2014*. Available from: https://www.eia.gov/outlooks/archive/aeo14/pdf/0383(2014).pdf.
(Accessed March 11, 2016).

[48] One million Btu is equivalent to approximately 7.3 gallons (27.63 litres) of marine distillate fuel or 6.7 gallons (25.36 litres) of marine residual fuel.

Oil-based fuel prices are expected to further increase with the costs of pollution controls (e.g. carbon capture and sequestration) at point sources together with the implementation of a carbon tax following the polluter pays principle thus increasing the external costs of oil products in comparison with natural gas. International natural gas contracts are used to be linked to crude oil prices although the linkage is expected to weaken with changing market conditions. Furthermore and in a scenario of cap-and-trade legislation, greenhouse gases will be priced to reflect their social costs and natural gas would be cheaper than traditional GHG-intensive fossil fuels. Investing in natural gas therefore could lead to a win-win situation (Liang et al. 2012).

The U.S. enjoys a highly competitive natural gas market and an increasingly efficient market for pipeline transport. Consumers have benefited from changes to both the structure and regulation of the industry in the past ten to fifteen years. These changes have lowered natural gas prices and broadened the range of services offered by gas companies. U.S. natural gas prices are determined primarily by the availability and cost of domestic natural gas resources (EIA, 2015) and are traded at the “Henry Hub” the pricing wholesale market price for large users of natural gas established in Erath, Louisiana.

According to the U.S. Energy Information Administration world NG proved reserves for 2015 are estimated in ~7,000 trillion cubic feet sufficient to meet 54.1 years of global production. Reserves estimates for gas are increasing as new discoveries are made, as existing fields are more thoroughly appraised, as existing reserves are produced, and as prices and technologies change. Proved reserves are estimated volumes that analysis of geologic and engineering data demonstrates with reasonable certainty are recoverable under existing economic and operating conditions. Beyond that, there are even more exotic sources, such as methane hydrates, that some experts claim can double available resources once more (Devold, 2013).

7.1.4 The pros: accidents and spills

Most authors, although recognising environmental and health benefits arising from the use of LNG do not address considerations about an important matter: accidents and sinks. Shipping is an industry which by nature involves risks and the fallibility of the human factor. When something goes wrong humans and the entire marine element suffers harmful consequences along with habitat destruction. In fact, by force of the growing number of vessels operating, the exponential increase in its scale and the emerging new routes that cross waters of extreme sensibility that already have weak levels of resilience means that when a fatality occurs and a ship wrecks the oil in her tanks spills or follows the ship directly to the bottom[49]. In the latter case, the oil will start leaking even decades after the spill by force of hull cracking. This is especially dramatic when the ship is a tanker.

When a maritime casualty occurs in international waters the applicable penalty points to the flag State and not to the ship-owner, which in most cases is a not resident holding different nationality than that of the flag of convenience (FoC). And it is precisely in this aspect that things get complicated because IMO, for itself, has no jurisdictional powers to apply the Conventions (e.g. the U.N. Convention of the Law at the Sea – UNCLOS)[50], and contentious issues are relegated to the scope of the countries involved. This is something of excessive reasonableness when we know that in international waters the law enforcement is a matter of each nation and many of them do not perform with sufficient accuracy or legitimacy, something that usually happens with FoC ships involved. Indeed, many stakeholders (The International Chamber of Shipping, The International Union of Marine Insurance, The International Salvage Union) point out as a serious flaw the inertia of the IMO to enforce the agreements related to the issue of safe havens to ships in danger of sinking[51]. According to the UNCLOS, foreign ships are subject to the jurisdiction of the State in whose waters they are; exceptions are military and State owned vessels, to whom applies jurisdiction immunity. In international waters, also known as high seas, the only applicable jurisdiction is the one of the State whose flag the vessel is flying, which contradicts the ability of international organizations to oversee and act on the deep sea, although stated by the European Union, as can be read in the paragraph *e* of article 3 of the Directive 2005/35/EC.

In the period 2005-2014 and according to data from the AGCS (2015), some 600 vessels of 100 GT or over (excluding pleasure craft and smaller vessels) were foundered (sunk or

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[49] In 2014 there were 55 shipping casualties in Arctic Circle waters. There were just 3 a decade ago (Allianz Global Corporate and Specialty – Shipping Review 2015, hereinafter only AGCS).

[50] The UN Convention on the Law of the Sea is a 1982 multilateral treaty concluded under the auspices of the UN that defines and codifies inherited concepts of customary international law relating to maritime issues as territorial sea, exclusive economic zone, continental shelf, among others, and the general principles for the exploitation of natural resources of the sea, like the living resources, soil and subsoil. This Convention also established the International Tribunal for the Law of the Sea, with jurisdiction over disputes concerning the interpretation and application of that treaty.

[51] The Maritime Maisie odyssey gives the “best” prospect of this statement.

submerged) together with oil trapped in pipes, tanks and hull structure. Salvage and removal of wrecks is costly and very often impossible due to the water depth at which the ship is. The infamous MV Prestige tells us a story of what can happen following an oil spill wreck (Figure 7.2).

Figure 7.2: The "Prestige" shortly before sinking off Galicia coast, Spain in 2002.

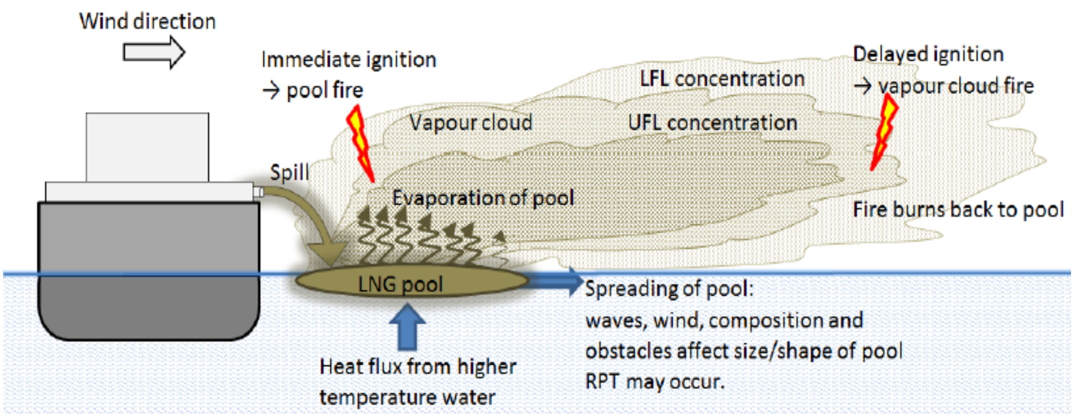
Source: ABC Galicia.

Available from: https://www.abc.es/local-galicia/20150210/abci-marea-negra-blanca-prestige-201502051205.html. (Accessed, December 8, 2015).

The Prestige was a 26-year old, single hulled oil tanker which was hit by strong winds and towering waves while enroute from Latvia to Singapore on the 13th November 2002. Suffering of hull damage and listing she approached coastline near Cape Finisterra, in the Spanish northern coast of Galicia. Some 77,000 metric tonnes of HFO were on-board. Spain, France and Portugal have refused safe havens and the ship was redirected towards open seas in an attempt to avoid dramatic impacts of oil spills all over the region. This decision was proved to be wrong; the ship finally broke in two and sunk. By 2004 less than 15% of the original fuel load has been recuperated; 25% leaked before sinking while 60% has been slowly dispersed in the ocean (Cozijn et al. 2012). The Prestige remains in the bottom of the ocean at some 3,500 metres deep leaking oil until the day of today. The total cost of the operation, including shore decontamination, removal of oil spills and environmental costs is estimated to be around 3.6 billion euro total economic value for Spain and France between 2002 and 2006 (Loureiro, 2006).

HFO contain light fractions called polycyclic aromatic hydrocarbons, heavy toxic chemicals that can poison plankton, fish eggs and crustaceans, whose metabolites have mutagenic effects in fish and humans along the food chain mechanism. Crude oil discharge into the sea has strong acute and long-term impacts on marine ecosystems, including effects from physical damages and toxicity of their chemical compounds (Almeda et al. 2015). Zooplankton cannot overcome the effects of currents, limiting their capacity to avoid crude oil patches and, potentially, forcing them into highly polluted water masses after crude oil spills. Given the key role of zooplankton in marine food web dynamics crude oil spills in pelagic zones have a harsh impact in marine environments. Environmental benefits from the adoption of LNG as a fuel for vessels include that residual and distillates have much more hazardous components. As such, the environmental consequence are less damaging for methane spills and sinks that in the use of a vessel using traditional fuels, since spills will disappear when in contact with water (Laugen, 2013)[52].

Figure 7.3: Possible outcome of LNG spill over water.



Source: Luketa-Hanlin, 2006[53].

The outcome from a LNG spill depends on factors like the size of the spill, and the surrounding environmental conditions. In the case where no immediate ignition occurs, the

[52] The same is true for biodiesel due to the fact that it is biodegradable, hence being less harmful in case of spillages.
[53] *"RPT": rapid phase transition. "UFL": upper flammability limit.*

LNG spill will boil-off generating dense gas which is then dispersed by atmospheric turbulence. The extent of the vapour cloud hazard depends on the pool spill rate, the pool size and the stability of the surrounding atmosphere (Basha, 2012). Indeed, assuming an unconfined spill of LNG into water, it will spread and boil at a very high rate due to the large heat source provided by the water and the turbulent interface (The Danish Maritime Authority, 2012, from now on DMA; Bengtsson, Fridell and Andersson, 2013). Due to contact with the water, which is at a much higher temperature there is a high vaporization rate that is maintained (Figure 7.3 above). High vaporization rate that leads to a greater distance to the lower flammable limit (LFL) of the vapour cloud. The vapour cloud from unconfined spills is stated to travel at roughly the wind speed before becoming buoyant and dispersing. Vapour concentrations are highest near the spill and then gradually decrease to the lower flammability limit at the edge of the cloud (Luketa-Hanlin, 2006)[54]. For spills resulting from events such as an impact, if there is immediate ignition of the released LNG, it is likely that there will be a pool fire because many of these types of events will provide an ignition source (impact of metal on metal), even though from a total of 96 marine environments spills reported in the U.S. databases, only one resulted in fire (DMA, 2012). From the above stated one can perceive a general environmental advantage of LNG fuelled vessels both in terms of air and water related pollution in the occurrence of spills originated from collisions or from sinks.

7.2 LNG as a marine fuel: the cons

Regulations and industry standards were put on place at a quite late stage at European and International levels[55]. Also there is several regulatory organisations having jurisdiction over vessel design, operation, and bunkering[56]. A major disadvantage for the widespread use of LNG as an alternative fuel at European level is the significant investments needed to

[54] Most of consequence analysis of large-scale LNG spills on water has been carried out focusing hazards posed by thermal radiation and flammable vapour dispersion from tank cracks in LNG carriers' membrane-type.

[55] ISO/TS 18683:2015: An ISO technical specification titled Guidelines for Systems and Installations for Supply of LNG as Fuel to Ships was released in January 2015. It describes the properties of LNG, the safety hazards, the risk assessment process, and the functional requirements for LNG bunkering systems.

[56] Regulatory Organizations and Required Approvals that will be involved with reviewing LNG bunkering system designs and arrangements, are as follows (ABS, 2015): Classification societies, in reviewing the design and construction of LNG bunkering systems on board gas fuelled vessels and any LNG bunker vessels; Flag Administrations, for enforcing international and national regulations related to the bunkering systems, processes, and procedures; The Port States, with primary jurisdiction over any land-based facilities that may be part of the LNG bunkering process.

be made both on board ships and in new infrastructures. Ferries, tugboats and LNG carriers have established supply chains especially through satellite LNG facilities that store LNG, but do not liquefy it, and only in a few elected places (Balon, Lowell and Curry, 2012).

7.2.1 The cons: the LNG supply chain

Indeed, the lack of a supply chain and of filling stations, was considered to be one of the main disadvantages for the widespread introduction of LNG. However, this fundamental barrier has been phased out, with several European ports having LNG supply facilities, and very briefly it will no longer be a disadvantage, and this was vital to overcome market failures (Wainwright, Peters and Gleave, 2017). LNG was previously considered mostly suitable for ships in coastal trades (e.g. short sea shipping) or ships engaged in regular trade mainly because of the limited shore infrastructure available. The storage, handling and distribution of LNG are directed at the land-based uses. Since there was not until now a commercial interest for this alternative fuel, there has not been much investment in this type of infrastructure. We assume that political intervention (e.g. regulatory support and financial incentives) at national/European level is necessary to reduce the uncertainty relating to port infrastructure for LNG as well as for security and safety risks assessment, regulatory framework, training and competence requirements and issues alike.

The availability of the LNG as a marine fuel is a challenge particularly for first movers because it depends on the existence of a cost-effective infrastructure meaning that it influences directly ship-owner’s first step to rethink their fuel strategy. Such an infrastructure consists roughly in an import terminal, storage tanks, pipelines or feeder ships bringing LNG from the terminal to jetties for direct bunkering, bunker ships, tank trucks and barges. Capacities for the different bunkering procedures will be dependent of the nature and the dimension of the port, its physical limitations, logistic issues, types of vessels and shipping companies, investment and operating costs. At present date, a number of projects for developing bunkering infrastructures for LNG fuelled ships are currently underway in Northern Europe and around the Baltic Sea and North Sea, whereas several U.S. ports are already in this race. Also in both East and Southeast Asia several governments and Port Authorities are concerned with the surmounting levels of pollutants around and near coastal areas; emissions of CO_2 from shipping freight traffic have doubled in the last decade in the main East Asia shipping lanes. In Hong Kong new rules requiring ships at berth to use low-sulphur fuels were recently announced and the Singapore Port Authority announced that they would be ready for LNG bunkering by 2020. Thus, as a result of the above factors, it is expected that in the near future both infrastructure and terminal facilities be ready to enter in operation all over the main shipping lanes and major ports of the world, so it is to be hoped that this handicap will be surpassed.

7.2.2 The cons: on-board storage and bunkering safety procedures

Because it is a gas at ambient temperature and pressure, NG is more difficult to transport, handle, and store on-board a vessel. To accommodate LNG engines extra space is required on-board. Laugen (2013) estimates that LNG configured vessels could require up to 3 times as much space required for LNG compared to HFO. For containerships some 2-4% of the cargo carrying capacity has to be sacrificed to provide space for the fuel tanks (EMSA, 2010), although this is no more fully correct since new CMA-CGM’s LNG fuelled mega containerships due for delivery in 2020 fuel tanks will be housed under the front arrangements (with the upper deck used as the LNG management and control center). Yet, and because propulsion systems need to be integrated in the ship design at an early stage, for the retrofitting and due to the fact that tanks require more space this directly influences the revenue of the trip, reason why retrofitting is also in need of funds to support vessel conversion whilst taking into account that the operational costs of LNG engines are very low and the maintenance needed is minimal compared to machinery running on HFO (more on Subsection 7.2.3).

Bunkering with LNG is a new process that presents different risks and hazards not seen with fuel oil bunkering. Both public and private investors will face not only investment and operating risks but also safety and security issues since LNG bunkering is for all effects considered as a dangerous substance. Those involved with bunkering should receive comprehensive, formal training, including emergency response training to deal with conditions of leakage, spillage, or fire and first aid training specific to LNG (ABS, 2015). A well-performed and well-presented safety assessment is instrumental to the calculation and estimation of possible outcomes of various accidental events, supported by both national and European authorities. International guidelines for adequate risk for personnel, property and for the environment and accidents reporting applied to bunkering concepts and facilities, from land as well as the sea side of the quay must be issued.

The definition of Safety zone means an area around the LNG bunkering station/facilities to ensure that only essential personnel and activities are allowed in the area that could be exposed to hazardous events, to accidental release or other incident with LNG during bunkering. Care should be given to coupling and hose or loading arms connections. The hoses should be suitably long and flexible to allow for relative movements, such that the hose can remain connected to both the supplier’s manifold and the receiving ship’s manifold during ship movements originated from wind, waves, current, and surges from passing vessels. The hoses should be capable of releasing without damage or significant spills if the relative position or movement of the receiving ship exceeds the limits and should remain sealed when excessive pull occurs. Instead of flexible bunker hoses, loading arms are rigid structures with swivel joints to allow for articulation of the LNG connection and relative movements. Loading arms eliminate some of the handling issues that are present with hoses, but they can induce higher reaction forces on the bunker manifold that need to be considered. The connectors will be exposed to frequent large temperature variations that may impose excessive loads on couplings, joints and seals. Hence, due attention should be given to the design and selection of the connector system to ensure high integrity and reliability. The connectors shall be of a drip-free, quick connect/disconnect type (DNV-GL, 2015b). A drip-free coupling avoids any spill of liquid or vapour or limits it to a minimum, hence reducing eventual methane spillage.

Different types of hazards can occur during operational bunkering phases which can be divided into three (DMA, 2012): i) loading/discharging of feeder vessel or bunker vessel/barge at the terminal; ii) a feeder vessel or bunker vessel/barge transiting a port and, iii) LNG bunkering subdivided into three modalities – STS, TTS and LTS. For STS and TTS bunkering modes a risk assessment used by the Swedish port of Gothenburg LNG operating port bye-laws is based essentially in the following procedures:

<u>Ship-To-Ship operations (STS)</u>

The Safety zone while a vessel is moored during STS bunkering operation at the sea side is set to 25 meters. The LNG bunkering must be stopped if a vessel or craft come closer than the safety zone. No ship to ship bunkering is allowed in Port of Gothenburg when wind force exceeds 20 m/s. LNG manifolds on-board and ashore should be separated into independent manifolds and spillage containments for each type of purpose.

• Oil bunkering to LNG driven vessel is allowed simultaneously as LNG bunkering.

• Oil bunkering to LNG vessel during cargo transfer operation of LNG is not allowed.

Truck-To-Ship operations (TTS)

The Truck to ship bunker operation is comparable to a bunker operation between a bunker vessel and receiving ship and hence the same regulations and checklist must be filled in.

Table 7.5: Safety zone distances in Port of Gothenburg.

TYPE OF VESSEL	SEA SIDE	BUNKER STATION	TERMINAL
LNG / LPG / Tanker	25 meters	25 meters	25 meters
Container / Bulk	25 meters	15 meters	15 meters
Ro/Ro	25 meters	25 meters	15 meters
Ferries	25 meters	25 meters	25 meters

Source: Port of Gothenburg.

Available from www.goteborgshamn.se. (Accessed March 25, 2015)

As for LTS mode, bunker terminals allowing the ship to refuel through hoses from a shore side facility, provides connections to the ship's fuel gas system to allow loading of LNG fuel. In the case of a fixed facility and in a commercial perspective, it may be necessary for the ship operator and terminal to perform simultaneous transfers of cargo on vessels while bunkering (ABS, 2015).

For passenger vessels, it refers to bunkering with passengers on- board or while embarking and/or disembarking. During normal bunkering operations, and in certain situations, natural gas vapour may inadvertently be released into the atmosphere resulting in a flammable mixture. Sources of ignition are not allowed in hazardous areas, so that even in the case of inadvertent release of gas the possibility of ignition is reduced.

Cargo operations can increase the potential for uncontrolled sources of ignition, for example, loading containers in a container bay adjacent to the ship's bunker station can provide a greater risk of producing sparks, which can be a source of ignition. Another concern is the possibility for de-bunkering (or emptying the fuel tanks) necessary when a ship is to be anchored for an extended period of time. In this case, the gas would boil off causing methane losses to the atmosphere. The same can happen in case of grounding accidents which calls for special LNG de-bunkering facilities available in the port (McGill, Remley and Winther, 2013). Accordingly, potential simultaneous operations need to be evaluated on their own merits, and their risk levels determined as part of the risk assessment process.

7.2.3 The cons: higher costs for new builds and retrofits

Retrofitting: As already cited, because propulsion systems need to be integrated in the ship design at an early stage the decision of building a new ship or converting an existing one to LNG is not simple, due to the cost to produce them while retrofitting is more expensive compared to applying technical measures in the design and building phase (Laugen, 2013), and some existing ships may not have enough space to retrofit LNG tanks (Fung et al. 2014). This can also be regarded as a cost, although probably more relevant for the container ship type (DMA, 2012). Moreover, existing marine engines are currently unable to burn alternative fuels and, if retrofitted, would require dry-docking and modification (Gilbert et al. 2015), that makes retrofitting a long-term investment[57] (Table 7.6).

Table 7.6: Investment costs for both LNG retrofitting and new buildings.

	Retrofit			New buildings		
	RO-RO	Coastal tanker	Container	RO-RO	Coastal tanker	Container
M€	3.2	5.1	4.8	4.3	6.8	6.4

Source: Adapted from The Danish Maritime Authority - DMA (2012).

Apart from the fuel supply system, the engine and related components and the fuel storage tank, an LNG-fuelled vessel is basically not different from a diesel-fuelled vessel. The size of fuel tanks is affected both by the energy density of LNG, but also by the additional insulation required, and by the cylindrical shape of existing tanks, which make sub optimal use of the space. For this reason it can also impact on the cruising range or the carrying capacity of the vessel. It is anticipated that prismatic tanks, when they become commercially available, will drive down the space requirements to some extent (Chryssakis, Brinks and King, 2015).

[57] DMA (2012) estimates a capital cost annualised by assuming a ship life time of 25 years. This means that for retrofitting ships, the economic lifetime of the investment is the remaining life time of the ship (i.e. 25 years minus actual age). Also the cost arising from taking the vessel out of service for a few months to be retrofitted must be included in the final calculation.

New orders: LNG engines are of similar size as diesel engines but insulated storage tanks needed for LNG contribute to the higher price tag. New ships' investment generally lies between €4.3M for a Ro-Ro ship and €6.4M for a container vessel, depending on the size and the complexity of the installation (EMSA, 2010; Kollamthodi et al. 2016), although a broader market of manufacturers is expected to reduce the prices in the future. In addition, due to the modification required in the main engine (although dual fuel retrofits are being discussed) subsequently, the capital expenditure for new LNG fuelled ships could increase by 25%. Looking to prices depicted in Table 7.6 it means that they are 10% to 25% more expensive to build than comparative vessels running on fuel oil, and it will take owners of gas-fuelled ships at least five years to recover those costs. Notwithstanding these incremental capital costs, China has been retrofitting LNG-powered ships (Lowell, Wang and Lutsey, 2013) and the reason is because a shift to LNG is indeed cost effective if the analysis is based on a societal perspective, weighting all benefits and costs including negative externalities[58].

7.3 The methane slip

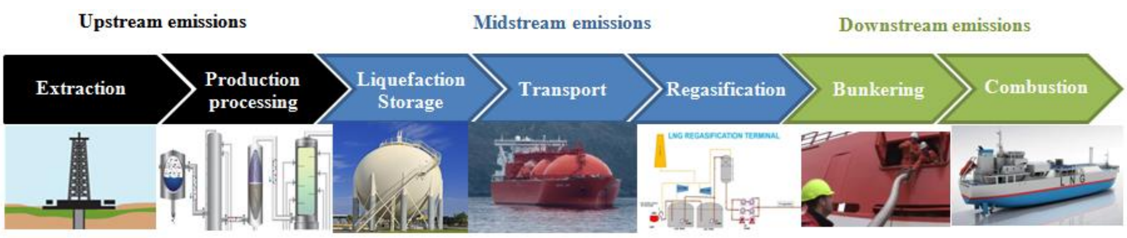
From literature review, if some studies point LNG as not providing climate neutral conversion (Laugen, 2013; Kolwzan and Narewski, 2012), others (Bengtsson, Andersson, and Fridell, 2011; Chryssakis et al. 2014) refer the reduced fugitive emissions during the life cycle which provides climate neutrality, yet depending on how the natural gas is extracted, processed, distributed and used (Thomson, Corbett and Winebrake, 2015), also stressing the fact that as an energy end-use fuel it produces less health externalities, reduces impacts over materials, crops and ecosystems. Nevertheless, methane slip emissions estimates wave from 1.8% of the fuel being lost to the atmosphere of up to 3.5% (Thomson, Corbett, and Winebrake, 2015). The large variations in estimates indicate that this is an area where there is a significant amount of uncertainty (Kollamthodi et al. 2016)[59]. For what follows, we assume for the case of marine fuels *Upstream* emissions as

[58] China established Domestic Emission Control Area (DECA) for sulphur since 2015 to constrain the increasing shipping emissions (Liu et al. 2018).

[59] Knowing that if methane slips at a rate of more than 2.5% the LNG do not offer climate benefits (Bengtsson, Andersson and Fridell, 2011). Therefore, one important task for future research is to assess to which degree those different perspectives and outcomes are genuine or wrong but having in mind that available studies refer only to energy generation comparing coal and natural gas emissions from electricity plants, not to end-use fuels.

those released from extraction, production and processing. *Midstream* emissions as those arising from liquefying, storage (including storage as LNG), transport of gas in pipelines and over long distance (LNG carrier), and those from regasification. *Downstream* emissions refer to bunkering operations and engine emissions, a methodology very close to that used by the EC to assess conventional NG GHG emissions (EC, 2015). The methane slip is such an important issue to address due to the fact that slippage along the supply chain will consequentially increase the LNG footprint and this could change LNG's position as the most environmental fuel in a life cycle perspective (Laugen, 2013) because few grams of methane per kWh add 10-15% to the GHG emissions (Verbeek et al. 2013). As such, GHG emissions from leaked methane emissions converted to CO_2-equivalent emissions (gCO_2e/MJ) using a GWP of 25 for methane over a 100-year time frame, meaning that each gram of methane leaked has 25 times the atmospheric warming effect of a gram of carbon dioxide emitted, reduce the net global warming benefit from 25% to about 15% (Kolwzan and Narewski, 2012; Lowell, Wang and Lutsey, 2013). Thus, fugitive emissions of methane along the supply chain appear as the fundamental problem to solve. Yet, and due to the intrinsic nature of this thesis where LNG is saw as an end-use fuel instead of electricity generator fuel special attention is given to downstream emissions. Yet, the amount of CH_4 released during downstream combustion in the engine can be easily reduced if compared with those from upstream processing and transport.

Figure 7.4: The LNG supply chain.



Source: Author's elaboration.

7.3.1 Upstream and midstream emissions

Like all other fuels, LNG extraction and liquefying processes requires upstream energy and the resulting emissions should be added into the final balance. The natural gas life-cycle starts with the production of natural gas and ends with its combustion resulting from stationary and mobile source activities (e.g. electricity generation, driving power, etc.). The life-cycle analysis will consider direct air emissions from the process (the combustion of fuels from lorries and other vehicles and those from electricity generation) including GHGs and other pollutants likewise (Jaramillo, Griffin and Mattews, 2007). It also includes emissions from flared and vented gas and reported fugitive emissions. Studies about upstream emissions from NG point that emissions from shale gas appears to have a GHG footprint some 8% to 11% higher than conventional gas (Fulton et al. 2011) which stresses the importance of implementing mitigation strategies and practices for the upstream stage of unconventional extraction. For example, the decrease by 31.6 million metric tonnes (MMT) CO_2e (or 16.3%) in transmission and storage CH_4 emissions in the U.S. between 1990 and 2015, was largely due to reduced compressor station emissions and to increased use of plastic piping, which has lower emissions than other pipe materials, and station upgrades at metering and regulating stations (EPA, 2017). Midstream emissions often refer to the transport of natural gas from the producing region to the consuming region, i.e. those produced from fugitive emissions during liquefaction, storage, transport and regasification including minor emissions from mobile sources (from vehicle diesel, mostly) and use of plant and equipment (CH_4 emissions released from pressure safety valves and LNG tanks). These emissions will be transient, intermittent and spatially variable (QGC, 2014). Fugitive emissions may arise due to trace leakage of gas through flanges, valves or other equipment, and from vents (QGC, 2014). Liquefaction plants are generally located in coastal areas and LNG tankers transport LNG to an onshore plant to be regasified at the country of destiny, in the case of LNG imported from abroad by ship as is the case of Portugal as we have seen supra. The import terminal will receive natural gas by pipeline and store the LNG in storage tanks. Finally, the importing country should have a regasification unit which operates in the reverse direction of that of liquefaction, returning the liquefied gas to its normal state. From this point ahead the regasified LNG enters the natural gas transmission system[60]. According to Abrahams et al. (2015) emissions from liquefying, shipping, and regasifying natural gas (midstream) are marginal relative to the production and combustion emissions, but the latter referring to electricity production.

[60] As of the present day around 60% of Portuguese natural gas imports come from pipeline (the so-called Europe-Maghreb pipeline from Algeria outwards) which crosses the Gibraltar Strait and enters in Spain then performing a detour to the Portuguese border. Long-distance pipelines can induce a greater slippage due to higher leakage rates (Abrahams et al. 2015).

7.4 Downstream slippage

Much of authors from literature review take the differences in carbon content between LNG and distillate or residual fuels in part due, to some extent, GHG benefit in the reduction of global warming footprint. Although these differences are genuine, the real-world effect on emissions is more complicated than that. Unburned methane from dual-fuel and lean burn engines[61] increases atmospheric methane emissions and lost energy. Methane slippage from tank to propeller may be due to the engine concept, engine design, and its operational profile or due to maintenance (RAE, 2013), which worsen if the vessel is propelled by an Otto Cycle engine (dual-fuel as well as spark-ignited). That said it is assumed as of paramount importance to reduce at most the methane slip both from bunkering operations and from engine combustion. The following subsection describes unburned methane emissions produced by engines and those escaped during bunkering activities.

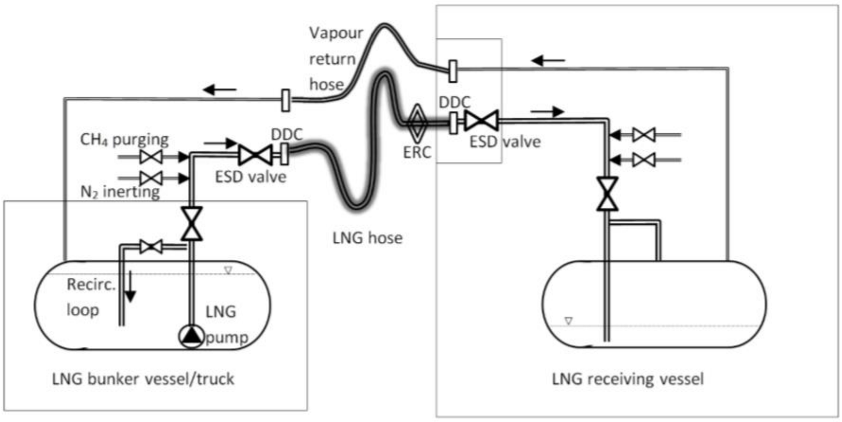
7.4.1 Fugitive emissions from bunkering activities

Bunkering activities include four different types of methane losses: i) losses due to heat absorption and venting from storage tanks over time; ii) venting of displaced vapour when filling a storage tank; iii) LNG liquid and vapour purged from hoses and lines after fuelling a vessel; and iv) flash losses created from precooling lines and storage tanks or from transferring LNG from a high-pressure to a low-pressure tank (Lowell, Wang and Lutsey, 2013). Plus, at atmospheric pressure, natural gas must be maintained as a cryogenically cooled liquefied gas inside insulated containers. Yet, and no matter how well insulated the containers are, some heat will continually seep into the container. As heat is absorbed, the head space pressure at the top of the container rises as LNG evaporates. When a vessel is lying at anchor or experiencing a delay in port, methane may have to be vented to maintain acceptable tank pressure levels resulting in additional GHG emissions. This is called boil-off gas or BOG for short, a form of venting to relieve pressure in the storage tanks and to remove some of the absorbed heat. One solution to reduce boil-off and additional methane leakages is by means of using pressurized tanks which can extend storage time events because it can withstand a higher internal pressure. The longer LNG is bunkered before being used, and the more times it is transferred from one storage vessel to another, the

[61] Lean-burn refers to the burning of fuel with an excess of air in an internal combustion engine.

more BOG are created. There are four main methods for dealing with the BOG created during LNG storage and handling: i) releasing it to the atmosphere; ii) flaring it; iii) capturing it for use as gaseous fuel, or iv) capturing and reliquefying it[62]. If BOG handling is warrant marine bunkering sites are likely to be connected to a natural gas pipeline that could be used to siphon the BOG created during tank filling, long-term storage, or vessel fuelling. To prevent or avoid methane spillage from bunkering activities, specific guidelines, including the use of emergency shutdown systems (ESD) that, in case of emergency situations, will stop the flow of LNG and LNG vapours and the use of emergency release systems (ERS) and/or safe breakaway couplings (SBC) that, in case the emitting and the receiving unit move away from each other, enabling a rapid disconnection of arms/hoses and/or breakaway couplings, should be implemented. Figure 7.5 displays a diagram of the bunkering process including two Emergency Shut Down (ESD) valves located close to the hose connection flanges on the respective vessels[63].

Figure 7.5: Schematic bunkering concept with basic system components.



Source: The Danish Maritime Authority – DMA (2012).

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[62] For example, some LNG carriers are equipped with reliquefaction plants that collect the gas, cool it to below –162°C so that the vapours condense, and inject the LNG that forms back into the cargo tanks. However, the low average volume and intermittent nature of BOG generation would likely make this method unattractive economically.

[63] The figure also depicts an Emergency Release Coupling (ERC) or a Safe Breakaway Coupling (SBC) for the case the distance or relative motions between the vessels exceed the limits of stretching the hose. The ERC or SBC would then disconnect the vessels and close both ends of the separated coupling. The hose connection flanges in the figure are also arranged with Dry Disconnect Couplings (DDC) in order to prevent any spill or venting of the hoses when stowed away on the bunker vessel after the bunkering operation.

These may be activated and closed automatically or manually if leakage is detected or in case of any other deviation from normal operation.

Specific LNG bunker operations trained personnel as well as technical measures implementation will further diminish methane releases. BOG generated during vessel fuelling could also be used to satisfy on-site process heat or space heating needs, but the practicality of such an approach would vary significantly from location to location (Lowell, Wang and Lutsey, 2013). The boil-off gas can be used efficiently as a fuel for generating electricity that will then supply electric charging stations or be injected into the grid. If there is no demand for electricity, the gas can be cooled back down, and becomes liquefied. It is then channelled back to the LNG storage tank for reuse. Finally LNG can efficiently be transformed to compressed natural gas (CNG) by pumping it up to high pressure and then vaporize on the desired pressure (ENGIE, 2016).

7.4.2 Fugitive emissions from engines

Methane can be released during vessel operation via unburned fuel combustion in the engine. Unburnt methane is trapped in clearances in the combustion chamber (piston rings, the anti-polishing ring, valve seats etc.) where the air-fuel ratio means that the gas does not burn during combustion but is released unburnt with exhaust gases during cylinder scavenging (Wärtsilä, 2013). There are two ways to ensure that methane slip is minimized in the engines: by continuous development of the combustion chamber technology to improve the combustion process and by the oxidation of unburnt methane using a catalyst. Further developments to reduce the methane slip can be achieved by correct gas admission valve timing, the use of pre-chamber technology to have complete combustion in every cylinder at all times.

Gas engines can be divided in two main categories: Dual fuel engines (e.g. Wärtsilä; MAN); and lean-burn gas engines (e.g. Rolls-Royce; Mitsubishi). The different engines and engine propulsion arrangements have varying characteristics and levels of efficiency. According to the technical specifications in a Wärtsilä gas engine the amount of unburnt gas following combustion is small. The methane slip in a Wärtsilä's slow-pressure 2-stroke engine, the RT-flex 50DF, is almost negligible and less than what is found in the equivalent 4-stroke engine still resulting in 25% less equivalent CO_2 emissions, because the combustion has much more time to burn more completely, which is not the case in 4-

stroke engines (Pospiech, 2014). The next step is to avoid any methane slip as is the case of the MAN Diesel and Turbo high pressure 2-stroke engines ME-GI concept, being GI the initials of gas injection. Operative tests of ME-GI engines have revealed a high efficiency with a negligible methane slip – 0.2% as a maximum when the engine was operating at low load (MAN Diesel and Turbo, 2014). This slip is 20-40 times lower in comparison to the methane slip recorded for the most modern, state-of-the-art dual-fuel engines. The GI engine requires pressurised gas at a maximum pressure of 300 bar. The technology to pressurise the LNG and evaporate it at this high pressure is available, and solutions have been developed by several marine engine builders. In sum, engine technology in maritime transport does not constitute a major obstacle for the application of LNG (Wurster et al. 2014).

8. Summary of Part I

For what we have learned so far it is most clear that current mitigation measures, abatement technologies and energy efficiency methods even considering them as important for lowering the carbon budget, are not enough to achieve deep cuts in carbon emissions from international shipping. Although a fuel switch to distillate fuel from heavy fuel oil allow to achieve compliance with current and forthcoming IMO emissions regulations on maximum allowable sulphur content in the fuel oil, reduced emissions may only, at its best, result locally not globally. As for mitigation actions and operational measures to tackle with reducing noxious emissions from international shipping, those can come along within the energy-mix general scheme to upright ships efficiency, but they do not correspond to the urgency of progress toward decarbonisation in the shipping sector, since the oil-based society paradigm is not altered. Those measures rather should be seen as small-scale mitigation strategies instead.

LNG produces no SO_x emissions and almost eliminates PM emissions; NO_x emissions are cut by up to 90% due to reduced peak temperatures in the combustion process and is expected a reduction of some 20-25% net in CO_2 emissions compared to refined oil products already including the emissions of non-burnt methane. LNG enjoys competitive advantages compared to petroleum products, in an equivalent energy basis, and is undoubtedly the best prospect to be the bridge fuel of choice following a deep short-term decarbonisation policy for shipping. LNG produces the lowest CO_2 emissions of all fossil fuels. However, the release of unburned methane (so-called methane slip) could reduce the benefit over HFO and MGO because methane has a superior GWP effect compared to CO_2. Nevertheless, engine manufacturers claim that the Tank-to-Propeller (TTP) CO_2-equivalent emissions of Otto-cycle dual-fuel (DF) and pure gas engines have very low methane slip, about 10 to 20 percent below the emissions of oil-fuelled engines (DNV GL, 2018). LNG gas engines cover a broad range of power outputs. Engine concepts include gas-only engines, dual-fuel four-stroke and two-stroke. Methane slip during combustion has been practically eliminated in modern two-stroke engines, and further reductions should be expected from four-stroke engines (DNV-GL, 2015c). Even though, we are aware that the slippage issue needs to be better addressed mainly at both upstream and midstream phases of the life-cycle since downstream phase seems to be the less difficult to resolve. A switch to LNG for marine purposes is not the “silver bullet” that will change the fossil paradigm within society but, for the time being, there are no cost-effective solutions to the LNG as a transition fuel for maritime applications and to start to phase out the oil from the shipping sector in the nearest decades (Grahn et al. 2013).

To better understand the prospects from potential shale gas as the source for marine LNG, there are some clear scientific objections and uncertainties with respect to fugitive emissions, because its high radiative forcing can contribute significantly to the global warming impact (Hultman et al. 2011). Ongoing debate around natural gas as its use provides a climate benefit or not appears to be based largely on whether we should look at the impacts of emissions: over twenty years or one hundred years’ time scale. Cathles et al. (2012), stress that, while methane is a potent GHG, it persists in the atmosphere for few years, while CO_2 emissions from coal and oil consumption persist for hundreds of years[64]. Even with leakage from gas wells, they concluded that the use of gas is vastly less damaging in terms of global warming than coal and oil. Different perspective has Howarth (2014), using a 20-year GWP because of the supposed urgency of cutting emissions immediately in an attempt to avoid Earth’s average surface temperature above 2°C by 2045, whether or not carbon dioxide emissions are reduced (Howarth, 2014:8). Also, the

[64] According to Maddison (1995), although there is an initial period of extremely rapid elimination the concentration of a pulse excess of carbon into the atmosphere does not go to zero even in the long term; only 15% of the carbon emissions are ultimately retained in the atmosphere but this process requires a period of several hundred years to complete. As for the methane concentrations in the troposphere, it only stays aloft for about 8 years, on average, before it reacts to the bombardment of ultraviolet radiation and bonds with O-H, anhydroxyl radical.

scales and different methodologies used are in the origin of a gap between bottom-up studies and top-down studies,[65] (Brandt et al. 2014; Tong, Jaramillo and Azevedo, 2015), especially in the U.S. where there is about half a million wells and a couple million miles of pipeline.

An important number of studies points that current leakage rates are higher than previously thought, and mitigate leakages are critical to maximizing the climate benefits of natural gas fuel-technology pathways. Significant progress appears possible given the economic benefits of capturing and selling lost natural gas (Alvarez et al. 2012). Improved science would aid if scientists and engineers can develop reliable methods to rapidly identify and fix the small fraction of high-emitting sources (Brandt et al. 2014). Of course, a particular scrutiny focused on shale gas extraction have to be made to assure if the production of a single unit of shale gas is more GHG-intensive than that of a conventional well. If so and consequently, the upstream emissions associated with shale gas have to be largely mitigated otherwise the growing share of shale gas, namely from the fastest growing North American industry would increase the average life-cycle gas footprint of the total natural gas supply; one must have in mind that local GHG emissions have a global effect.

Calling for a tighter regulation of the industry, tight planning, careful extraction, and environmental impact monitoring may be the best way to reduce methane leakages. Quoting Stephenson and Shaw (2013): "*reconciling shale gas and climate action requires institutions capable of responding effectively to uncertainty; intervening to mandate emissions reductions and internalise costs to industry*". The California's Global Warming Solutions Act (Assembly Bill 32) fourth pillar proposed to reduce the release of methane, black carbon, and other short-lived climate pollutants, the EPA's corporate average fuel economy program (EPA, 2011b), for Medium Heavy Duty Vehicles (MHDVs), as well as methane regulations in the U.S. (e.g. EPA's GHGRP and the Natural Gas STAR Methane Challenge Program), or even the Norwegian Petroleum Directorate, 2013 for zero flaring among the oil and gas industry (Malins et al. 2014), are such examples. Another example of direct regulation includes the States of Wyoming and Colorado regulations' requiring the implementation of flareless completions. Operators of new wells in this region are

[65] Top-down methods take air samples from aircraft or tall towers to measure gas concentrations remote from sources. Bottom-up methods take measurements directly at facilities.

required to complete wells without flaring or venting. These completions have reduced flaring by 70% to 90% (EPA, 2011a).

In order to assess the full societal costs of a fuel switch it is necessary to assess the impacts of each fuel option on environmental and health external costs as well as the impacts on capital costs and operating costs. Finally, the environmental advantages and economic benefits from the adoption of the LNG must be communicated to investors and to the general public. Following this approach, LNG-powered ships represents the most likely alternative fuel to be seen as to replace oil-based fuels for ships and the best cost-effective choice for the society as a whole as demonstrated further along.

The adoption of LNG will be driven by fuel price developments, technology, regulation, increased availability of gas and the development of the appropriate infrastructure. Also, to LNG to become a competitive solution it is imperative to attract investor partners in the bunker market. Not putting aside the importance of a wide portfolio of solutions for the sector energy-mix above displayed, LNG presents undoubtedly the best prospects to be the bridge fuel of choice for short-term decarbonisation policy for shipping. As a result, the fuel switch to LNG, though not without costs and some technical hurdles, could effectively allow ships to sidestep the need for low-sulphur marine fuel and after-treatment.

The LNG industry is becoming increasingly global and is starting to link regional markets in Asia, Europe and North America. Yet, markets are still fragmented regionally and with differing price-setting mechanisms, a sensitive question. According to DNV GL (2018) the European and Japanese LNG spot market can be regarded as an indicator for the worldwide LNG prices, regardless of major local deviations. Apart from its price, a future fuel must be available to the market in sufficient quantity and technology needs to have been sufficiently tested. The question is what would happen if a fuel alternative were to become so attractive that a large number of operators would want to adopt it for their ships within a short period of time. In the case of LNG, a switchover of the entire global fleet would be possible right now since the current LNG production is higher than the shipping industry’s energy requirement, and the share of LNG in the total gas market is only 10% (DNV GL, 2018).

Environmental health and non-health externalities are those that relate to the emissions of air pollutants and greenhouse gases. These environmental externalities are not borne by transport operators or users, but by society as a whole. For air pollutants, these costs are damage costs that represent the impact that emissions have on human health, crops, materials, and on economic activity. The state of carbon lock-in to current carbon intensive economies, resulting from a process of technological and institutional co-evolution, driven by path-dependent increasing returns to scale produces adverse effects for the development of more sustainable technologies which have high unit costs, meaning that firms will be reluctant to invest. This situation should be changed by means of more stringent regulation on emissions from oil-based fuels accompanied by effective supervision measures in order to promote innovation and research applied to new low-carbon fuels and engine technologies.

The transition from a global economic model based mainly on oil is a huge challenge which cannot be realized overnight but will take large parts of the 21st century until clean renewable energy sources are available. Meanwhile, all countries will need safe, reliable and cleaner alternatives as a “bridge” to a decarbonised future, in order to hold the 2°C target without reducing the prospect of further economic development and social well-being. The main issue however is that change in technology, energy models, business practices, consumer behaviour and overall people’s daily lives activities are of the utmost importance if we want to reduce GHG emissions. In reality, people need to be aware of the basis for proposed policies. If not, we can risk that they are unlikely to adopt appropriate policies or generate political support for legislation to implement them, especially when policy implementation depends on widespread citizen understanding and behaviour change, as it will be seen in Part II of this thesis when people will face the possibility to pay to improve the air they breathe and to reduce climate change impact from shipping.

PART II: GIVING A PRICE TO A PRICELESS GOOD

9. ANTHROPOGENIC EMISSIONS AND GLOBAL RISKS

The consequences of carbon-based economic human activities are changing precipitation patterns and melting snow glaciers and ice caps, increasing ocean acidification, change on crop yields and causing harsh impacts in human health, to mention only some few. Climate change poses both direct threats to sustainable development because impacts negatively over human health, water, energy, land use and biodiversity and indirect threats by exacerbating other threats to social and natural systems. Anthropogenic emissions reached, in late-May 2018, 411.89 parts per million of CO_2 concentration in the atmosphere, at the Mauna Loa observatory, in Hawaii. These observations, together with other indicators (e.g. determined from ice core data, from direct atmospheric measurements and satellite altimetry) are strong indicators of a changing global climate. According to the IPCC (IPCC, 2013), each year human activities release a total of 8.9 Gigatones (Gt) of carbon into the atmosphere. New plant growth and air-sea exchange remove about 4.9 Gt/yr; the remaining 4.0 Gt stays into the atmosphere.

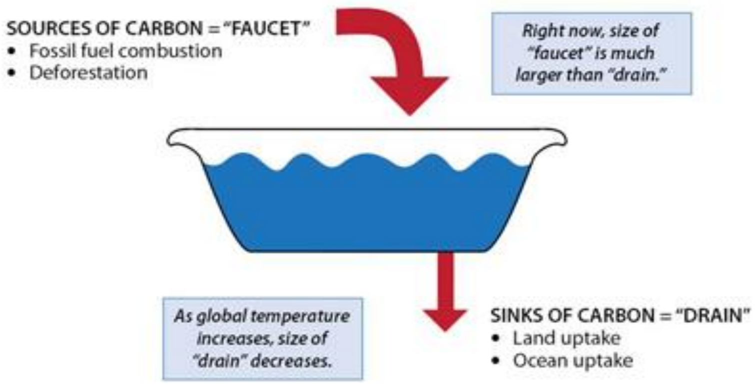
In Portugal, summer of 2016 saw the devastating effect forest fires can have over nature and properties. Temperatures above 40°C with the help of human intervention triggered through all country leaving a legacy of burned trees, ashes carried out hundreds of kilometers by the winds and naked soil exposed to erosion, floods and posterior groundwater contamination. By mid-August, two thirds of fires registered in Europe occurred in Portugal and the country has activated the EU Civil Protection Mechanism. Given the worrying trend of the summers of 2017 and 2018 with wildfires releasing tonnes of CO_2 contributing for cumulative emissions, the catastrophic environmental events are here to stay.

Forest wildfires accompanied with severe droughts lead to shortages in crops, higher prices and to food crisis which can feed popular discontent (The Center for Climate and Security, 2013). Climate change can indirectly increase risks of violent conflicts by amplifying well-documented drivers of these conflicts such as poverty and economic shocks (IPCC, 2014:16). This process means that if the amount of emissions continues to increase, a rise in the mean temperature can most probably change the composition, structure and function of marine, terrestrial and freshwater ecosystems, including wetlands. The worrying is that these effects have long timescales which will result in changes lasting hundreds to thousands of years even if global surface temperature is stabilized. Next Sections give a brief explanation about environmental threats the Humanity is facing.

9.1 Annual CO_2 emissions vs. cumulative CO_2 emissions

It is worth to explain the differences between annual and cumulative CO_2 emissions in an attempt to dissipate some existing confusion among public climate debate and to reinforce the notion that delaying action is dangerous and costly. Indeed, most of people believe climate change poses serious risks but also that reductions in GHG emissions sufficient to stabilize atmospheric concentrations can be deferred until there is greater evidence that climate change is harmful (Sterman, and Sweeney, 2007). Global temperature rise is driven by cumulative emissions of GHGs. To avoid catastrophic warming, it is required to stabilize CO_2 levels in the atmosphere, not annual emissions. Sterman and Sweeney (2007) report an interesting analogy between carbon dioxide levels, carbon sinks and cumulative emissions in what they have called "the bathtub analogy" (Figure 9.1).

Figure 9.1: The carbon bathtub and its components.



Source: U.S. Environmental Protection Agency.
Available from: https://19january2017snapshot.epa.gov/climate-change-science/causes-climate-change_.html. (Accessed December 20, 2016).

While CO_2 atmospheric concentrations – the total stock of CO_2 already in the air - might be assumed of as the water level in the bathtub and annual emissions, the yearly new flow into the air, is the rate of water flowing from the faucet. The bathtub has a drain, which is analogous to the carbon sinks as oceans, forests and soils. The water level won't drop until the flow through the faucet is less than the flow through the drain. Atmospheric CO_2 rises only when the inflow to the tub exceeds the outflow (net removal), is unchanging only when inflow equals outflow and falls only when outflow exceeds inflow. Looking at Figure 9.1 above one can distinguish that anthropogenic CO_2 emissions are already superior to net removal so, as terrestrial and oceanic carbon sinks fill, the cumulative emissions jump, or using the analogy, the level of water in the tub is rising, even if annual emissions are flat.

In ordinary daily tasks people have no need to infer how flows relate to stocks; it is better to simply wait and see how the state of the system changes, and then take corrective action. Yet, for complex systems like the climate these delays between actions and impacts are long, outcome feedback is ambiguous, many actions have irreversible consequences and the costs of error are potentially large (Sterman and Sweeney, 2007). Furthermore, if climate change enhances carbon release from boreal forests, tundra, the tropics, and other biomes, net removal is likely to fall. As the Earth warms, frozen methane in the Arctic permafrost escapes to the atmosphere increasing the amount of this gas in the atmosphere and making Earth's climate warm up even more. Melting permafrost will also cause more landslides and the degeneration of boreal forest ecosystems. With the continuing rise of global temperatures, melting of permafrost as well as the drying of the boreal micro-climates is likely release CO_2 and CH_4 to the atmosphere, turning current carbon sinks into sources of carbon, thereby creating a positive feedback to global warming: a circular causation phenomenon. A warmer climate will also increase the prevalence of forest pests conducting to tree defoliation. Mild winters allow egg stages of insects to survive until the following summer, thereby increasing their population (Lutz, White and Shugart, 2012).

9.2 Contribution of shipping emissions for climate change

The international maritime fleet, excluding fishing boats and military vessels, produced in 2012 (latest year with available data) around 796 million tonnes of carbon dioxide and 816 Mt of carbon dioxide equivalent (CO_2e) of greenhouse gases combining CO_2, methane and nitrous oxide (N_2O) corresponding to about 3.1% of global emissions (IMO-International Maritime Organization, 2015; Rahman and Karim, 2015) and is one of the fastest growing GHG emissions sector (Gilbert, Bows and Starkey, 2010; Bows-Larkin, 2014). CO_2 is the largest contributor to GHGs from the maritime sector. The reason why there is such a focus on CO_2 mitigation is mainly because CO_2 does not have a finite lifetime unlike other greenhouse gases. It accumulates; 25% of CO_2 emissions remain in atmosphere on 1000-year timescale (Meinshausen, 2013). Therefore CO_2 cumulative emissions mean so much as we have seen above in Section 9.1. Ship emissions are projected to increase between 102% and 193% from 2000 to 2050 levels (Bows-Larkin, 2014), growing at a rate higher than the average rate for all other sectors, with the exception of aviation. In Portugal and according to the World Resources Institute, CO_2 emissions from marine fuels grew by 24.5% between 2003 and 2012, in line with world growth (of 26.8%) over the same ten-year period (World Resources Institute, 2015).

In Portugal the transport sector accounts as the second source of GHGs with 24.7% in 2016[66] contribution for the overall emissions (the first is energy production and transformation which accounts for 25.7%) and although is allowed to emit 1% more GHGs into the atmosphere in 2020 than it did in 2005 (Decision n. 406/2009/EC) the National Program for Climate Change (PNAC 2020/2030) and the National Strategy for Adaptation to Climate Change (ENAAC 2020) both focuses on mitigation strategies for the nation remain on a low carbon trajectory. As such, reducing emissions from sectors where the possibility exists for deeper emission cuts to accommodate those from sectors where it is not possible, should be adopted as the linchpin of environmental strategy. Similar to worldwide fleets domestic shipping relies heavily on oil for propulsion and, being the Portuguese maritime fleet – due to the small number of units - a minor source of pollution and climate emissions, the contribution for the National Inventory is by no means insignificant, which presupposes that the costs of a doing nothing scenario are extremely high.

9.3 Air pollutants from shipping

Scientifically and broadly assumed facts: ship plume emissions have direct health and environmental harmful impacts (Mueller et al. 2011; Merk, 2014; Turner et al. 2017, etc.), the potential for air quality degradation in coastal areas (Mueller et al. 2011; Viana et al. 2014) and likewise on the inland (Corbett, Fischbeck and Pandis, 1999) including transboundary effects (Nore, 2011). Plus, for NO_x as a photochemical ozone precursor, it reduces life expectancy due to acute effects and yield loss for crops (Aksoyoglu et al. 2016; Tagaris, Stergiou and Sotiropoulou, 2017). As for SO_2 it causes physical structure

[66] Available at: https://rea.apambiente.pt/content/greenhouse-gas-emissions?language=en

degradation due to corrosive processes and contributes for the acidification and eutrophication of ecosystems, health costs, material damages, and costs for further damages for the biosphere, soil and water (Miola et al. 2008).

The impact from primary[67] and secondary pollutants resulting from the combustion of hard fuel oils has the potential of acidification, eutrophication, human health damage and photochemical ozone formation (Bengtsson, 2011)[68]. Acute and chronic PM exposure can induce to, respectively, short-term (e.g. cardiovascular diseases or asthma) and long-term health effects (e.g. lung cancer) in exposed populations (Corbett et al. 2007).

Ozone (O_3) formed through the reaction of precursor species; NO_x and volatile organic compounds (VOCs) reduce life expectancy due to acute effects and yield loss for crops and: " *may counteract the benefits derived from the anthropogenic emissions reduction strategies* [on land]" (Aksoyoglu et al. 2016; Tagaris, Stergiou and Sotiropoulou, 2017). High levels of toxic compounds of HFO's emissions produce more detrimental acute and chronic toxic effects than marine diesel. Yet, even though diesel-based fuels correspond to present and future Tier III Regulation issued by the IMO for maximum sulphur and strictest NO_x limits, air emissions from diesel fuels were recently classified as human carcinogens by the International Agency for Research on Cancer (Oeder et al. 2015).

9.3.1 Marine traffic emissions in Portugal

According to the European Environment Agency (2015): "[*In Portugal*] *the number of episodes of tropospheric ozone pollution and of fine particles pollution* [remains] *higher than the long-term target established*" urging for a deep understand about the nature and size of emissions and technical features of emitters, namely within the whole transport sector including domestic shipping. In this aspect, Portuguese domestic fleet (our study excludes riverine boats and cruise ships emissions) uses mostly high sulphur fuel content and there is a lack in detailed knowledge about the effects on climate and over exposed population at country level scale. Such effects in terms of public health and climate change

[67] Primary pollutants are pollutants present in the state that they were emitted, whilst secondary pollutants are not emitted as such, but formed in the atmosphere through chemical reactions between one or more pollutants. SO_2 is a primary pollutant because it is emitted as SO_2 from various combustion processes. Ozone is not a primary pollutant, because it is not emitted as such, but forms through the reaction of precursor species: NO_x and VOCs (Holland et al. 2005).

[68] The ozone layer protects life on Earth from the sun's harmful ultraviolet rays. But the ozone layer is 15 - 45 km above the Earth far above the air that we breathe. Closer to earth, ozone is an air pollutant that can be harmful hanging around in the layer of air near the ground where it affects everything it comes in contact with.

are not being monitored and the topic is regretfully absent from academic literature; likewise, the benefits arising from a switch to a less polluting marine fuel for crops and cultural heritage are not subjected to any broad evaluation at national level. As such, the contribution for the field of final energy consumption and mitigation measures herein on this Part II of the thesis can have a threefold use: first, it gives the rationale to evaluate overall costs of emissions by energy sector; second, by comparing benefits from mitigation strategies, it provides to public agents an important tool for responsible energy consumption policies; third, it contributes for people's awareness and knowledge about the whole range of damages related with the use of oil-based fuels in the transport sector. Despite Portuguese domestic emissions from shipping account for a small percentage of national emissions when compared with those produced by international navigation, given the fact that as a passage country Portuguese coast is exposed to emissions from international fleets and in this particular people are not aware as they should be about their exposure as they should be, scarcely aware of the contribution for climate change and completely unaware about the non-health damages from shipping emissions. These assumptions were underpinned from the in-person interviews.

Despite the humble size of the national merchant fleet the contribution of emissions released from ships in Portuguese waters to the national oxidised sulphur deposition ranks the fifth position in percentage right after Malta, Denmark, The Netherlands and Ireland (European Environment Agency, 2013). In 2014 and according to the Portuguese Environmental Agency Inventory Report (whose Portuguese initials are APA), the emissions from fuels burnt in vessels' engines accounts for (in kilotons): 33.6 of carbon dioxide (CO_2); 3.1 of nitrogen oxide (NO_x); 1.7 of sulphur oxide (SO_2) and 0.6 of particulate matter (PM). Those emissions contribute to the national inventory are, respectively: 0.4%; 1.9%; 4.9% and 0.6%. Due to perception and policy reasons this sector has been since long out of sight despite recent enacted International laws and regulation concerning ship pollution and strict limits of noxious substances burned on-board. In a time people awareness about the challenges climate change poses grows and official efforts to curb down air pollution levels are reason of greater concern, it is time for negative externalities from this sector be scrutinised. Externalities when expressed in monetary units are called external costs. For air pollutants, these costs are damage costs that represent the impact that emissions have on climate, human health, crops, materials, built infrastructure and on economic activity. In 2014, residual oil consumption from both national and international shipping amount to 624,400 tonnes of residual fuel oil and to 92,625 tonnes of distillate and if national consumption contribution for total in 1990 was about 18.7% of both fuels, it was only of 8.2% in year 2014 (APA, 2016), which demonstrates the growing importance of international shipping for the total amount of emissions along Portuguese coast, by one hand, and the ongoing diminishing number of national registered vessels, by another. Therefore, and even though the adoption of LNG as a marine fuel addresses only domestic navigation, the outcome should be possible to be replicated. *Ergo* and beforehand, the results should be proportional to the size of the fleets.

10. CONTINGENT VALUATION METHODOLOGY

Stated preference (SP) are methods used to value ecosystem services as is the case in the situation under analysis. Estimation of non-market commodities requires the use of hypothetical markets where a public good or service is transacted.

Contingent valuation (CV) are SP methods which focus on the valuation of a non-market good and is one of two SP categories being the other *choice modelling methods* which focus on valuing specific attributes of a non-market good. For the following, the term “contingent” refers to the estimated values people are willing-to-pay (WTP) to obtain a given positive outcome (in this case environmental, health and non-health benefits) using the data collected being contingent on the features of the scenario (Carson and Louviere, 2010). CV method involves directly asking people, in a survey, how much they would be willing-to-pay (WTP) for a specific environmental use-value service revealing the monetary trade-off each person would make (Cameron et al. 2011; Carson, 2012). CV assumes that people understand the service in question (even if for some people it could be unfamiliar to attach money values to something taken for granted) and will reveal their preferences in the contingent market just as they would in a real market. In this particular, care was taken to avoid potential biased or non-responses including detailed information and a comprehensive preamble in the pre-test evaluation and in the web-based questionnaire, respectively. To what concerns the good to be evaluated - the atmospheric air, a non-tradable use-value asset - and to the best of our knowledge, this is the first time this topic is subjected to people's elicitation.

10.1 Contingent Valuation technique: the theoretical foundation

CV applications for policy purposes have been largely used, for example by the U.S. Environmental Protection Agency (EPA) for quality studies to provide a functional relationship between maximum willingness-to-pay (WTP) and changes in water quality. It is worth to say that the practice of putting a price tag on environmental natural resources is not without its limitations and criticism. Related to accuracy, valuing the worth of non-marketed goods can be an imprecise exercise. Secondly, one can argue about the fact of monetising natural assets should not be judged on the same scale as the consumption and production of goods. On the other hand, the CV has two advantages over other indirect methods which exploit data on observed, actual, behaviour. First, it can deal with both use and non-use values, whereas the indirect methods cover only the former, and involves weak complementarity assumptions. Second, in principle, and unlike the indirect methods, CV answers to WTP questions go directly to the theoretically correct monetary measures of utility changes. According to Carson and Louviere (2010):

> "[…] while there may be a "best" mode of survey administration, elicitation method or statistical estimator for a particular application, there is unlikely to be a "best" approach for all applications. That is, it may well be that different methods can yield useful information for making decisions about particular issues. What matters is to communicate what was done in a study such that it is broadly understandable."
>
> Carson and Louviere (2010:556)

Furthermore and in accordance with what was stated by Perman et al. (2003:420), "*If we can elicit the correct answer to an appropriate WTP question from an individual, the answer is the correct monetary measure sought for that individual*". Therefore, and since the objective is to estimate values for a one-dimensional attribute, the online questionnaire design was intended for interviewees to respond to simple direct questions for economic empirical valuation purposes on a non-tradable asset: the atmospheric air, more precisely, a change in an environmental resource or, using other words, the object of choice[69].
According to Carson and Louviere (2010), CV conveys three main elements:

[69] The object of choice is the thing for which an economic value is desired. Objects of choice can be public goods like local police protection, ambient air and water quality, or species and habitat protection. They can be any tangible or intangible object, process or activity that can be described in a way that allows a choice to be fashioned (Carson et al. 1996).

i) information related to preferences is obtained using an SP survey;

ii) the study's purpose is placing an economic value on one or more goods, and

iii) the good(s) being valued are public ones (pure public or quasi-public).

The empirical portion of the questionnaire addresses a closed-ended dichotomous choice format asking people direct questions. The difficulty with direct questions is that few people think about their WTP for a good, whether a marketed or non-marketed one, which often leads to high non-response rates (Carson and Louviere, 2010). However, two main arguments were proposed for the use of dichotomous choice: simplicity for respondents and; reduced incentives for strategic responses (Bateman et al. 2001). Nevertheless, care was taken to avoid potential non-responses: a comprehensive preamble to the online questionnaire and the introduction of a third possible choice, which therefore can be viewed as a triple-bounded dichotomous choice, a variant of the former.

10.2 The utility theoretic model of consumer preference

To measure an individual's monetary value for some item we denote the item being valued by *q*. The utility theoretic model of consumer preference provides the framework for interpreting the CV responses. In the following and in accordance with Carson and Hanemann (2005) it is assumed that the individual has a utility function defined over the quantities of various market commodities, denoted by the vector *x*, and *q*, $\boldsymbol{u}$ (*x*, *q*). Corresponding to this direct utility function, we can write an indirect utility function, $\boldsymbol{v}$ (*p*, *q*, *y*), where *p* is the vector of the prices of the market commodities and *y* is the person's income. If the agent regards *q* as a "good," $\boldsymbol{u}$ (*x*, *q*) and $\boldsymbol{v}$ (*p*, *q*, *y*) will both be increasing in *q*. The act of valuation implies a contrast between two situations – a situation with the good provided (improved in our particular case), and one without it (business as usual). What is being valued is a change in *q*. Suppose that *q* changes from q^0 to q^1 the person's utility changes from $\boldsymbol{u}^0 \equiv \boldsymbol{v}(p, q^0, y)$ to $u^1 \equiv \boldsymbol{v}(p, q^1, y)$. If the respondent regards this change as an improvement, $\boldsymbol{u}^1 > \boldsymbol{u}^0$ and the value of the change to him in monetary terms is represented by a Hicksian measure, the compensating variation *C* (a mean) which satisfies:

$$v(p, q^1, y - C) = v(p, q^0, y) \tag{10.1}$$

$C > 0$ denoting C the compensation variation measuring the individuals' maximum WTP for the change, in our particular case the maximum WTP to initiate the policy.

10.2.1 Willingness-to-pay and survey responses

The utility theoretic model of consumer preference outlined above provides the framework for interpreting the CV responses and the way one links the responses to the measurement of WTP can be derived from the survey responses. This subsection follows the methodology from Carson and Hanemann (2005) which is strongly recommended for further details about statistical modelling and analysis. In a closed-ended question format like the one developed for this thesis, the respondent is asked to answer: "*Would you support the change from q^0 to q^1 (from a worst to a better air quality) if it would cost you A€*?" In the case the response is *yes*, this means that for this individual, his/her value of C it's worth more than *A€*. As for obtaining a '*yes'* response the probability is given by:
Pr (probability of a 'yes' response to a closed-ended question)

$$= PR\,(C \geq A) \equiv 1 - G_c\,(\,A\,) \tag{10.2}$$

The closed-ended format does not reveal the exact value of C but it does provide an interval in which C must lie. A WTP distribution introduces an additive random error term directly in the utility function appealing to the notion which contains some random components that are unobservable to the econometric investigator like characteristics of the individual and/or attributes of the items considered for. This stochastic component of preferences is denoted by ε, and the indirect utility function is rewritten as $\boldsymbol{v}$ $(p,\ q,\ y;\ \varepsilon)$, substituting (10.1) yields:

$$C(q^0, q^1, p, y; \varepsilon) \tag{10.3}$$

Therefore: Pr {probability of a 'yes' response to a closed-ended question}

$$= PR\left\{v(q^1, p, y) - A; \varepsilon \geq v(q^0, p, y; \varepsilon)\ \right\} \tag{10.4}$$

10.3 Eliciting Willingness-to-pay

Pricing public goods might be estimated through an appropriately structured survey in which the interviewer presents the good to a sample of members of a hypothetical market to elicit how much they would be willing-to-pay in order to avoid something undesired. To establish the marginal external costs of air pollution on climate, human health, crops and infrastructure it resorts to the use of “monetary value” (in Euros), designed to capture personal preferences for a particular pre-existing level or, in this particular, to avoid climate change, a lower health status, changes in life expectancy and risk of premature death (as well as to prevent structural damages). This was estimated by stated preferences approach a method that, as already explained, allows the collection of data about respondents’ preferences for environmental goods by observing choices in hypothetical situations presented in a survey (Carson and Czajkowski, 2012). For the sake of this purpose, data was collected using a convenience sampling to whom a link for an online survey was sent.

The questionnaire framework includes a *description* of how the commodity is going to be valued (in this case, a reduction of GHGs, NO_x as ozone precursor and PM and SO_2 as primary and secondary inhalable particles generator, respectively) to improve the atmospheric air, a non-marketed good which have the characteristics of non-excludability and non-divisibility. The *mechanism* by which the good will be improved is by the adoption of LNG as a marine fuel opposed to those traditionally burned by vessel’s engines even considering the possibility to put in place mitigation measures. The chosen *payment* vehicle was a three year energy/environmental tax or equivalent fiscal measure in accordance with payback periods between 2-4 years (including fuel, capital and operating costs) to implement a switch from HFO to LNG as suggested by Kollamthodi et al. (2016). The online questionnaire to elicit the average WTP was available between July and October 2016. Data analysis of the survey results was conducted using Gretl® software.

10.4 The pre-test/pilot study

Before the final survey was drawn up a pre-test/pilot study was administered under field conditions, i.e. by means of in-person interviews to help to identify questions that make less sense to participants, or problems with the questionnaire that might lead to biased answers. The pre-test/pilot was also used to:

i) provide adequate power to test the hypotheses of interest; and,
ii) to delimitate the upper and lower bound people are willing-to-pay for the improvement in the good.

Some key issues were addressed during this phase. First, enough information was provided to respondents to help them make an informed decision but without overwhelming them with information. Also, the formulation of the scenario in which the good is to be improved was set. A second issue concerns to the payment vehicle; the way, how much and whether it is a one-time *lump sum,* or a recurrent payment people will pay for the good. Another underpinned preoccupation was to respondents feel comfortable with making either a “favour” or “oppose” decision. In-person interviews were made containing ancillary visual aids (paper slides) depicting the harmful effects of marine traditional fuels over people’s health and the environment emphasising its expected increase in the decades ahead (Annex 1). Extreme care was taken for persons realise implicitly the high-level risk for people’s health if the atmospheric air is not improved. The inherent problem here was to make people perceive they are not dealing with a low-level risk as suggested by Carson, Flores and Meade (2000), also because some of them, at least, could have the motivation to consider it as a “bequest value” and might want to preserve it for their children and grandchildren[70]. As such, the risk problem was due communicated during the survey.
Respondents will face the hypothetical situation to pay a one-time amount once a year for air quality improvement in that given period of time albeit results will last for a much longer period. Notwithstanding the question asking exposed population has to pay a tax for an universal good seems to be not righteous, eventually, if national/European funds are allocate to the adoption of LNG as a marine fuel, the nature of those funds come in fact from taxpayers. By the other hand, if ship-owners must support the retrofitting and/or new orders costs by themselves, due to a more stringent regulation, for example, amortization costs will assume the form of higher freight rates and ultimately it will be reflected in the final price goods will exhibit in the supermarket shelves[71]. Hence the money value attached

[70] A “bequest value” concept means that some people’s concern to future generations’ would like to pay for. Even if they see it as something they cannot control they care about and thus, it enters their utility function.
[71] In this aspect see for example the article “Maersk asks customers to pay for $2 billion low sulphur fuel bill through new Bunker Adjustment Factor”.

to the good be seen as a cost for the CBA elaboration purposes. If this is what actually happens in the real world, thus is consistent with standard neoclassical economic theory.

In-person interviews were performed around the Great Lisbon area, thus including part of the Centre and in the Setúbal area, at North (Porto-Braga areas) and South (Faro-Portimão-Lagos areas), not limited to shore near areas, and after interviewers have been trained about the face-to-face method. To what matters about the location in this stage and different from what was later decided with the online survey, a sensitive question was to know at what distance from the ocean respondents live to evaluate environmental awareness as a function from distance from shore (i.e. interior versus littoral) if there is some. Special attention was given to provide interviewers with an insight about the delicacy of the subject of asking people if they are "*willing to pay*" for an asset people assume as universal and free of charge provided, and that challenges can be magnified when gathering such kind of information among some portions of the population (i.e. the elderly and less educated strata, for instance but not restricted to). This action was performed between the second half of April and mid May 2016 and the responses to a normalised paper questionnaire were filled out by the interviewees themselves in the presence of the interviewer. Target population was set as an equally distributed sample of men and women aged 18-69 living or not in the specific areas where they were interviewed, and participants were randomly assigned once they fulfil those previous conditions and people were approached in public places (cafeterias, traditional markets, shopping malls and others alike).

Of course, in-person interview surveys are more time-consuming and considerably expensive especially when there is a need to travel and meet the respondents at different locations. In face of such constraints a considerable part of the territory was obviously left out. Further studies should be carrying on in the future to partially eliminating this gap. However, knowing that about 70% of the Portuguese population is located in the so-called littoral stripe - about 500 km long and 50 km wide belt - such asymmetric distribution is not as deep as one initially might think. Post-interview follow up assessments to verify to what extent respondents understood the questions were not conducted *per se*; instead during the interviews, to ensure that the core questions were broadly understandable and perceived as consequential; people were asked about their perception about what was at stake, their doubts or less clear questions[72]. This procedure has had also the intent to avoid potential protest bids that could therefore bias willingness-to-pay results. From the pre-test/piloting survey analysis some conclusions were made (Table 10.1).

Table 10.1: Pre-test: demographic characteristics.

Demographic Characteristics (pre-pilot)				
Division		Frequency (N=68)*	Percentage (100%)	Mean (€uro)
Gender	Male**	32	47,1%	9,0
	Female***	36	52,9%	8,5
Age	18-34	10	14,7%	7,5
	35-54	41	60,3%	9,4
	55-69	17	25,0%	6,4
Academic Background	Basic education (up to 9th degree)	15	22,1%	4,6
	Secondary (9 to 12th degree)	25	36,8%	7,5
	University	28	41,2%	11,3
Gross monthly Income (euro)	500-1000	29	42,6%	6,4
	1000-2000	35	51,5%	10,2
	>2000	4	5,9%	9,5
Geographical location (km from ocean)	0-30km	55	80,9%	8,2
	30-60km	8	11,8%	10,1
	>60km	5	7,4%	5,5

* Not including three "no" responses
** Not including one "no" response
*** Not including two "no" responses
Note: We follow the Portuguese educational system
(https://en.wikipedia.org/wiki/Education_in_Portugal#Secondary_education)

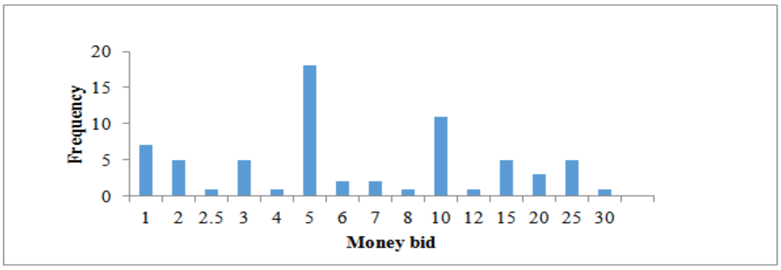
Each interview could easily be longer than 30 minutes. At the end of the pre-test a simple direct question was asked: if the respondent is willing-to-pay and, in the case he/she respond “yes”, how much is the amount that best represent his/her WTP (Annex 2). Then, the upper and lower bounds delimitated by the first and the third quartiles (the interquartile range) were used to obtain the initial and second elicitation amounts for the questionnaire questions since the true value people are willing-to-pay for lies somewhere between the two. Roughly around 200 individuals have been invited to respond to the pre-test survey.

[72] Yes/No responses should be followed up by the open-ended question “*Why did you have chosen Yes/No?*” as Arrow et al. (1993) suggest as part of the Guidelines for value elicitation surveys. These type of follow-ups focus on giving respondents the opportunity to change their responses from Yes to No and vice-versa which, for what matters, was proposed before the interview ended (as well as the bid amount).

From those, a total of 71 acceded (35M; 36F). Three (3) of the interviewees have decided to respond "no" to any amount at all. Here, the assumption wasn't that those do prefer to breathe a bad air or not prevent climate change; rather they are not willing-to-pay for the improvement. Age does not seem to have a negative effect from what we have gathered from this in-person survey. Conversely, the respondents' level of academic qualifications, geographical location and higher income appear as the major contributors for high WTP, presenting a positive effect, even though in the two latter cases, the respondent's number within the higher income class (> €2,000) and farther away from the coastline (> 60km), were minimal. In this study a completely nonparametric approach was adopted, letting the data speak for itself without imposing any assumptions about the nature of the data generating process. Although the price people would be willing-to-pay ranks from one to a maximum of 30 Euro, no extremely high responses (outliers) were registered. Descriptive statistics from the pre-pilot test are summarized in Table 10.2.

Table 10.2: Descriptive statistics for willingness-to-pay for a better air quality (pre-pilot).

Descriptive statistics for willingness to pay for a better air quality (pre-pilot)	
N (number of observations)	68
Mean	8.45
Std. Deviation	7.25
Variance	52.52
Maximum	30
Minimum	1
Upper quartile	10
Median	5
Lower quartile	3



As it was expected, the main problematic issue to transpose was the initial unease people demonstrate when asked about their WTP a given exact amount. For that large majority who were willing to pay, defining an exact amount became a defying exercise with their inner conscience. It was not provided any kind of help from the interviewers in the sense to avoid any interferences in delimiting the values even when some of them request a "reference" value to be provided. From the 68 valid responses, lower and upper quartiles have been set, for both lower and upper money bounds, respectively, as it follows: lower: €3; upper: €10, which will consist in the questionnaire's first and second questions. The third question, the minimum amount, was set as €1 (one) single Euro. Next Section provides the rationale in which our questionnaire is based upon and gives people the full insight of what is at stake.

10.5 The questionnaire's framework

Once the problem was due identified, the survey asks people to elicit WTP to avoid climate change consequences, a lower health status, changes in life expectancy and risk of premature death by means of improving the atmospheric air, a non-marketed good, through the adoption of LNG as a marine fuel, as opposed to those traditionally burned by vessel's engines. The main features in the construction of the web survey include: i) a preamble section which helps set the general context for the decision to be made: noxious emissions derived from traditional marine fuels in comparison with less harmful emissions from LNG and the consequences of a doing nothing scenario; ii) a description of the good to be improved; iii) the manner in which the good will be paid for; and, iv) the collection of a set of respondent characteristics (personal data and demographic information).

In this research it was assumed that people truthfully answered the questions that were asked about, implicitly supposing that the core questions were broadly understandable albeit Carson and Groves (2011) argue that in general, this assumption is likely to be false if the survey question is consequential and the respondent is acting like a rational economic agent[73]. The key question is how to interpret such information and the nature of the deviations from truthful preference revelation that were likely to be observed in particular instances (Carson and Groves, 2011). In this aspect, the answer to the key question is, based on the simple perception of the situation and facts, that people prefer undoubtedly to breathe a better air increasing the likelihood for the agent to accept to pay to obtain the good, as defined by Carson, Flores and Meade (2000).

As mentioned before, the web questionnaire was bounded by a lower and upper value people had been willing-to-pay rather than confined to a single presumably exact value.

[73] Carson and Groves (2011) divide questions into two types: consequential and inconsequential. For a question to be consequential, survey respondents need to believe, at least probabilistically, that their responses to the survey may influence some decision they care about.

Usually, in a *double-bounded* questionnaire the lower and upper bound questions asked respondents who said yes to the initial amount whether they would pay the second higher amount or not, since the true value is assumed to lie somewhere in-between. The response reduces the length of the interval in which the respondent's WTP lay and decreases the confidence interval introducing a second choice set without changing any attribute of the good other than cost (Carson and Czajkowski, 2012). However, the chosen format was an extension of double-bounded choice: for those who would not willing-to-pay for the lower bound, a third question was asked: would they be willing-to-pay for a *lower* bid amount used in the first question? In this case, the minimum value was considered to be one single Euro. This "triple bound" format was considered by Bateman et al. (2001). In this case, with three valuation questions, the response probability model would be given by four possible response outcomes: (no, no); (no, yes); (yes, no) and (yes, yes). The Euro amount in the initial valuation question is denoted by A. If the response to that question would be no, it is followed up using a lower amount A_L, if yes (to A), this would be followed by a second valuation question using a higher amount A_U.

Accordingly, the general formula for the various response probabilities is:

Pr (Response is no/no) = Pr $(A_L \geq C) \equiv G_C\,(A_L)$,

Pr (Response is no/yes) = Pr $(A \geq C \geq A_L) \equiv G_C\,(A) - G_C\,(A_L)$,

Pr (Response is yes/no) = Pr $(A_U \geq C \geq A) \equiv G_C\,(A_U) - G_C\,(A)$,

Pr (Response is yes/yes) = Pr $(C \geq A_U) \equiv 1 - G_C\,(A_U)$.

C denotes the compensation variation measuring the individuals' maximum WTP for the change and G_C is the WTP cumulative distribution function for a given individual, specifying the probability that the individual's WTP is less than the given amount.

The population was set to be those aged between 18-69 years, some 7,016,000 which represents around 82% of the Portuguese population aged 18-85 living in Portugal, including the Atlantic archipelagos of Azores and Madeira, roughly divided into three large rectangles: North, Centre and South[74]. The Azores and Madeira archipelagos were considered as to belong to South division. An "other" location was also included to allow

[74] In accordance to the legal voting age in Portugal and the age when digital divide grows substantially. Only 11.8% of the Portuguese population aged 65 and over are Internet users (Rebelo, 2016).

those who are living abroad the possibility to respond (Figure 10.1). The questionnaire, available between July and October 2016 has received a total of 261 responses.

Figure 10.1: Geographic division of the territory for population location purposes.

Following this method, the respondents' city of residence question also foresees the proximity to some major coastal Portuguese cities distributed from north to south of the country, including its hinterland. North: between Viana do Castelo and Coimbra (including major cities as Braga and Oporto), Centre: between Coimbra and Lisbon, a densely populated region, and South: between Lisbon and Faro (excluding the former), comprehending all the regions from the left bank of the Tagus river unto the southern littoral.

Given the size of the population and inherent physical constraints to set an appropriate random sample, the chosen sample was not a probability-based sampling but instead a quota sampling or, by other words, a non-probability sampling technique. With quota sample, better say, a proportional quota sampling**,** the aim is to end up with a sample where the strata being studied are proportional to the population. This procedure allows conveniently for time and resources savings. By the time daily response rates become lowering the sample collected have reached 248 valid responses. The number of responses was then divided into male and female constituents to verify if sex ratio among the sample was representative of the same ratio for the population (M-48%; F-52%) according to national statistics. Since this was not achieved, and male contributors were over represented, the following procedure was to collect female-only responses until the ratio was achieved. According to Griskevicius et al. (2012) this ratio is an important parameter because: "*sex ratio [also] has pervasive effects in humans, such as by influencing economic decisions*"[75]. This does not mean the other ratios (age, income, occupation and geographical location) does not. It was simply a choice that was to be made in accordance with obvious time-consuming restrictions. In face of this dilemma, it was necessary to continue with the collection until the true ratio was matched or nearly equalled. As such, the sample format is likely to be similar to a proportional quota sampling method, a non-probabilistic version of stratified sampling. Nevertheless, after data have been processed, some other socio-economic ratios do somewhat fit in proximity with those from real world (see Annex 3). This method of achieving equal sex ratio representation led to a final sample of 261 collected responses.

Indeed, due to the "opportunistic" character of the sample this sample may not be representative of the population. Yet, in spite of its scientific fragility, this type of sampling can be used successfully in situations where grasping general ideas and identifying critical aspects may be more important than scientific objectivity as it was written by Couper:

> "Any critique of a particular Web survey approach must be done in the context of its intended purpose and the claims it makes. Glorifying or condemning an entire

[75] According to the cited study "(…) *sex ratio influences saving, borrowing, and spending. Findings show that male-biased sex ratios (an abundance of men) lead men to discount the future and desire immediate reward*". Portuguese sex ratio is the quotient of males versus females in the Portuguese population as from the INE/PORDATA database as of December 31st 2015.

> approach to survey data collection should not be done on the basis of a single implementation, nor should all Web surveys be treated as equal".
>
> (Couper, 2000:465-466)

Similarly to the pre-test major preoccupation of the online questionnaire was to ensure that the core questions were broadly understandable and perceived as consequential. Finally, and to ensure respondents provide thoughtful responses to the questions, was explicit written in the questionnaires' preamble that the information they provide will remain anonymously and for this thesis sole purpose.

10.6 Foreword of the questionnaire

The survey was posted at Survey Monkey and Survio, two online survey platforms, one in English, in the former case, and in Portuguese language in the latter. The English translated preamble text, which gives the rationale and the aiming for the survey, is at it follows:

"*Emissions from traditional shipping fuels are an invisible killer that cause lung cancer, heart disease, atmospheric ozone, damage heritage, crops and ecosystems, and contribute to the greenhouse effect. The costs of harmful effects associated with these energy options are borne by society as a whole and tend to be exacerbated in the near future. For example, if another type of less polluting fuel is adopted about 60,000 premature deaths per year in Europe can be avoided. The viability of Liquefied Natural Gas (LNG) as an alternative fuel for maritime transport is the case under study; a gas that eliminates practically 100% of sulphur dioxide (SO_2) and microparticles and nitrogen oxide (NO_x) by about 90%. LNG is assumed to be a bridge fuel applied to the maritime industry because there is* ***NO*** *global available fuel at short-term for this industry to replace traditional fuels while fulfilling three fundamental assumptions: being abundant, cheap and whose technology is proven. A transition fuel because, although it contributes to a 25% reduction in carbon dioxide (CO_2) emissions, it is a fossil fuel. However, with the introduction of LNG there is a non-negligible reduction of Greenhouse Gas emissions and an extreme improvement in the air we breathe - a public and universal good - to which is possible to ascribe an "economic value". However, as such a market does not exist it is through this questionnaire that an approximate value can be determined. This research follows a contingent valuation approach; a technique based on the idea of a hypothetical market* *where a public good is traded. The good to be valued by members of the hypothetical market (the atmospheric air) conveys the approximate value of their willingness-to-pay for the good. The value of the statistical mean will then be used as a metric in the development of a Social Cost-Benefit Analysis for the purpose of analysing the economic feasibility of adopting LNG at the national level. Note that "willingness-to-pay" does not mean that a hypothetically adopted policy should be paid by the taxpayers. It is simply intended to attribute a price to an asset for which there is no market. All contributions will remain anonymous*".

10.7 Analysis and discussion of the survey results

A total of 261 responses have been collected. This represents an acceptable number if one takes into account the difficulty to reach people and make them respond to this type of inquiries even when the subject is perceived as of broad interest for people throughout the Nation and affecting global commons. Although the sample size does not change much for populations larger than 20,000 in this case, (using a confidence level of 95%), the number of respondents points to a margin of error of 6%. Sent emails were initially those provided from authors', adviser and co-advisers' private, professional and academic contact lists. After, a particular strategy have been adopted where existing study subjects recruit future subjects from among their acquaintances resending the survey link to their contacts lists or by announcing it on social media: a sort of emulating "*snowball*" sampling. It is thought that around 700/800 emails were sent at total. From the collected 261 responses, 19 (9M; 10F) assume their willingness not to pay any amount at all representing 7.3% of the respondents. That is, there are respondents who would not be willing-to-pay anything. Those responses can be interpreted as protests bids because protesters may state a zero value for a good that they actually value or because they think that is unethical to place a monetary value on public goods (e.g. for example Halstead, Luloff, and Stevens (1992)). On the other hand they can be seen as real "zeros" meaning that even when those respondents agree in improving the level of the good they do not feel responsible for the origin of the externalities and/or they think that they already pay too many taxes and also believe the solution of the problem should solved at governmental/institutional level. For what follows we have assumed zero values as legitimate values since the respondent have agreed to participate in the survey and also in accordance with Freeman, Herriges, and

Kling (2014). Anyway, the nature of the online survey do not allow for the follow up regarding the individual's motive for his/her response, for instance, to ask the respondent about i) if he/she can't afford to pay for the good; ii) the good is not important; iii) if he/she don't think that should have to pay for the good; or, iv) if he/she consider the improvement proposed as unrealistic (Freeman, Herriges, Kling, 2014:388).

The mean WTP was calculated in €6.8 after been rounded up to the nearest decimal. Female respondents in the number of 136 are those who are willing-to-pay the most in average: €7.2 against €6.5 average from their 125 male counterparts. Differently from what happened in the pre-study (M: €9,00; F: €8,50) women present a higher tendency to value more the asset in question, in average, with more than 66.2% bidding €10, while 56.8% of the men does it. The distribution based on age shows 23.8%, 43.3% and 33% of the respondents are situated in the 18-34, 35-54 and 55-69 years age groups, respectively. In CV theory and in the case of use values age has a negative effect, differently from obtained results: the 35-54 and 55-69 groups components are those who are willing to pay more (€6.7 and €6.4 respectively). However, the difference between those and the younger group (€5.4) may be due to the fact that, as "opened" rank groups, it may, and it will, include considerably wealthy strata individuals within. In this case, the probability that WTP could fall with age is not a priori discarded (see, e.g. Bleichrodt, Crainich and Eeckhoudt, 2002; Itaoka et al, 2005).

As for the academic background, 38.7% of the respondents have, at least, a complete graduate level education. To what matters about the average willingness-to-pay based on academic background, linearity was not found since those who hold an MSc or a PhD are willing-to-pay "only" €6.6 in contrast with those belonging to the graduate level (€7). The complete secondary and incomplete secondary group's mean is €6.1 and €3.3, respectively, in accordance with results from related studies on environmental improvements (e.g. Belhaj, 2003; Wang and Zhang, 2009; Wang et al. 2015).

The distribution based on the occupation shows that 67.4% of the respondents are employed and from the statistical analysis they are also those who want to pay more for a better air quality: €6.8. Students, i.e. those who are, in theory at least, younger, more educated towards environmental challenges and more prone to react in conformity, are willing-to-pay only €4.9, which in fact is in accordance with their expenditure capacity, disposable income or lack of it. Indeed, higher income levels display higher mean WTP:

the amount increases as wealth's increases too and, in accordance with other similar surveys (e.g. Wang and Whittington, 2000; Wang and Zhang, 2009; Baumgärtner et al. 2011; Wang et al. 2015), this was expected to happen even tough income is different from wealth for it captures monetary influx but not existing cash reserves or fixed expenditures. Hence, the >2,000 income strata average is €7 followed by the 1,000-2,000 (€6.8) and by those earning 500-1,000 (€3.8). 37 of the respondents have opted not to answer the income question and if this number would be accounted for it could have produced distinct outcomes.

According to the health status, those 45 who admitted suffer from air-related diseases show a lower propensity to pay: €5.6 whereas those who declared not to suffer would pay €6.4. This apparently surprising result is nonetheless in accordance with the results from surveys pertaining to air pollution-related respiratory disease and WTP (e.g. Wang and Zhang, 2009:5). In reality, being those who address to respiratory problems the exception, very few studies reporting that people with respiratory symptoms are more willing-to-pay for air quality improvement than those who had no symptoms do exist.

From the fifteen respondents located abroad (for this study purposes those who are living in the islands of Madeira (2) and Azores (2) were considered as from located in the South region) the distribution is as it follows: Brazil: 3; France: 2; Germany: 3; Luxemburg: 1; Netherlands: 1; Switzerland: 2; UK: 2; and U.S.: 1. Geographic proximity usually has a positive effect even though this issue is not such relevant for the study since the capacity of pollutants to spread within long distances from the point they occur was due stressed, and, by another hand, people who live near or nearby the littoral are not necessarily aware of the problem: maritime pollution is almost produced at high seas and not near the coast, nor the intensity of traffic at Portuguese ports imparts such impression. Nevertheless respondent's location displays an interesting outcome: those who live abroad are willing-to-pay more (€8.6) than those living at North (€4.9), in the Centre of the country (€6.5) and South (€7.0).

Table 10.3: Weighted distribution according to the independent variables.

		No amount		€ 1,00		€ 3,00		€ 10,00			
		n	%	*n*	%	*n*	%	*n*	%	Σ	Mean (€)
Gender	Male	9	7,2%	19	15,2%	26	20,8%	71	56,8%	125	6,5
	Female	10	7,4%	15	11,0%	21	15,4%	90	66,2%	136	7,2
									Sample (n) =	**261**	**6,839**
Age	18-34	3	4,8%	15	24,2%	17	27,4%	27	43,5%	62	5,4
	35-54	12	10,6%	4	3,5%	31	27,4%	66	58,4%	113	6,7
	55-69	4	4,7%	10	11,6%	26	30,2%	46	53,5%	86	6,4
Education	Incomplet.	5	9,4%	23	43,4%	14	26,4%	11	20,8%	53	3,3
	Compl.	3	5,0%	11	18,3%	15	25,0%	31	51,7%	60	6,1
	Grad.	6	5,9%	4	4,0%	30	29,7%	61	60,4%	101	7,0
	MSc/PhD	5	10,6%	3	6,4%	12	25,5%	27	57,4%	47	6,6
Occupation	Student	3	8,8%	8	23,5%	10	29,4%	13	38,2%	34	4,9
	Unempl.	2	9,5%	8	38,1%	6	28,6%	5	23,8%	21	3,6
	Employed	12	6,8%	15	8,5%	43	24,4%	106	60,2%	176	6,8
	Retired	2	6,7%	5	16,7%	13	43,3%	10	33,3%	30	4,8
Income*	500-1000	3	7,1%	23	54,8%	28	66,7%	16	38,1%	70	3,8
	1000-2000	7	8,6%	5	6,2%	24	29,6%	52	64,2%	88	6,8
	>2000	2	3,3%	3	5,0%	22	36,7%	39	65,0%	66	7,0
Location	North	5	14,7%	11	32,4%	28	82,4%	23	67,6%	67	4,9
	Center	8	9,1%	9	10,2%	28	31,8%	58	65,9%	103	6,5
	South	6	7,6%	7	8,9%	15	19,0%	48	60,8%	76	7,0
	Other	0	0,0%	0	0,0%	3	15,8%	12	63,2%	15	8,6
Health	Yes	4	11,1%	8	22,2%	12	33,3%	21	58,3%	45	5,6
	No	17	9,2%	23	12,5%	58	31,5%	118	64,1%	216	6,4

* 37 of the respondents (14%) didn't answered this question.

To what concerns to a potential value transfer application from this study to other locations or countries one should note that, as some authors claim, (e.g. Barbier, Czajkowski and Hanley, 2015), the WTP for environmental improvement variation with respect to income are often based on the assumption that the income elasticity of these WTP values must be constant. If this elasticity varies significantly with income levels, then assuming a constant elasticity will lead to significant errors in the WTP estimates based on these value transfers. As so, the best way to proceed is by estimating local/national income elasticities of the WTP for the improvement to ensure that the correct functional form of the WTP-income elasticity relationship is estimated.

10.7.1 Theoretical construct validity and predictive power

Theoretical construct validity is assessed by considering the relationship between the CV result and other variables that theory suggests are related to it in some particular way. It often refers to how well the measurement is predicted by factors that one would expect to be predictive a priori, providing an equation that relates some indicators of the respondent's WTP to the respondent's characteristics and to characteristics of the good. For the air we all breathe, environmental attitudes that come specifically from the sample should have a significant impact in respondents' willingness-to-pay. Of course, even if it has predictive power, this does not necessarily mean it will have ex ante predictive power (Pearson et al. 2003). Indeed, questionnaires' construct validity was demonstrated by the agreement level with other measures as predicted by theory. For example, income has a positive effect on WTP; the upper monthly gross revenue range presents a higher WTP compared with the previous ranges. Conversely, in CV theory and in the case of use values, age has a negative effect, differently from our results: in fact, people aged 36-54 and 55-69 evidence a superior WTP in contrast with younger people. Geographic proximity usually has a positive effect but in the present study this issue is not such relevant. Nevertheless respondent's location displays an interesting outcome. Those outside the Portuguese territory, even though they are very few, are willing-to-pay more than those located in the North and Centre of the country and the South presents a somewhat discrepancy in comparison with other parts of the Portuguese territory. Also variables related to the unsuccessful of the program to provide the good or that the payment vehicle is not appropriate tend to be very negatively associated with WTP

(Carson, Flores and Meade, 2000). In our specific case this was, even admitting partially, assumed by those who have responded no to any bidding amount.

11. Summary of Part II

The survey format, namely the nature of the most important question asked – the willingness-to-pay for improving the air we breathe – has at its core an important semantic disadvantage: several respondents have asked if the meaning of the question was really true and their subsequent responses could have sapping our efforts to explain that the overall aiming was to know how much society value the asset rather than how much people will pay for it. As Carson et al. (1996) point "[…] *Contingent valuation choices provide information along with noise*" but the question the researcher as to deal with is how to yield stated choice information that is *informative* about people's preferences. In this sense, the direct question asked – to hypothetically pay for air quality improvement -, both in the pre-pilot study and in the online questionnaire, embodies this delicate issue having in mind that the rule of thumb is that the best response depends whether the question is easily understood by respondents, despite their initial reaction of constrain. An important participation incentive to survey respondents is that their opinions will be heard and that action will be taken based on their feedback. For those respondents who believed that participating in this survey was important, they can for sure be right.

At last a statement following those words from Carson and Groves (2011) to illustrate the aforementioned:

> "As long as the preference information collected in surveys is used by governments and private firms to help make decisions, then people should use the opportunity provided by their survey response to help influence those decisions."
>
> (Carson and Groves, 2011: 301)

Assessing willingness-to-pay for improving atmospheric air is a complex task. Without any doubts, one interesting question to be further analysed refers to the low WTP expressed by those who holds an MSc or a PhD – the higher educated group and with (assumptive) ability to pay more. In fact, those respondents' willingness-to-pay "low amount" for a better air quality seems to be the surprising outlier from this study. Differently from what one can imagine from more educated people awareness to climate and health impacts from air pollutants, the results have shown that this premise was not fulfilled, or perhaps, there is no argument to support such an assumption. It is hereby assumed, however, that perhaps one explanation for this "refusal" to pay more can be due to the fact that more informed people (despite information being different from knowledge) can be more concerned about the nature and destiny of some state expenditures collected from taxpayers, not to mention the sorrowful memory left behind by recent austerity policies the middle-class have had suffered in the last years, which could partially explain their responses.

If this experiment is to be conducted elsewhere, it would be very critical to compare the outcome by performing a representative subset cross-sectional regression analysis in order to sort out the causal inference from one or more independent variables upon the dependent variable (the national WTP) after eliminating the differences in price levels between the different regions. Such a comparison could be useful to find out the existence, or not, of a "standard" individual: that is, a respondent of identical age, gender, etc. with the same expected WTP (Pearce, Atkinson and Mourato, 2006) according to the causal factors displayed in Table 10.3 while ignoring the size of the representative subset or the point time of the study. It should be econometrically interesting but also from both sociological and anthropological standpoint of view.

PART III: SOCIAL COST-BENEFIT ANALYSIS

12. SOCIAL COST-BENEFIT ANALYSIS FRAMEWORK

Part III of this thesis estimates the costs and benefits of the policy/project implementation. Social cost-benefit analysis is an analytical tool to evaluate the feasibility of a project (or policy) adjusted to consider more than just financial costs and benefits but rather the full spectrum of costs and benefits including social and environmental effects borne by society as a whole as a result of an intervention (Kotchen, 2010). Implementation costs are those resulting from the price people are willing-to-pay. Benefits are those resulting from a potential change in the provision level, in the case a better atmospheric air as a direct outcome from emissions mitigation due to a fuel switch from traditional fuels to LNG. It provides the accuracy and relevance of an empirical economical study. A cost-benefit analysis informs and supports the decision-making on resource allocation. An evaluation decision could then be made using net present values or benefit/cost ratios (Cameron et al. 2011). An economic valuation is easier when an environmental externality results in a change in production of a good or service for which market prices can be used as metric. The more tangible and more direct the impacts are, the easier they are to value in economic terms. While changes in the production of crops, forestry, fisheries, and the impacts on health from air pollution can be more or less easy to "value" other types of environmental externalities are more difficult including biodiversity, cultural values and human life. This does not mean that economic valuation is impossible just that it is often more challenging; in fact there are many examples of such valuations in the literature (Dixon, 2013). For those difficult environmental impacts usually they are valued using CV approaches, and the situation under analysis falls into this category as we have seen above. In fact, the purpose of this particular approach herein developed is to provide an empirical estimation of social approval obtained from a random sample of the Portuguese population and their willingness-to-pay (WTP) in face of the trade-off between the improvement and disposable income (Moreira, 2018).

There are four main principles of cost-benefit analysis:

i) Consumer sovereignty: the principle that the choices made by consumers with respect to how to spend their income are accepted and are treated as data; ii) Valuation of goods according to willingness-to-pay; iii) Pareto-optimality: as the criterion of welfare maximization; and, iv) Neutrality with respect to income distribution: it remains neutral with respect to the distribution of benefits and costs among groups of the population provided that benefits in total exceed costs.

The framework also gives systematic insights into choice of techniques and the assignment of distributional weights (Cameron et al. 2011). The development of a SCBA requires the metric of "monetising" costs and benefits even when societal values are not necessarily a field where the main objective should be "efficiency maximisation", as it happens with environmental nonmarket assets such as the atmospheric air we breathe. The SCBA ponders costs and social benefits of a project or policy in order to determine the Total Economic Value (TEV) attributable to environmental assets in question. Usually, total value is decomposed into direct and passive use values. Atmospheric air has indeed a direct use value though it requires that the agent physically experiences the commodity. The Rule of the Net Present Value (NPV) transmits to the analyst whether the policy should be implemented according to the following formula:

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} \qquad (12.1)$$

Where:

CF_t: Cash-flow in year *i*
t: The discount rate (since this is a short-term project a 0% social discount rate was applied).

12.1 Air pollutants and effects on health

NO_x, SO_2 and PM emissions relationships between effects on health are causal. NO_x acts as a precursor in the formation of ground-level ozone, a threat to the health of humans and for the environment. Moreover, NO_x through effects of nitrate aerosols damages forests and arable lands leading to crop losses. SO_2 through sulphate aerosols produces harmful effects on health, and acid damage to building materials. As for the PM they cause primarily health effects. Table 12.1 provides an outlook to main health external costs from the air pollutants as it will be performed in this study. Avoided climate, health and non-health costs represent direct benefits. In this sense, the words “costs”, “damages”, “externalities” and “external costs” may be used interchangeably.

Table 12.1: Ozone and particulate matter effects on health.

Pollutant	Health effects	Quantification
Particulate matter	Bronchitis Nonfatal heart attacks (myocardial infarction) Lower respiratory symptoms Ashtma exacerbations Upper respiratory symptoms Subchronic bronchitis cases Low birth weight Pulmonary function Chronic respiratory diseases Altered host defense mechanisms Cancer …	Minor restricted-activity days Work loss days Premature mortality Hospital admissions (respiratory and vascular) Infant mortality Emergency room visits for ashtma
Ozone	Premature mortality (short-term exposures) Hospital admissions: respiratory Ashtma attacks Respiratory symptoms Chronic respiratory damage Inflamation in the lung Premature aging of the lungs Accute inflammation and respiratory cell damage Increased susceptibility to respiratory infection …	School loss days Outdoor worker productivity Minor restricted-activity days Emergency rooms visits for ashtma Hospital admissions (respiratory) Non-ashtma espiratory emergency room visits

Source: Adapted from Holland (2014).

12.2 Willingness-to-pay and risk reduction: the VSL concept

The Value of Statistical Life (VSL) is used for long-term mortality effects and the Value of a Life Year (VOLY) is used for both short and long-term mortality effects, depending on the metric chosen in the epidemiological computations (Chanel, 2011). The process of risk assessment of living, that is, the risk of mortality, involves estimating the willingness-to-pay to ensure risk reduction arising from a policy or project[76]. The procedure involves taking the change of the risks involved and divides them by the willingness-to-pay to reduce this risk to obtain the “value of statistical life” (VSL). Basically VSL is the WTP divided by risk. To derive the WTP for a risk reduction, let U(y) denote the utility function expressing the level of well-being produced by the level of consumption y when the individual is alive.

[76] The concept of VOLY is related to the VSL but it assumes that a VOLY is constant over the rest of one’s remaining lifetime. As such, as long as the VOLY is constant with respect to age, a policy that saves young adults, who have a longer life expectancy, would be concluded to offer greater benefits if the VOLY is used instead of the VSL, concept that raises some questions in terms of intergenerational equity.

$$EU = (1 - R) * U(y) \tag{12.2}$$

Where EU refers to expected utility if it is further assumed that the utility of income is zero when the individual is dead (Alberini, Tonin and Hunt, 2008). The mortality benefits are computed as VSL* L, where L is the expected number of lives saved by the policy. The concept of VSL is generally deemed as the appropriate construct for ex-ante policy analyses, when the identities of the people whose lives are saved by the policy are not known yet (Alberini, Tonin and Hunt, 2008). Ex-ante perspective refers to the statistical risks before the damage happens and not an ex-post perspective, i.e. it is not a measure for the life of a known individual or a certain death (Bickel and Friedrich, 2001).
Thus, the usual procedure is to take a measure “objective” risk from some changes in an environmental variable, for example, pollution. Dose-response function is used to estimate the number of premature deaths, and these mortalities are multiplied by VSL to give an aggregate measure of the benefit. Suppose a policy that promises to reduce risk from 5 in 10,000 to 3 in 10,000, a change of 2 in 10,000 (Δr). Now supposing that the average WTP to ensure that risk reduction is €6.8. Then the VSL is usually calculated as:

$$\frac{\text{WTP}}{\Delta r} = \frac{6.8 * 10,000}{2} = 34,000 \tag{12.3}$$

The VSL would be €34,000. The WTP should vary directly with income has it was demonstrated in our survey. Indeed, it is widely considered that the sensitivity to income and absolute risk are the two basic tests of the validity of any technique based on preference-based technique to measure VSL.

12.3 The Value of a Life Year (VOLY)

For mortality from PM and O_3 exposure, the annual number of premature deaths avoided per year is used. In view of the way these data are computed, the gains in life expectancy corresponding to each of these premature deaths can be considered to be in the range of a few months, certainly lower than one year (Hurley et al. 2005). Consequently, in our study we focus on the value of each unit that makes up the monetised mortality benefits of economic policies using a VOLY, preferred to value short-term mortality effects as it comes from Holland (2014) economic values. VOLY estimates can be derived from the following equation:

$$VSL_j = VOLY \sum_{t=i}^{T} \frac{\mathrm{s_{t,j}}}{(1+\delta)^{t-j}} \tag{12.4}$$

Where:

- VSL_j is the VSL for an individual of age *j*,

- δ is a discount rate (more precisely, the marginal rate of time preference),

- $S_{t,j}$ is the survival probability at age *t* conditional on having survived until age *j*,

- *T* is the maximum age an individual can reach.

Health endpoints affected by environmental exposures are grouped into mortality and morbidity benefits. The method traditionally used to quantify the mortality benefits of environmental policy is the so-called damage function approach, which consists of two main steps. The first is to estimate the reduction in mortality risks (or increase in life expectancy) attributable to policy. This is usually accomplished by reviewing evidence in the epidemiology studies or clinical medical literature, or through expert assessments. In the second step, the risk changes (or the increase in an individual's life expectancy) are aggregated over the population of beneficiaries of the policy, and then multiplied by the (economic) value of each such unit. Once the mortality benefits of the policy have been calculated, they can be compared with other categories of cost. Even more important, they can be summed together with other benefits for the purpose of comparing them with the costs. In our study, the starting point to calculate health costs from exposure to those pollutants - and hence the benefits arising from their diminishing - is given by the share from domestic navigation for total emissions at national level. Those costs comprise mostly premature deaths but aggregated health costs from Holland (2014) were used. Holland (2014), presents values for health impact assessment ranging from €57,700/€133,000 per life year lost (VOLY) to €1.09/€2.22 million per premature death (VSL). Table 12.2 depicts costs from main pollution effects over population's health.

Table 12.2: Quantification of morbidity and mortality for both VSL and VOLY metrics.

Impact / population group	Unit cost	Unit
Ozone effects		
Mortality from chronic exposure as: Life years lost, or Premature deaths	 57,700 / 133,000 1.09 / 2.22 million	 €/life year lost (VOLY) €/death (VSL)
Mortality from acute exposure	57,700 / 138,700	€/life year lost (VOLY)
Respiratory Hospital Admissions	2,220	€/hospital admission
Cardiovascular Hospital Admissions	2,220	€/hospital admission
Minor Restricted Activity Days (MRADs)	42	€/day
$PM_{2.5}$ effects		
Mortality from chronic exposure as: Life years lost, or Premature deaths (all-cause and cause-specific mortality)	 57,700 / 133,000 1.09 / 2.22 million	 €/life year lost (VOLY) €/death (VSL)
Mortality from acute exposure	57,700 / 138,700	€/life year lost (VOLY)
Infant Mortality	1.6 to 3.3 million	€/case
Chronic Bronchitis in adults	53,600	€/new case of chronic bronchitis
Bronchitis in children	588	€/case
Respiratory Hospital Admissions	2,220	€/hospital admission
Cardiac Hospital Admissions	2,220	€/hospital admission
Restricted Activity Days (RADs)	92	€/day
Work loss days	130	€/day
Asthma symptoms, asthmatic children	42	€/day
NO_2 effects (though not quantified in this report)		
Mortality from chronic exposure as: Life years lost, or Premature deaths	 57,700 / 133,000 1.09 / 2.22 million	 €/life year lost (VOLY) €/death (VSL)
Mortality from acute exposure	57,700 / 138,700	€/life year lost (VOLY)
Bronchitis in children	588	€/case
Respiratory Hospital Admissions	2,220	€/hospital admission

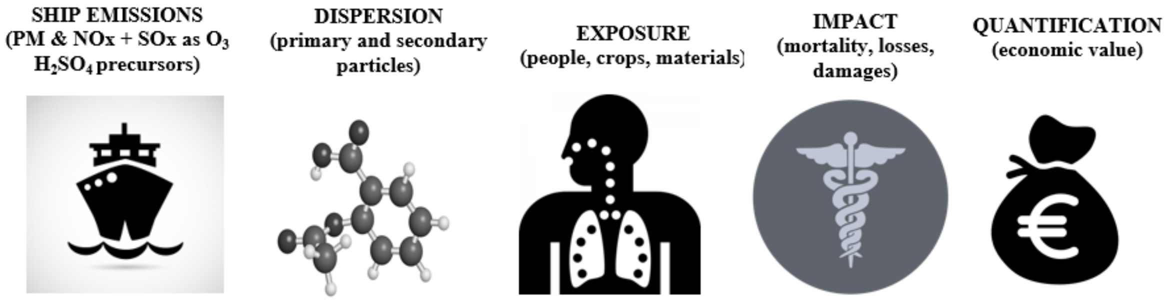
Source: Holland (2014).

12.4 The Impact Pathway Approach

Impact pathway approach (IPA) traces emissions from air pollutants through dispersion to exposure of sensitive receptors, impacts and finally economic valuation. In practice, the IPA is a damage cost approach (also known as dose-response method)[77] focuses on the quantification of the explicit impact that emissions have on human health, environment, etc. Our study begins by calculate the share of emissions by pollutant from national shipping and ends with the quantification based on VOLY aggregated damages costs for Portugal year 2014 as it stems from Holland, 2014 (Figure 12.1).

[77] The dose–response function, or exposure–response function, or concentration-response function describes the change in effect on an organism caused by differing levels of exposure (or doses) to a stressor (usually a chemical) after a certain exposure time.

Figure 12.1: The Impact Pathway Approach.



Source: Author’s elaboration.

The IPA has been used in many research projects and policy-related studies and is recognised as the most reliable tool for environmental impact assessment (Korzhenevych, et al. 2014). Yet, some uncertainties and limitations do exist. For instance, the IPA requires a lot of detailed information, much of which cannot be updated. As a result, outdated information is transferred from study to study without proper correction or adjustment. This also makes the comparison of the results of different integrated assessment studies very difficult. Nevertheless, there is a broadly scientific consensus about the use of IPA as the preferred methodology. Yet and diversely than valuate the respective health effects based on the willingness-to-pay, as usually used to perform an IPA, our economic value analysis is based in the benefits that come from the reduction of the pollutants concentration as described below:

i) For the health impact assessment, account is taken from aggregated health damages over Portuguese territory population in year 2014, based on Holland’s report year 2014;

ii) For the effects on crops and materials (non-health damages impact assessment) we use the data available for the same year for each type of impact quantified (NO_x as ozone precursor and SO_x as acid rain precursor), based on Holland and Watkiss (2002) damages cost after values have been adjusted.

With respect to exposure and conversely to what is appointed to mobile sources there is not an important difference between local pollutants for which population exposure in port’s vicinity largely determines the health impact. Thus, the impact assessment does not take account of the differing population densities between port areas and areas outside port proximity. Emissions produced in the shore based of maritime operations are extremely low if we compare with those emitted at sea because auxiliary engines run mostly on MGO when ships are loading and unloading at port (De Meyer, Maes, & Volckaert, 2008). Emissions from HFOs at sea mode are long-range pollutants disseminated all over the coastline and thus the link to population densities is not clear or at least, difficult to establish and to model. As such, we do consider that pollutants around the source – port areas and emissions while on route - are dispersed evenly throughout the national territory.

12.5 Assessing climate change impacts

Portugal and other European countries (mainly the Mediterranean and Central Europe, according to the IPCC, 2018) are among the most vulnerable with regard to the impacts of climate change, the bigger challenge human race has to deal with. The use of LNG lead to representative reductions of greenhouse gases by 12-27% (Lowell et al. 2013), or to 10-20% (Chryssakis et al. 2014), compared with conventional oil-based fuels including the emissions of non-burnt methane (EMSA, 2010). More substantial GHG reductions are possible if fossil LNG is substituted with biomethane (Wurster et al. 2014), in both well-to-tank and tank-to-propeller leakages. Based on values from literature review we consider a reduction of 20% in CO_2 emissions from domestic shipping year 2014. Carbon is priced at 96.5€ per tonne as it comes from Korzhenevych et al. year 2010 values updated to 2014 prices using the Eurozone CPI deflector.

12.6 Measuring health impacts

The emissions of fine particles, nitrogen oxide and tropospheric ozone are currently the two most important pollutants in Europe, representing a serious risk to human health and the environment (Fowler et al. 2013), affecting the quality of life and reducing life expectancy.

The majority of ozone formation occurs when NO_x and volatile organic compounds (VOCs) react in the atmosphere in the presence of sunlight. For this reason those substances are called ozone precursors. Owing to its highly reactive chemical properties, O_3 is harmful to vegetation, materials and human health leading to a wide range of health problems (Amman et al. 2008). Although these precursors often originate in the vicinity of port areas, winds can carry NO_x hundreds of kilometres, causing ozone formation to occur in less populated regions as well (Evtyugina et al. 2007). Moreover, NO_x present in nitrate aerosols damages forests and arable lands leading to crop losses. Furthermore, those emissions have the potential of acidification (Eyring et al. 2009), eutrophication, and photochemical ozone formation (Bengtsson, Andersson and Fridell, 2011) and impacts negatively over water supply, energy, land use and biodiversity (Cofala et al. 2007). For instance, photochemical production in rural areas, has clear implications for the air quality in regions far away from coastline (Saavedra et al. 2012), and can cause transboundary effects. For a coastal country like Portugal and even though the large of emissions occur far from shore, due to prevailing North/Northeast winds (associated with upwelling and coastal low level jets) pollutants can spread for over hundreds of kilometres with implications for the air quality in regions far away from coastline (Evtyugina et al. 2007).

Particulate matter are ultrafine particles that may cause important respiratory problems; the smaller the particles, the more likely to penetrate deep into the respiratory system and greater the risk of inducing adverse effects. These particles can remain in the atmosphere from days to weeks and travel through the atmosphere hundreds to thousands of kilometres (Li et al. 2015).

By its side, sulphur dioxide from combustion exhaust gases during the process of oxidation in the atmosphere forms sulphate aerosols being harmful to health and is a precursor of sulphuric acid rains. In the upper atmosphere SO_2 reacts with the water molecules to produce acid rain that has been shown to have several adverse impacts including corrosion of steel structures such as bridges, and weathering of stone buildings and statues as well as having impacts on human health. Since LNG reduces emissions of NO_x by 90% and SO_2 and PM at practically 100% (Corbett et al. 2014; Rahman and Karim, 2015) human health risk to air pollution will fall to lower ranges. An introduction to those substances and respective effects is what we describe in next subsections.

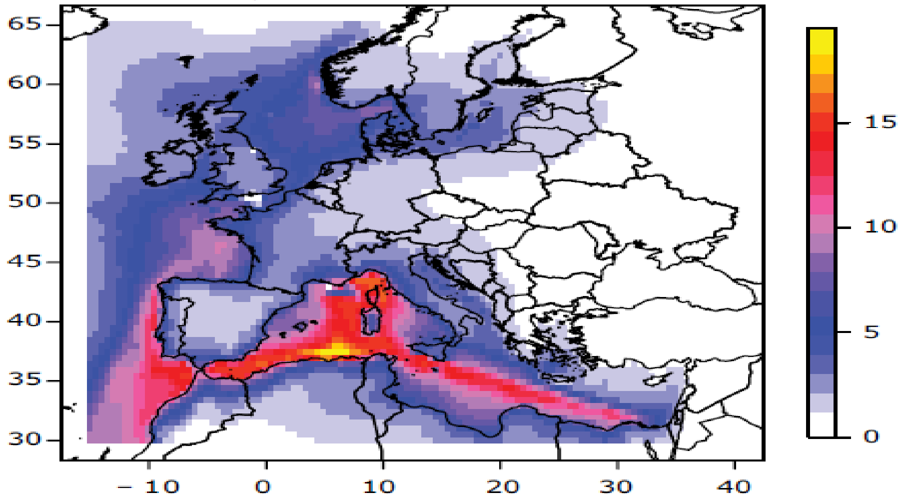
12.6.1 Tropospheric ozone (O_3)

Differently of stratospheric ozone which protects life on Earth from the harmful effects of the sun’s ultraviolet rays (UVs), the ground-level ozone, or tropospheric ozone, is an air pollutant that damages human health, vegetation, and many common materials[78]. Tropospheric ozone is a harmful substance that affects the health of most of the populations of Europe, leading to a wide range of health problems (Amman et al. 2008). O_3 is a form of oxygen but its molecule contains three atoms of oxygen instead of two like the oxygen molecule (O_2) we find in the atmosphere. Ozone is unstable, very reactive and with strong oxidizing power because of its single atom of oxygen and will readily combine with other atoms. That is why oxygen is almost always found in pairs, in its more stable diatomic form while the O_3 is less stable because it wants to return to the diatomic state by giving up an oxygen atom.

The majority of tropospheric ozone formation occurs when NO_x and volatile organic compounds (VOCs) react in the atmosphere in the presence of sunlight. For this reason are called ozone precursors. Volatile organic compounds consist of unburnt or partially burnt hydrocarbons remaining from the combustion process, emitted as gases in the exhaust. They are also emitted directly from cargo such as oil and petroleum products by evaporation (Goldsworthy, 2010). In the specific case of shipping, O_3 precursors primarily generated during the combustion of bunker fuels react with daylight ultraviolet rays and these precursors create ground-level ozone pollution. Although these precursors often originate near port areas, winds can carry NO_x hundreds of kilometres, causing ozone formation to occur in less populated regions as well. According to Evtyugina et al (2007), "*the initial concentrations of air pollutants such as NO_x and VOCs at the coast are crucial factors influencing the level of ozone production in inland rural areas*" spreading for more than 70 km inland. Although Evtyugina et al's article do not addresses specifically to water borne pollutants if one looks at Figure 12.2 is possible to see the high intensity of ozone formation along Portuguese coast due mostly to international shipping. The air masses during the sea breeze circulation will carry on the photochemical O_3 furthest from coast to interior at a regional-scale.

[78] Tropospheric or ground-level ozone formed in the portion of the atmosphere from the earth's surface to about 12 km.

Figure 12.2: International shipping contribution for ozone formation in Europe (%).



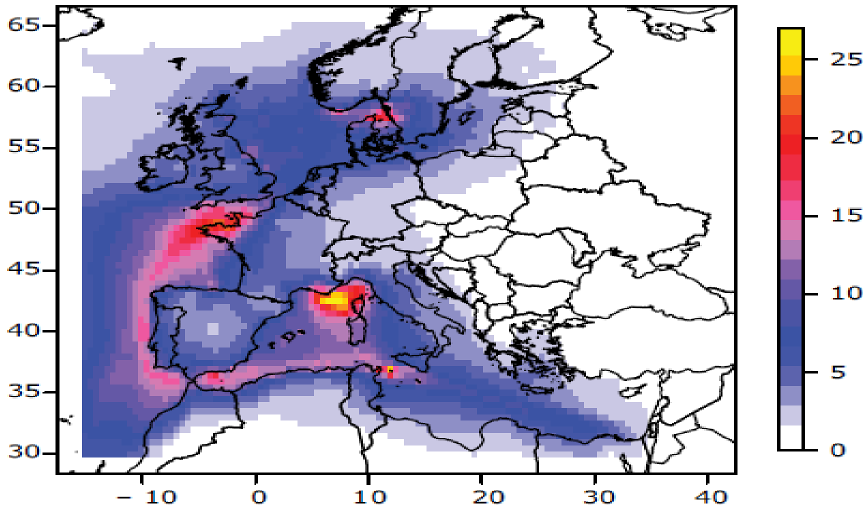
Source: European Environment Agency (2013).

As we have stated elsewhere, LNG fuelled ships reduces NO_x emissions by up to 90% and VOCs to almost 100% during voyage thus reducing the formation of ground-level ozone from shipping proportionally. Reduction of NO_x is achieved due to lower combustion temperature comparing with oil fuels. As for VOCs their cooling on-board helps to recover the otherwise lost cargo vapours.

12.6.2 Particulate matter (PM)

Globally, shipping is thought to contribute almost as much primary PM as road traffic: 1.7 Tg a^{-1}compared to 2.1 Tg a^{-1} (Eyring et al. 2005). PM is a generic term for a broad class of chemically and physically diverse substances often called fine PM, and also comprise ultrafine particles having a diameter of less than 0.1 µm (referring to particles with a nominal mean aerodynamic diameter less than or equal to 0.1 µm). The smaller the particles the more likely to penetrate deep into the respiratory system and greater the risk of inducing adverse effects. Particles having an aerodynamic diameter less than 10 µm are the most harmful for they penetrate the respiratory tract whereas those of less than 2.5 µm, reaches the pulmonary alveoli and interfere with the gas exchange in the lungs. The chemical and physical properties of PM may vary greatly with time, region, and meteorology and source category. PM may include a complex mixture of different pollutants including sulphates, nitrates, organic compounds, elemental carbon and metal compounds. These particles can remain in the atmosphere for days to weeks and travel through the atmosphere hundreds to thousands of kilometres (Li et al. 2015). The suspended particles are also an effective vehicle for transporting other air pollutants which adhere to the surface, especially hydrocarbons and heavy metals. A further layer of complexity comes from a particle's ability to shift between solid/liquid and gaseous phases, which is influenced by concentration, meteorology, and temperature. In addition, there are also physical, non-chemical reaction mechanisms that contribute to secondary particles (World Health Organization, 2013b, hereinafter simply WHO). There is good evidence of the effects of short-term exposure to PM_{10} on respiratory health, but for mortality, and especially as a consequence of long-term exposure, $PM_{2.5}$ is a stronger risk factor than the coarse part of PM_{10} (WHO, 2013b), referred to as thoracic coarse particles or coarse-fraction particles. Chronic exposure to particles contributes to the risk of developing cardiovascular and respiratory diseases as well as for lung cancer. Exposure to PM affects lung development in children, including reversible deficits in lung function as well as chronically reduced lung growth rate and a deficit in long-term lung function (WHO, 2013). As a waypoint of international shipping, Portuguese coast presents high concentration of PM as can be seen in Figure 12.3 below.

Figure 12.3: $PM_{2.5}$ contribution from international shipping emissions in Europe (%).



Source: European Environment Agency (2013).

There are well documented effects, both in the literature and in evidence, which proof the positive impact on health by decreasing PM concentrations in specific areas and in specific industrial activities. (e.g. a steel mill in the Utah Valley, U.S.) This example, *mutatis mutandis*, can be transposed to shipping reality. In the following, we will use the approach with no differentiation of $PM_{2.5}$ and PM_{10} with respect to toxicity impacts (i.e. we assume both particles as one).

12.7 Non-health impacts

To perform a non-health impact analysis, detailed quantification of effects on ozone damage to crops and acid damage to buildings would be necessary requiring additional pollutant metrics and a very strong effort to collect data. Such information isn't available at national level, which implies to follow the same approach as used for health impacts calculation: the share from domestic shipping for total emissions multiplied by net benefits resulting from its reduction.

As previously cited, damage to other non-health receptors, notably ecosystems has not been quantified. Such assessment limitations incur against benefits which, if taken into account, will positively impact the final outcome. For the effects on crops and materials (non-health damages impact assessment) we use the data available for the year 2014 for each type of impact quantified (NOx as ozone precursor and SOx as acid rain precursor), based on Holland and Watkiss (2002) damages cost after values have been adjusted to year 2014. Nevertheless it is worth to note that there are several limitations of this approach for quantifying non-health impacts as referred by Holland:

> "It only permits quantification of crop and utilitarian material damage; it does not fully quantify effects on either utilitarian buildings or crops. For example, no account is taken of changes in the productivity of grassland that may impact production of livestock and associated goods, and no account is taken of the effects of particle emissions on building soiling."
>
> (Holland, 2014: 14)

By the other hand, damage to other non-health receptors, notably cultural heritage, has neither been quantified for the same reasons pointed above. Such assessment limitations also incur against benefits which, if considered, will positively impact the final outcome. Nevertheless, even without those monetary quantifications, we believe that the final score does not reflect any doubt.

12.8 Data sources and methodology

Pollutant emissions indicators were collected from the national inventory as it stands from the Portuguese Environment Agency (APA) 2016 National Inventory Report on GHGs (NIR) which fuel consumption in 2014 estimates follow a sector-specific category bottom-up approach (Tier II) combined with a top-down approach for calibration (for CO_2 emissions). The GHG emission inventory is the official annual accounting of all anthropogenic (human-induced) emissions and removals of greenhouse gases in Portugal. The inventory measures Portugal's progress against obligations under the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the European Union agreements. Final emissions share by pollutant substance type were defined according to the data given by the national inventory for the year 2014.

Monetised climate benefits are those obtained from reduced climate change-induced damages translated into carbon prices which reflect expected uncertainties about real-world climate change related problems in the future and the costs incurred with adaptation measures. Monetised health benefits are those from the aggregated health damages reduction (saved human lives from premature death and other health benefits) in accordance to Holland (2014) methodology using the scenario envisaged for year 2014. Non-health benefits are those from net benefits to crops from ozone reduction and benefits to materials from a reduction in SO_2 levels (sulphur dioxide is the starting material in the production of sulphuric acid - H_2SO_4). Costs are those incurred with the implementation of mitigation measures and by which people are willing-to-pay for, deduced from the survey's results. Marginal costs for pollutant from maritime transport damages were those from EcoSense model as used by Korzhenevych et al. (2014)[79] for sea areas costs per pollutant together with those used by Holland and Watkiss (2002) for rural areas values. CO_2 was valued at 96.5€/tonne mean assuming a 20% reduction or 33.6kt net emissions. Further to this, it is here assumed that the effects quantified for NO_x as ozone precursor was estimated to account for 20% of total ozone damages on crops whilst materials damage accounts for around 10% of SO_2 externalities (non-health damages), as suggested by Holland and Watkiss (2002).

[79] EcoSense was developed to support the assessment of priority impacts resulting from the exposure to airborne pollutants, namely impacts on human health, crops, building materials and ecosystems.

12.8.1 Deriving pollutants at national sector level

In 2014 and according to APA's NIR, CO_2 emissions from domestic navigation were estimated in 168 kt, totalling only 1% of EU-28 and ISL (Iceland, Switzerland and Liechtenstein)[80]. Also, in year 2014 and according to the APA's NFR, domestic navigation was responsible for the following emissions: 3.1 kt of NO_x, 1.7 kt of SO_2 and 0.6 kt of PM considering both $PM_{2.5}$ and PM_{10} (Table 12.3). For what follows, pollutant emissions emitted by ships will be derived by considering the total concentration of this pollutant at national level and by determining which part of the total concentration is imputable to domestic shipping, according to the same methodology used by Miola et al. (2008), for the SO_x emitted by ships. We do consider only domestic navigation emissions due to the fact that we want to measure costs and benefits at national level and if we calculate emissions from international shipping the final costs and benefits should be taken into account and therefore the WTP should be elicit at international level, which is not the case.

Table 12.3: Emissions share from domestic shipping for the national inventory.

	Substance	NOx	SO_2	PM	CO_2
a	National inventory (kt)*	159,6	34,8	99	47 215
b	National shipping emissions (kt)	3,1	1,7	0,6	168
c	National contribution	1,9%	4,9%	0,6%	0,4%
d	% Reduction from LNG vs. HFO	90%	100%	98%	20%
e	Weighted % for damage reduction on:	Health: 100%; Crops: 20%	Health: 100%; Materials: 10%	Health: 100%	GHGs: 20%
f	Net emissions (kt) (*f=b*d*)	2,79	1,7	0,6	33,6
	Effects on:	Health (nitrate aerosols); Crops (O_3)	Health (sulphate aerosols); Materials (acidity)	Health ($PM_{2.5}$ and PM_{10})	Climate change

* Without land-use, land-use change and forestry (LULUCF).

Source: Author's elaboration from APA's NIR on GHGs, 2014.

[80] National Inventories and annexes should be standardised as to make methodologies and results easier to compare. For instance, most of the countries exclude NIR's estimates of the so-called indirect greenhouse gases only displaying information about CO_2, CH_4 and N_2O.

A 20% CO_2 reduction equals 33.6kt net emissions (Table 12.3). As stated before, annual value of damage costs were based in Holland (2014) report prepared under contract to assess and to inform the revision of the EU's Thematic Strategy on Air Pollution for $PM_{2.5}$ and O_3 considering the anticipated development of emissions and their effects over the period to 2025 and 2030, featuring several expected scenarios.

Critical values for inputs are those calculated from Holland's - year 2014. Holland's time series values are not discriminated in a way to compare with the same years' data from the Portuguese NIR. Therefore, the values respecting the year 2014 were estimated according with an interpolation established between years with available data: 2010 and 2015 (Annex 5).

Following the percentage in the specific emissions as from literature reviewing (EMSA, 2010; Kolwzan and Narewski, 2012) national quotas for health damages from domestic shipping is as it follows: CO_2 a reduction of 20%; for NO_x was considered a reduction in 90% as ozone precursor; 100% for SO_x and 98% reduction for PM (health). Those percentages are based on the expert estimates, as depicted in Table 12.4[81].

Table 12.4: Emission reduction with LNG as fuel.

Emission component	Emission reduction with LNG as fuel	Source
CO_2	25% 12-27% 20-25%	Winnes, Styhre, Fridell, 2015 Lowell, Wang, Lutsey, 2013 Laugen, 2013
SOx	100% 100% 100%	DNV-GL, 2015a Deal, 2013 Jónsdóttir, 2013
NOx	85% 85-90% 85-90% 85-90%	DNV-GL, 2015a Laugen, 2013 Herdzik, 2011 Jónsdóttir, 2013
PM	95-100% 100% 98-100%	DNV-GL, 2015a Laugen, 2013 Deal, 2013

Source: Author's elaboration.

[81] Although NO_x also contribute for the formation of acid rain, causing damages in infrastructures, forests and crops, it was not considered in the non-health benefits assessment. Similarly, VOCs are not addressed as ozone precursors because those emissions are more than an order of magnitude smaller than NO_x contribution from domestic navigation: about 0.1%.

Holland (2014:9), have considered not including quantification of impacts against functions for NO_2 because under The Clean Air for Europe (CAFE) Programme: "*separate inclusion of functions for these pollutants would incur at least some double counting*". Diversely of that report however, our analysis includes the quantification of NO_x since the purpose is to estimate the overall effect of air pollution on the exposed population.
According to Hurley et al.:

> "It does not matter much if the identified pollutants are really causal or are tracers of the overall mixture, provided that: i) the mixture being evaluated is similar enough to those studied epidemiologically; and ii) care is taken to ensure that health effects attributable to the mixture are neither missed nor double-counted."
>
> (Hurley et al. 2005: 5)

In fact the Health Risks of Air Pollution in Europe – HRAPIE project of the WHO (2013a) indicates that NO_2 effects should be quantified and added. As such, in the form of NO_x it was included as ozone precursor in a way to achieve a broad completeness. The present study does not take into consideration effects on productivity losses and healthcare costs. It also does not include assessment of impacts to ecosystems due to lack of verisimilar data.

12.8.2 Estimated health benefits

According to Holland (2014; Table A3.1.), data from Portugal show a decrease in people's years of life due to chronic PM exposure in the year 2014 to reach a total of about 58,000 years. For the same year, deaths from chronic PM exposure should affect some 5,825 individuals, as an alternative metric to the above whilst deaths from short-term O_3 exposure in 2014 were estimated in 512. All aggregated damage costs are quantified in a total of €4,610 million according to year 2014 for Portugal (Table A3.6 – Aggregated Health Damages - in the aforementioned study)[82] with mortality valued using the median VOLY. Based in the aggregated health damage costs, the following health benefits from a reduction in marine airborne pollutants with the introduction of LNG as an alternative fuel have been collected:

[82] For information purposes only, lost working days due to acute PM exposure rise to 1,544,272 days (valuated at some €201M year at EU average value).

Monetised health benefits (using VOLY)

According to year 2014 and in line with our conclusions PM emissions from shipping are responsible for 0.6% of the national inventory, SO_2 for ~5% and ~2% for O_3 as displayed in Table 12.3. Health benefits attributable to shipping emissions reduction are valued according to the following equation:

$$NB = \sum [V_p * R_a] \tag{12.5}$$

Where:

NB is net health benefits;

V_P is the aggregated health damages for Portugal, year 2014;

R is the pollutant (NO_x, SO_2, PM);

a = as % of domestic shipping emission[83].

As such:

O_3 (NO_x) = €4610M *0.02= €92.2M/year → €276.6M for the three years policy

SO_x (as SO_2) = €4610M*0.05 = €230.5M/year → €691.5M for the three years policy

PM ($PM_{2.5}$ and PM_{10}) = €4610M*0.006= €27.7M/year → €83M for the three years policy.

All summed equals ~**€1052M**, being the first benefit from avoided damages, in this case respecting health status (the values have been rounded to the nearest unit).

12.8.3 Estimated climate and non-health benefits

Monetised climate benefits

Monetised climate benefits are those obtained from reduced climate change-induced damages translated into carbon prices which reflect expected uncertainties and the costs incurred with adaptation measures. Domestic shipping was responsible for 0.4% CO_2 emissions in the year 2014, or some 168 kt. A reduction of 20% (33.6kt) net emissions derived from the fuel switch from the adoption of the LNG was set, as it stands from literature review (Laugen, 2013; Lowell, Wang and Lutsey, 2013; Winnes et al. 2015).

[83] To make this calculation reasonable, it is assumed that % of domestic emissions contributes exactly the same % of the aggregated damage costs for Portugal.

CO_2 was valued at €96.5/t mean according to Korzhenevych et al's (2014) after values have been adjusted to CPI index year 2014. Therefore, 33.6kt reduction represents an annual value of €3.24M or **€9.7M** benefit for the three year's policy timetable.

Monetised non-health benefits

Non-health benefits are those from net benefits to crops from ozone reduction and benefits to materials from SO_2 reduction levels as a sulphuric acid (H_2SO_4) precursor and they were much more complicated to estimate. Unfortunately, Holland's study do not address marginal external costs for ozone and sulphur dioxide reduction – it only depicts yearly benefits arising from the compliance of several scenarios compared with 2010 baseline year drawing on past €/t estimates. Thus, we took hand from Korzhenevych et al. 2014 Report which settle damages costs of main pollutants in sea areas referring to year 2010. After adjusting remaining North-East Atlantic (referring to Bay of Biscay and Iberian Coast) values to CPI year 2014 European average damage, NO_x costs are €2,379 per tonne; SO_2: €3,067 per tonne. This data could be used directly as inputs due to its nature of damage costs borne by maritime transport in Portuguese waters. Nevertheless, and according to Holland and Watkiss, the quantification of effects of NO_x emissions:

> "[…] emissions transported at some distance before chemical processes in the atmosphere are able to generate significant levels of the secondary pollutants associated with them, typically in a range of 1,000 km from the site of emission should be derived from values for rural areas."
>
> (Holland and Watkiss, 2002:13).

So it is necessary to calculate emissions average costs from offshore emissions and rural (€5,315/t.) emissions values for NO_x marginal external costs as ozone precursor: 2,379 + 5,315/2 = €3,847/t (adjusted to CPI year 2014 European mean prices). Then, the calculation for rural values of SO_2 (€3,991/t) and offshore (€3,067/t) gives an average price of €3,529/t. Finally we can proceed with calculations to quantify crops and materials benefits from a reduction in NO_x and SO_2 levels as ozone and acid precursors following Holland and Watkiss (2002) methodology in which O_3 damage to crops is estimated to account for a little over 20% of total O_3 damages, whilst materials damage accounts for around 10% of SO_2 externalities (Table 12.5)

Table 12.5: Materials and crops damage reduction in a 3y period (non-health benefits).

NO_x (O_3 precursor)	SO_2 (H_2SO_4 precursor)
2,800t x €3847/t = €10.8M x 3 = €32.4M (20% = €6.5M)	1,700t x €3529/t = €6M x 3 = €18M (10% = €1.8M)
Net benefits to crops from Ozone reduction: €6.5M	Net benefits to materials from SO_2 reduction: €1.8M

Source: Author's elaboration.

All summed equals **€8.3M** for the three years policy, being our analysis' third benefit. Last benefits have shown to be very small in comparison to those quantified for health.

12.8.4 Estimated costs

Costs are those incurred with the implementation of mitigation measures and by which people are willing-to-pay for, deduced from the surveys' result. Mean WTP reveals the cost to avoid a certain level of air pollution-related effects. Individual's willingness-to-pay estimates was set as €6.8 defining the maximum amount that can be subtracted from an individual's income to keep his/her expected utility unchanged. To estimate society's willingness-to-pay that value was multiplied by the resident population in the Portuguese territory comprising the Atlantic islands of Madeira and Azores as of 2015 obtained from the PORDATA Database (http://www.pordata.pt). Thus, the number of 7,016,000 individuals aged between 18/69 years was multiplied by the WTP obtained from the sample giving a total of €47,7M/year which multiplied by the three years' time project/policy gives the sum of **€143M** that is, the theoretical amount that around 83% of Portuguese nationals would be willing-to-pay in the period of three years to improve the quality of the air in the terms presented by the survey's rationale. Yet, it also provides an indication for the amount national government could hypothetically collect through energy/environmental taxes, or equivalent, to spend in order to achieve a better air quality by introducing financial aid allocated to achieve a better air quality by introducing financial aid allocated to ship-owners to invest in vessels' LNG retrofitting and/or new orders, including public aid to install new or upgrade existing facilities at ports and/or to help establish an LNG supply chain. Following this reasoning this also implies that the European Commission or other governmental body or country organisation can achieve similar findings assuming that the inherent results can be replicated elsewhere. Summarising we have:

a) Health benefits: €1,052M; b) Climate €9.7M; c) Non-health benefits: €8.3M; d) Costs: €143M. Table 12.6 gives a general overview of costs and benefits and the resulting Net Present Value (NPV) of the policy if implemented.

Table 12.6: Net Present Value.

Costs		Totals
	From Willingness-To-Pay	€143M
Net costs		€143M
Benefits		
Mortality reduction (health benefits)		
	From Ozone	€276.6M
	From SOx	€692M
	From PM	€83M
Climate		
	In reduced CO_2 as a GHG	€9.7M
Materials		
	In avoided damages	€1.8M
Crops		
	From reduced losses	€6.5M
Net benefits		~€1,070M
Net Present Value: ~€928**M**		

Source: Author's elaboration.

According to equation (12.1) Net Present Value is positive in €928M and the benefit-cost ratio is 7.48. To further increase the robustness of this value one should bear in mind that direct benefits are specific to Portuguese population, but the actions proposed also brings benefits to third party countries through the transboundary decrease of pollutants because others who suffer but live in a different country should count[84]. This outcome also doesn't

[84] About 90% of the sulphur and 80% of the nitrogen deposited in Norway originates in other European countries. This means that the amount of acid rain falling on Norway is to a large extent determined by

take into account the effects from the reduction of acid rains on forests nor ecosystems eutrophication which will positively impact the general assessment and the final benefits' result. By another hand, if we have used the Value of Statistical Life (VSL) instead of VOLY, for the calculation of net benefits for human health, the final value will surpass at least in two thirds (Holland, 2014:27) which will strengthen the conclusions drawn here. Finally, we should consider that whilst costs are to be incurred in a time span of three years, the benefits, that is, air quality improvement, and reduced risks from a changing climate will last for long. The present analysis shows that beneficial results are undoubtedly superior to costs, even assuming some uncertainties from external costs quantification, benefit-cost ratios of such order of magnitude are bullet-proof. The SCBA outcome is not intended to make this analysis as doctrine but make it compatible with other in their differences in order to obtain, by the multiplicity of looks, a broader view.

12.9 Uncertainties and gaps

The approach to calculate pollutant emissions from shipping based on NIR indicators relies basically, by one hand, in the degree of certainty embedded in the national inventories and by another hand, in the method itself. Indeed we are well aware that this process of quantification involves uncertainties and some gaps. Since we assume national data values as trustfully accurate major uncertainties are thus relegated to the process of calculate benefits from climate change impacts, health aggregated costs and non-health damage costs. For those, the quantification process should be a proxy and this means that the outcome described here is not one monolithic value describing external costs with high certainty but rather displays a close proximity range in which true value lies with. Knowledge gaps are assumed where information about monetary valuation is lacking (e.g. GHG reduction effect, the impact of noxious substances over the ecosystems, i.e. acidification and eutrophication and cultural heritage, the macroeconomic effects of reduced crop yield, altruistic effects of impacts and other unknown effects), so that benefits estimates cannot be provided. This would seem to be the most serious of the known omitted impacts. With respect to acidification, the most evident impact is the loss of fish. Ocean acidification can also cause many parts of the ocean to become under saturated with

developments elsewhere in Europe, with the UK, Germany and Poland among the largest sources (Nore, 2011).

calcium carbonate minerals, which is likely to affect the ability of some organisms to produce and maintain their shells. Problems of eutrophication's most visible effect is one of reducing the viability of rarer species of plant, allowing other species, particularly grasses, to invade land that was previously too nutrient deficient for them. As for damages to cultural heritage, such as cathedrals and other fine buildings, statues, etc. it is unknown whether the rate of deterioration is important or not. Analysis is not possible because of lack of data on stock at risk (e.g. number of culturally important buildings, their surface areas, number and size of statues, repair and maintenance costs) not only at national level but also at European/International level. It should be noted that identified gaps can be closed and uncertainties reduced by performing further research; with this effort we are intended to give a contribution for the study of such important but somewhat neglected topic. Despite these uncertainties, this method is seen to be useful as the knowledge of an order of magnitude on health, crops and materials benefits and is obviously better for policy decisions than having no quantitative information at all since important parameters that cause costs and how these costs can be mitigated resulting in benefits were identified. Citing Holland et al. (2013): "*If there is a substantial distance between estimates of benefit and cost for a particular policy, uncertainties become irrelevant to the decision making process*". Moreover, uncertainties about overall benefits mostly reflect the uncertainties in our knowledge about the true impacts from a reduction in atmospheric pollution. This is correct and not a deficiency of methodology; a scientific method cannot transfer uncertainty into certainty (Bickel and Friedrich, 2001).

13. CASE-STUDY

To perform our social cost-benefit analysis some basic steps were taken. First we have decided whose benefits and costs count (the standing). Secondly, we have assessed noxious impacts and select measurement indicators (by pollutant substances). After that, we have monetised (attach Euro values to) all impacts followed by discounting benefits to costs to obtain present values. Then, we have predicted the impacts quantitatively over the life of the project (three years). We have then computed the net present value (NPV) of the policy. Thereafter, we will perform a voyage-base model to test the effects of such a policy. This case-study will transmit the practical results of such a policy in the context of value for society instead of "value for money" and condenses all the information gathered beforehand. This case-study uses a bottom-up approach in which total external costs are derived from ship engines emissions multiplied by marginal external costs. The theoretical framework was given by the SCBA inputs and technical and operational data was adapted to a particular case: three feeder vessels in a round trip comparison between one 3.5% sulphur content heavy fuel oil (HFO) fuelled vessel engine equipped with scrubber, to reduce emissions from exhaust stream, and selective catalytic reduction (SCR) devices (Scenario 1), one marine gas oil (MGO) fuelled vessel with 0.1% sulphur content together with SCR (Scenario 2) and another LNG fuelled vessel (Scenario 3) between the two main continental Portuguese ports in which emission values accrues from rural values of pollutants originate from ships close to shore in Eastern Atlantic Region as calculated by Holland and Watkiss (2002) updated to consumers price index (CPI) 2016. This study is done by means of an online statistical tool from the Danish Ship-owner's Association (Danmarks Rederifonering) to calculate ships' fuel gas emissions and energy efficiency. From specific engine fuel consumption, on-board technologies and sulphur content in the fuel, the emissions factor for each scenario is calculated. Final results gives the amount of pollutants emitted from ships as the product of fuel consumption resulting from the engine load, including auxiliary engines at harbour, multiplied by correspondent emission factors (Annex 6). Moreover for Scenario 1 and 2 the following assumptions were taken: HFO fuelled vessel equipped with both cleaning technologies – scrubber and SCR – and an MGO vessel equipped with SCR to reduce NO_x emissions in an anticipated scenario for an existing NO_x and SO_x ECA in the Bay of Biscay and the Iberian Coast.

Table 13.1: Engine type and technologies.

Engine type & Technology	un.	Scenario 1 HFO	Scenario 2 MGO	Scenario 3 LNG
Main engine type (slow speed = 1; medium speed = 2)	(-)	2	2	2
Main engine service rate	pct. MCR	90	90	90
Fuel type (HFO = 1; MGO = 2; LNG = 3	-	1	2	3
SFOC at 75% MCR in normal ME mode (default = 1)	g/kW/hour	1	1	1
Normal tunning = 1; low load = 2	-	1	1	1
Sulphur content in HFO	pct	3.5	0	0
Sulphur content in MGO	pct	0.1	0.1	0
Derated 2 stroke main engine? (NO = 0; YES = 1)	-	0	0	0
Fuel optimised main engine? (NO = 0; YES = 1)	-	0	0	0
Tier 1, 2 or 3 engine? (1 - 3)	-	3	3	3
NOx reduction technology: EGR = 1; SCR = 2	-	2	2	-
Scrubbers (NO = 0; YES = 1)	-	1	0	0

Source: Author's elaboration.

In order to find which scenario is the best alternative, what is the final external cost of pollutants there will be no need for a base case since we just want to compare the final performance. Indeed, Scenarios 1 or 2 are not "*business-as-usual*" scenarios due to the fact that abatement measures are already in place and an alternative less pollutant fuel is in use, respectively.

As already learned, HFO engines equipped with scrubbers and SCR devices are able to comply with the IMO's Tier III low sulphur requirements and have the advantage of being cheaper solutions for the "end-of-pipe emissions, i.e. the exhaust emissions. Hence, the 3.5% sulphur content of the HFO makes the fuel costs smaller than LNG or MGO although there are costs that are not negligible from the installation of such abatement technologies and others (e.g. educational costs for crews to operate with). In the case of the MGO fuelled feeder ship[85] the diesel fuel sulphur content complies with IMO's Tier III; plus, the use of a SCR for NO_x reduction is considered. The distinction of LNG engines is usually made between dual fuel and single fuel engines. Single fuel engines have slightly higher efficiency and lower emissions than comparable dual fuel engines Madsen and Olsson, 2012). Therefore, Scenario 3 only addresses a single fuel engine. The model for the case-study is presented as below:

$$C_{ij} = E_{ij} * MC_i \tag{13.1}$$

Where:

i represents four types of substances; NO_x, SO_x, PM and CO_2;

C_{ij} represents the external costs of substance i from ship j (in Euro);

E_{ij} represents the total amount (kg/hour) of substance i from ship j;

MC_i is the marginal external costs (Euro) of substance i.

13.1 Ships characteristics

The vessels chosen for this study have all the same main particulars and characteristics and are considered as new builds; exception is made to fuels. Therefore we analyse a 10,569

[85] Feeder vessels collects containers from different ports and transport them to central container terminals where they are loaded to bigger vessels or further transport by truck or rail

design deadweight (dwt), 7.82 meters maximum draught, 2-stroke engine type feeder vessel with a load capacity up to 800 TEU (Figure 13.1)[86].

Figure 13.1: An 800 TEU ship similar to that used in the study (Samskip Express).

Source: Shipspotting.com.

Available from: www.bgfreightline.com. (Accessed April 7, 2017)

The following route is established: Sines - Leixões – Sines. The distance per leg is found to be 209 nautical miles (nm) resulting in a roundtrip of 418 nm (c. 774 km) with a constant speed of 16.7 knots while at sea. Each ship spends 25 hours in transit per roundtrip, 24 hours loading/unloading and 4 hours manoeuvring. It is estimated that the vessel has 56 roundtrips every year, one per week which gives a total of 2,968 duty hours/year.

13.1.1 Operational Profile.

The operational profile has two modes; "in harbour" including time spent hotelling, loading/unloading and manoeuvring), and "at sea". The sea mode is responsible for around 80% of total emissions. Manoeuvring is responsible for around 5% of emissions (Madsen

[86] Dwt and draught were set by statistical tool default. TEU (twenty-foot equivalent unit) is a standard capacity of a container (c. 6.0x12 metres).

and Olsson, 2012) and operations for the remaining 15%. In order to calculate the fuel consumption and emissions, assumptions regarding the engine load are necessary for the different ship operational modes. While at sea, the specific fuel oil consumption (SFOC) for the main engine is calculated as a function of the main engine loading in percentage of the maximum engine power, also known as *maximum continuous rating* (MCR). In this case it refers to 75% of engine tuning at which rate the lowest fuel consumption occurs. Main engine power (MCR) for the HFO fuelled ship is assumed to be 8,086 kW engine and 8,105 for both the MGO and LNG fuelled ships. Thus, since this value is below 10,000 MCR the auxiliary power is set in 5% of the MCR in accordance with the IMO guidelines on Energy Efficiency and Design Index for new ships (EEDI) for operational mode while at harbour. Assumptions are presented in Table 13.2.

Table 13.2: Pollutant emissions from different ship fuels.

Emissions (at sea and at harbour)		HFO	MGO	LNG
CO_2	kg/kWh	3,500	3,300	2,300
NOx	g/kWh	13,000	13,000	7,000
SOx	g/kWh	2,000	2,000	0
Particulate matter (PM)	g/kWh	4,100	1,500	200

Source: Author's elaboration.

For the "at sea" operational mode the total emissions *i* from ship *j* is:

$$E_{ij} = EF_{ij} * D_j \tag{13.2}$$

Where:

EF_{ij} is the emission factor (g/kWh);

D_j is the sailing distance in hours between origin and destination of ship *j*.

13.1.2 Calculating Fuel Oil Consumption

The energy consumption is found by multiplying the installed power and the engine load according to the following equation:

$$EC_j\left[\frac{g}{kWh}\right]=\sum_{j=1}^{n}P_j\,[kW]*MCR_j\,[\ \%\ ] \tag{13.3}$$

Where:

j is the index referring to main and auxiliary engines (ME, AE);

Pj is the power of engine *j* (kW); and

MCRj is the engine load for engine *j* (%).

The fuel oil consumption, FOC_j, is then calculated by multiplying the specific fuel oil (or gas) consumption, $sfoc_j$, with the energy consumption. The total fuel oil and gas consumption for each ship class is then found by summing the fuel oil consumption for all the engines in both operational modes:

$$FOC_j\,[g]=\sum_{j=1}^{n}EC_j\,[kWh]*sfoc_j\left[\frac{g}{kWh}\right] \tag{13.4}$$

The specific fuel oil consumption for the Scenario 1 (HFO) is assumed to be 207.1 g/kWh, 190.7 g/kWh for Scenario 2 (MGO) and 155.6 g/kWh for Scenario 3 (LNG).

13.2 Calculating Emissions

The amount of fuel used is based on a "bottom-up" approach, using vessel and engine characteristics to generate an estimate of the NO_x, SO_x, PM and CO_2 emissions based on the emission factor for each pollutant. The amount of emissions of a certain pollutant, m_i, from a certain ship is found by summarizing the product of the engine load, MCR_j, the engine size, P_j, the ships estimated time at sea and the emission factor, EF_{ij} . This can be calculated by equation (13.5) below:

$$mi\,[\,g\,]=\sum_{j=1}^{n}EF_{i,j}\left[\frac{g}{kWh}\right]*P_j\,[kW]*MCR_i\,[\ \%\ ]*t_j\,[\,h\,] \tag{13.5}$$

Where:

i refers to the selected pollutant;

j is the index referring to main and auxiliary engines;

m_i is the amount of pollutant emission *i* (g); and

EF_{ij} is the emission factor for pollutant *i* for engine *j* (g/kWh).

13.2.1 Calculating SO_x emissions

<u>The SO_x Emission Factor</u>

Since the molar mass of SO_2 (64 g/mol) is two times the molar mass for sulphur (32 g/mol), the theoretical amount of sulphur dioxide formed is two times the amount of sulphur in the fuel (Madsen and Olsson, 2012). Based on the specific fuel consumption for the engine and the sulphur content in the fuel, the sulphur emission factor for each scenario is calculated:

$$EF_{SO_2}\left[\frac{g}{kWh}\right] = \frac{2 * \mathrm{S\%} * sfc_{\mathrm{j}}}{100}\left[\frac{g}{kWh}\right] \qquad (13.6)$$

Where:

S% is the sulphur content in the fuel; and

sfc_j is the specific fuel/gas consumption for engine *j* (g/kWh).

For Scenario 1 we have 0.31 g/kWh emissions of SO_x from AE and 0.01 from AE, and 0.40 g/kWh for both ME and AE in the MGO case for Scenario 2. As already explained, since LNG produces almost zero amounts of SO_x no emissions are considered. SO_x emissions are derived assuming that all the sulphur present in the fuel is burnt to SO_2.

13.2.2 Calculating NO_x emissions

<u>NO_x Emission Factor</u>

The emission factor is assumed to be 2.40 g/kWh for both ME and AE, and for both HFO and MGO fuelled ships. For the LNG fuelled ship this value is 1.30 g/kWh for both engines. The NO_x emission is calculated according to the following formula (Scenarios 1 and 2):

$$mNO_x\,[g] = EF\left[\frac{gNOx}{kgfuel}\right] * \left[\frac{FCj\,(g)}{1000\,[g/kg]}\right] \tag{13.7}$$

13.2.3 Calculating PM emissions

PM Emission Factor

The emission factor for PM is assumed to be 0.81 for the ME and 0.12 g/kWh for the AE, in the case of the HFO fuelled ship. For the MGO ship, emission factors are equal for both main and auxiliary engines: 0.27 g/kWh. In the case of the LNG fuelled vessel the EF is 0.03 g/kWh for both engines.

13.2.4 Calculating CO_2 emissions

CO_2 Emission Factor

The emission factor for CO_2 is assumed to be 661 for the ME and 646 for the AE, for the HFO fuelled ship. For the MGO ship, emission factors are 609 for both engines. The LNG fuelled ship presents the value of 426 for both engines.

In the possession of all data we multiply correspondent emissions emitted during the 2,968 duty hours/year and then by pollutant marginal external costs in rural areas for Portugal as provided by Table 13.3. The external costs from those substances were calculated after adjusted to Consumer Price Index 2016.

Table 13.3: Marginal external costs in rural areas for Portugal, 2016.

Pollutant	NOx	SO_2	PM
Euro/tonne	5 400	3 960	7 700

Source: Author’s adaptation (From Holland and Watkiss, 2002).

We have considered feeder vessels due to its trade nature to navigate close to shore. Therefore, as suggested, applicable emission values are those from national rural areas for Portugal. With respect to CO_2, the value of €96.5 tonne is based on Korzhenevych et al estimates after CPI adjustment to year 2014, considering the fact that those authors warned about their own value of €90/tonne (measured in 2010 prices) as a value that should be updated. Given the inputs (fuel consumption, speed, distance, etc.) and the outputs (emissions per pollutant per roundtrip) generated by the spreadsheet multiplied by external damage costs per pollutant in rural areas, is now possible to calculate the final results in the context of a "value for society" instead of "value for money" (Table 13.4).

CO_2 emissions are overwhelming and accounts for more than 60% of total emissions for the HFO fuelled vessel, of around 64% for the MGO ship and for around 74% in the case of the LNG fuelled ship, followed by NO_x, PM and SO_x in decreasing order of importance.

Table 13.4: Marginal external costs of emissions from marine fuel consumption from case-study.

		Scenario 1 HFO	Scenario 2 MGO	Scenario 3 LNG
Fuel consumption per hour	t/hour	1.11	1.02	0.84
Total yearly consumption	t	3 295	3 027	2 493
NOx emissions per year	kg	38 584	38 584	20 776
Total damage costs per year	€	208 354	208 354	112 190
SOx emissions per year	kg	5 936	5 936	0
Total damage costs per year	€	23 507	23 507	0
Particulate emissions per year	kg	11 872	4 155	594
Total damage costs per year	€	91 414	31 994	4 574
CO_2 emissions per year	ton.	10 091	9 498	6 826
Total damage costs per year	€	973 801	916 518	658 748
Totals	€	**1 297 075**	**1 180 372**	**775 512**

Source: Author's elaboration.

13.3 Conclusions drawn from case-study

The main goal of this case-study was to quantify and give a monetary value to pollutant emissions from a voyage-based model. After impacts to society have been evaluated, in order to achieve better air (and water) quality, to improve human health and promote sustainable use of ecosystem goods and services, the best available technique and best environmental practice should be elected. This view is in accordance with the ecosystem approach - a comprehensive integrated management of human activities based on the best available scientific knowledge about the ecosystem and its dynamics - as recognised by the

Convention for the Protection of the Marine Environment of the North-East Atlantic ("OSPAR" Convention)[87]. The results from this case-study show that both HFO fuelled ship equipped with scrubber in combination with SCR and an MGO fuelled SCR equipped ship are not cost-effective solutions. Marginal external costs from an LNG fuelled ship are lower if we compare with the other two alternatives. Regardless of which compliance strategy a ship-owner chooses this study do not address operational and investment costs neither this was meant to be done. Nevertheless, HFO prices are low and stable and MGO prices are higher and this trend is expected to continue mainly due to limited refinery capability. If the LNG fuel price becomes as high as the MGO fuel price, MGO will be more cost-effective. If the LNG price stays between the HFO price and the MGO price, the opposite will happen. In spite of the higher investment costs especially if single fuel technology is to be installed, from the viewpoint of the society as a whole LNG is the most environmentally friendly alternative and cost-effective solution. Yet, attention must be given to a certain detail: if the emissions standards are tightened even more in the future, as we just anticipate in our trip considering Bay of Biscay and the Iberian Coast as included in an ECA region, with increasing expected investment and operational costs maritime transport can become more expensive; thus, modal shift to either rail or road has to be prevented, especially for the latter, if not, at the end we just shift emissions from one mode to another. Moreover, for a marine fuel switch to be succeeded is therefore necessary to create the conditions for such investment take place from a long-term economic perspective as already mentioned elsewhere in this thesis.

At present time shipping profit margins are almost 70% less than 10 years ago and this could be problematic for the large majority of those operating within the industry. The extra costs to pay such a large fuel switch will certainly have a profound impact on the economics of shipping. This case-study addresses climate change impacts from CO_2 only. Together with the high level of uncertainty surrounding the downstream effects from methane slip, marginal emissions from the LNG fuelled ship might have to be considered. However, modern 2-stroke LNG engines produce almost no methane emissions and if so, the amount of CH_4 released into the atmosphere can be reduced from tank-to-propeller

[87] OSPAR Contracting Parties that are EU Member States have agreed that the OSPAR Commission should be the main platform through which they coordinate their work to implement the EU Marine Strategy Framework Directive (MSFD) in the North-East Atlantic. The MSFD aims to achieve good environmental status for the EU Member States' marine waters by 2020, applying the Ecosystem Approach.

perspective to almost zero emissions. Furthermore, sludge deposit into sea from scrubber after-treatment was neither considered. Following this line of thought - and even crediting some additional methane emissions - the LNG vessel Scenario shows that aggregated costs reduction range between 1.7 and 1.5 times compared with the HFO and MGO vessels, respectively, even after the adoption of mitigation procedures. Assuming Portuguese waters as included in a future ECA region and evaluating the impacts for the society as a whole, this voyage-based model contributes for a deeper understanding within the wider scope of environmental sustainability perspective for the feasibility of LNG as an alternative fuel for marine purposes.

14. Summary of Part III

As already stated before, CBA ponders costs and social benefits according to the equation: NPV = PV (B) - PV (C) known as the Rule of the Net Present Value, where PV (B) represents the current gross value of the benefits whereas PV (C) the current gross value of the costs being NPV>0. It provides the analyst whether the policy should be or not implemented, in our case a policy that improves the quality of an environmental asset, improves life expectancy and prevents crop losses and damages to materials. Accordingly, benefits equal the positive variation of the total economic value (TEV) which is the case.

The amount of €143M is the value resulting from the survey’s preamble and specific to its hypothetical contingent background. Therefore, this amount represents the societal costs stemming from taxes or other form of fiscal collection exclusively in order to comply with such a policy. This amount could be used, for instance, to partially subsidize the retrofitting of ships from HFO and MGO to LNG or/and to encouraging new orders[88]. Another option to be considered is to grant financial aid to develop an integrated logistics and supply chain and/or the implementation of new or to scale up of existing facilities.

[88] Indeed, newer ships less than ten years old, once capital costs are dependent of the remaining lifetime of the ship – around 25 years - can be economically retrofitted to use LNG (DMA, 2012).

Table 14.1: Number of new builds and retrofitted vessels.

	Retrofit			New buildings		
	RO-RO	Coastal tanker	Container	RO-RO	Coastal tanker	Container
€uro (M)	3,2	5,1	4,8	4,3	6,8	6,4
Vessels (units)	45	28	30	33	21	22

Source: Author's elaboration (values collected from DMA, 2012).

Likewise the German Government who has launched a program that will subsidize the conversion and new build construction of ocean-going vessels to liquefied natural gas fuel and according to Table 14.1, this amount could be invested in the retrofitting of 27 Coastal Tankers/Chemical Tankers/Bulk Carriers between 10,000-25,000 tonnes or build some 21 new 800 TEU container ships[89]. Figures 14.1 and 14.2 displays a model of both the vessels which could be retrofit or ordered and their main technical and operational characteristics.

Figure 14.1: Example of bulk carrier to be retrofitted or ordered.

Dimensions		Energy demand	
Approx length	125-180 m	Estimated main engine power	8,500 kW
Approx breadth	20-27 m	Estimated bunkering volume	500-1,000 m³ LNG
Deadweight	10,000-25,000 tonnes	Bunkering frequency	Every 10- 14 days
Available bunkering time	8-12 hours	Amount LNG /year (and vessel)	3,200 tonnes

Source: The Danish maritime Authority – DMA (2012).

[89] Portuguese merchant ships owned by nationals is very small in number and tonnage; slightly more than 10 units (not be confused with ships registered under Portuguese flag most of them owned by foreigners or with those registered elsewhere) https://www.cia.gov/library/publications/the-world-factbook/fields/2108.html

Figure 14.2: Example of container ship to be retrofitted or ordered.

Dimensions		Energy demand	
Approx length	135 m	Estimated main engine power	8,000 kW
Approx breadth	20 m	Estimated bunkering volume	500-700 m^3 LNG
Deadweight	9,000 tonnes	Bunkering frequency	Every 10 days
Available bunkering time	6-12 hours	Amount LNG /year (and vessel)	4,500 tonnes

Source: The Danish maritime Authority – DMA (2012).

Of course, it should be stressed that public authorities guidelines to allocate financial support to ship-owners in order to proceed to the conversion or to new orders should be in line with common interest policies for the sector (e.g. the CEF- Connecting Europe Facility mechanism, the Portugal 2020 partnership agreement consistent with the EU 2020 strategy for decarbonisation or through the European Fund for Strategic Investments (EFSI). By this we mean that such financial assistance should be seen as an initiative to implement measures to curb down GHG emissions, to reduce the environmental footprint from shipping improving people's health and reducing crop losses and material damages.

Before financial support for the fitting out of new vessels and the conversion of existing fleet is granted, criteria assessing the merit of the planned expenses need to be defined. The financial aid should therefore cover part of the finance of the investment and not all the costs as such, since the philosophy behind this financial aid should be to spread costs among stakeholders and not burden taxpayers. The percentage of contribution is a political decision and therefore we do not assume here any values at all.

PART IV: FINDINGS, ANALYSIS AND DISCUSSION

15. FINDINGS

This last Chapter will exhibit some considerations about what has been learned throughout this research, what contribution this thesis gives to the field of LNG as an alternative fuel and for the understanding of climate change and health issues related to marine emissions also describing limitations and pointing out future research.

15.1 What has been learned from this experiment?

Environmental externalities of shipping cover a wide range of different impacts of a large number of pollutants on environment, human health, crops, materials, ecosystems, fauna and flora. Despite the number of studies and research articles over those noxious effects most studies focused on shipping and environment follow a specific thematic rather than a global approach. We think that what best describes this project is its innovative characteristic of giving a general and broad outlook about the chain of causal relationships noxious effects pollutants from shipping provoke and by describing an alternative marine fuel to counteract those effects, while at the same time people were asked about their view in face of such problematic issues. By eliciting an approximate price people are willing-to-pay for a better air quality and climate change mitigation strategy by means of contingent valuation approach to measure their preferences – empirically documented through the elaboration of a Social Cost-Benefit Analysis -, we think our contribution for the field of social and environmental sustainability studies related to shipping, by means of a social-economic approach, was achieved. The major findings are presented below:

1 – While most field-related studies contribute solely for a single field of knowledge (e.g. epidemiological studies, climate change, noxious pollutant effects from transport modes on exposed population, technical and/or economic feasibility of alternative fuels), this thesis enlarges this view by trying to bring most of them together. This can be considered as a holistic and quite new approach;

2 – Notwithstanding the harshness of the challenge, roughly some 48 months of intense work dedicated to the mission, the main goal was achieved, albeit some questions still need to be better clarified. Certain assumptions have to be deeper understood and some gaps need to be filled, as long as pertinent data collected by institutional agencies enable it as such. A more sophisticated CBA would also take into account, among other things, damage costs to other receptors: Ocean acidification and eutrophication, damages to

ecosystems fauna and flora and damages to cultural monuments, for instance. The design of the CBA itself and the related costs and benefits has to be made more precise. Also to validate the conclusions, extended studies with large sample of respondents are needed;

3 – Quantification methods here depicted are not to be seen as the state-of-the-art methodology but rather as a starting point to perform further deeper research. Even so, it allows having a view of the whole picture and it can provide policy-makers with a tool to understand the phenomenon and to support decisions concerning air quality, health and environmental issues vis-à-vis LNG as an alternative fuel;

4- For those users of the results here described, emphasis should be stressed in the way that uncertainties exist and certain assumptions were to be made. Nonetheless, even if some doubts persists about delicate questions as for example the intensity of the methane slippage or about aggregated costs in which our study was based, all results point to a satisfactory role LNG can play in the way to achieve a less carbon intensive shipping while at the same time it provides a better outcome for both people's health and the environment.

❖

Social-cost benefit analysis is a useful technique to decide if the total benefits exceed the costs. Costs and benefits are not always tangible or can be expressed in monetary terms. The main challenge thus is to monetise all or most of costs and benefits. This particular social cost-benefit analysis was a very difficult and challenging task to perform and extremely time-consuming process. However, since we were able to quantify almost all (or the greater part) of costs and benefits, the empirical robustness that findings require was achieved. One needs to carefully look to what extent it can be prejudicial to the society as a whole to impose, to economic agents by themselves, by means of less permissive legislation the obligation to adapt new technologies to achieve emissions caps. If we only rely on market conditions ignoring the support from all stakeholders involved there is no way to change the game whereas noxious effects from pollution will rise. In order to rapidly introduce measures to mitigate air pollution and to diminish externalities produced by shipping, the strategy to follow cannot be exclusively market driven. In fact, this behaviour promotes business-as-usual when what is in need to be conquered is the opposite, a rapid downturn in emissions intensity. As already noted both domestic fleet and foreign ships on route within Portuguese waters burn essentially residual fuels. Unfortunately national and international literature does not exist for the sake of comparing the results obtained in this research, at least as far as we are aware of. Regretfully the outcomes cannot be confirmed or excluded and this peculiarity gives to the present study its novelty in academic terms. By the other hand, maritime-based policies to counteract this status quo are none so no measures are planned to be adopted in the near future.

15.2 Contribution to the field of LNG as an alternative fuel

Major contributions for the field bringing up by this thesis came from the voyage-based model where we compare energy performance of vessels equipped with mitigation on-board technologies vis-à-vis one LNG fuelled, anticipating an ECA area for the Iberia coast. Also the study carried on the viability of LNG supply facilities at a Portuguese port, even though its nature as an appendix to the thesis, can be seen as an innovative approach to the field since there is virtually no studies whatsoever about LNG as bunker fuel at national level.

Yet, major contribution is undoubtedly the social cost-benefit analysis performed based on society´s willing-to-pay rooted on social acceptability gathered by means of a questionnaire which openly asks people about their trade-off between the provision level of a public good – the breathing air – which characteristics are non-rivalry and non-excludability, and their disposable income, a cross-cutting approach indeed which is apparently innovative within the European energy agenda. By identifying issues of health and environmental risks from marine pollution, this will help to fill gaps in the knowledge of decision makers and policy makers. In this sense, this study can help design future policies related to marine fuels, highlighting the issue of LNG as a transition fuel, giving it the visibility it deserves. The adoption of LNG as an alternative fuel is a cost-effective solution in the context of "value for society" instead of "value for money" and is consistent with real-world efficiency gains. The applied research method used here seeks to find a solution for an immediate problem the society is facing and, although assuming Portuguese particularities, aims that findings can be reproduced and applied elsewhere.

Because of the innovative approach we took along this thesis, we were forced to compare the pluses and minuses from the adoption of such fuel by means of a heuristic process derived from readily accessible information. Since we have followed both an investigative approach to problem solving and an empirical study to ascertain its scientific validity, from the viewpoint of technical, operational, economic, social and environmental burdens and benefits, the final balance is arguably suitable for the adoption of LNG as an alternative fuel.

15.3 Limitations to the study

Although assuming Portuguese territorial and population particularities, it is intended that findings can be reproduced and applied elsewhere and this means, at first hand, that people in other locations should be inquired about their WTP and, at second, that particular country-level studies to evaluate benefits shall be performed. Of course the outcomes will vary as different are people's preferences and perceptions and country's particulars, i.e. population and merchant fleet size. In fact, some of the toughest challenges faced while elaborating the survey was to override the difficulty for message-passing be effectively apprehended by people about what do we mean with "willingness-to-pay" for a non-market asset. Some have thought they were asked to pay from their own pockets to repair something they were not directly responsible for damaging. While we sympathetically recognise their feelings, after all no one can discard its part of responsibility due to the simple fact that all of us belong to the society and society is driven by our wishes and consuming preferences; we are all self-interested *homo œconomicus*. Ethical consumers hoping to minimize their carbon footprint should be able to ask about not only the provenance of, - saying - his/her new pair of sneakers, but also should be able to capture the process in which it was produced. At the end we need to take into account the live cycle of economic goods and products, from the raw material extracted, the manufacturing stages and usage until its final disposal on a landfill as by-product (or worst, in the Oceans, while keeping the intention, whenever possible, that this waste can be recovered, reused or recycled). Those considerations were already present at the time the pilot-study was conducted and it was relatively simple to explain to the interviewee what those concepts and questions meant. Inversely to personal interviews, the online survey does not allow the detailed description of what is at risk, despite the effort spent to accomplish that task. Nevertheless, according to the questionnaire preamble it is assumed that the generality of the respondents have recognised the facts and the problem's origin and the mechanism to remediate it.

15.4 Future studies and research

In practice, future studies and research related to shipping should aiming a threefold use: First, by identifying issues of risks to health and to environment from airborne pollution, by comparing benefits from mitigation strategies and by giving birth to a discussion about the counterfactual, i.e. the lack of ongoing or expected policies, they should be useful for the design and implementation of future fuel strategies and to help to fill gaps in stakeholders' and policy-makers' knowledge; Second, they should contribute for people's awareness and knowledge about environmental and health issues related with the use of oil-based fuels in the transport sector; Third, cost-benefit analysis shall be of social component since this format is meant to provide the rationale for the need of state funding programs to incentive the adoption of alternative fuels and the promotion of sustainable transport, because for the sake of us all, environmental protection cannot rely exclusively on market strategies.

Another envisaged possibility is to apply this social approach as a benchmark to other transport modes and mobility related issues. By attaching all negative externalities to fuel consumption one can explicitly be aware of the spill over effect of a particular transport vis-à-vis inefficiency to allocated resources. By doing so, there might happen that a market anomaly is taking place which provides the justification for government intervention in the public interest.

As previously mentioned, the expression of the sample either in the pre-test or in the web questionnaire should be increased to better represent the population. It should be stated that in the case of personal interviews, these are very time consuming and incorporate additional expenses, especially when there is a need to travel and meet the interviewees in different places. Thus, to accomplish such a task, some funding process scheme must be implemented. With the monetary resources allocated, it will then be possible to develop an in-depth questionnaire and, finally, to compare the results. However, in this case, the challenge of capturing respondents is posed, which can eventually be achieved through an "*incentive*" strategy of some kind; shopping vouchers or similar rewards, which incorporates other expenses at the end. The methane slippage and the radiative forcing effect from methane emissions from LNG fuelled ships is a controversial question that deserves much more attention. A study that incorporates the slippage along the natural gas supply chain both from the so-called Algerian pipeline and from gas carriers unloading at Portuguese ports should contribute for a holistic approach on this subject.

One efficient approach for the field study could be to assess to which degree the imposition of an internationally harmonized tax levy on the carbon content can provide market incentives for a quick fuel switch by means of innovative technologies and processes to replace the current generation of oil-based fuels and associated technologies (e.g. Yaramenka et al. 2017). Because it seems reasonable that by raising the price of fuels by a carbon tax can provide strong incentives to reduce carbon emissions (e.g. by signalling ship-owners about which fuels use more carbon, thereby inducing them to move to low-carbon alternatives). A carbon tax raises fuel market price by the tax, times the carbon content of fossil fuels making ship-owners pay for the social cost of their decisions. To what extent a carbon tax would improve economic efficiency because it would correct for an implicit subsidy not paying for the costs of their activities from the use of carbon fuels is a topic worth to study.

Finally it should be stressed that, to the best of our knowledge, this is the first time that such a study was conducted at nationwide scale combining environmental, health and non-health impacts caused by airborne emissions even though the scope being limited to marine fleet emissions.

15.5 Discussion: policy implication for the society as a whole

At present, with the exception of the danger of widespread nuclear war, climate change is the biggest challenge for society as a whole. From the many causes of climate change, GHGs produced by maritime transport is a subject that is in need to receive greater attention from academicians and decision makers. Here, we have discussed the viability of the LNG as an alternative fuel to ships' engines based on the rules and principles for progressive decarbonisation for maritime transport. Since all industrial sectors need to contribute with their share for energy transition, the ultimate objective of this study was to verify to what extent the substitution of oil-based fuels by natural gas – until feasible technically and economically renewable energy sources are available -, can reduce GHG emissions, contribute for the phasing out of oil dependency and provides better air quality, taking into account social negative externalities. In fact, under the scenario of a widely decarbonised transport sector fossil gas can merely represent a bridge technology – to renewable energy sources must be given preference as quick as possible. Yet, for marine applications, there is no immediate alternative to the LNG to ensure the transition to a more sustainable fleet.

The adoption of LNG as a bridge fuel for the next decades – until feasible technically and economically renewable energy source(s) is (are) available – is given by the assumption that there is virtually no other alternative fuel at present that can replace traditional fuels at large scale without causing a disruptive chain reaction, both to economic agents and for the society. Logically and for the sake of a pathway towards progressive decarbonisation of the economies, the adoption of LNG as a bridge fuel does not preclude other low-carbon fuels or mitigation techniques to be implemented simultaneously, on the contrary. The main question is how to find a fuel to replace world's fleet fuels in a short period of time but taking into account all true benefits and costs borne with that option. The thesis results show that LNG is a cost-effective solution and it can be an efficient end-use fuel to assure the transition thus promoting people's health and minimising shipping footprint, at least for the next few decades ahead. For consumers, the LNG will improve their utility function regarding this option, an option that can also winning consumers by accentuating desirable climate, health and non-health qualities. People are mindful and willing-to-pay for to breathe a better air when confronted with the challenge of the upcoming environmental and climate-related damages. Both pre-study and the online questionnaire had the merit to make them aware of. The price people, and hence, the society, are willing-to-pay provides the accuracy and relevance of an empirical study to fully assess the economic desirability of an environmental change. Furthermore and albeit focusing on the issues of one single country this article embodied sufficient contributions to a new body of knowledge from the international perspective of LNG as a substitute fuel for marine purposes assuming that the methodology and findings can be replicated to other countries (e.g. Baltic, Black Sea countries), even though cost-benefit ratios will be dependent of country´s particularities.

A new insight brought by the way investment costs are those people are willing-to-pay opens a door to look more broadly the problematic. In fact, to change oil-based society's paradigm the transition needs support from all stakeholders and, in the public interest, public funds, the same is to say taxpayers' money. Obviously this issue lacks support from citizens who should identify the purposes and recognise the importance of such policy, and is dependent upon the level of knowledge from decision makers who should implement it.

By another hand, the idea of lowering carbon consumption by applying taxation on consumers can be obviously risky and no one should be surprised if the poorest of them begrudge paying for decarbonisation while they are struggling with stagnant wages, cuts to benefits and rising prices for food, transport and other essentials. As such, this is a delicate question that should be broadly discussed by experts, decision makers' and by ordinary people before policies are on place in order to avoid social discontentment.

16. FINAL CONCLUSIONS AND RECOMMENDATIONS

As like other fuels and technologies, at the beginning there is no great empathy or economic interest to change the rules of the game; it happened when coal was replaced by oil-based fuels and it is happening just now. The shift to modern marine diesel engines was a slow process taking more than 100 years (Endresen et al. 2008). The big difference is that before pollution was an image of development and is now seen as a major challenge; climate change, for instance, is one of the greatest challenges for the survival of the human race, and there is no question of utmost importance than that.

Mitigation technologies to reduce noxious effects from traditional fuels are already in use. Yet, since on-board cleaning technologies work primarily with use of distillate fuel, yields additional energy consumption on-board to operate further increasing carbon dioxide life-cycle emissions due to the extra energy required for the refining process and promotes business-as-usual. Thus, this is not a sufficient condition to be considered as a step-change for a long-term low-carbon perspective for shipping contribution to environmental and social sustainability and this can be seen as business-as-usual instead of drivers of change.

LNG can contribute to a significant reduction of shipping related air pollution improving health and non-health benefits. To reduce emissions along the supply chain – from well to propeller - biomethane as a raw material can be a wise solution beneficial from economic view in addition to the environmental view. Even tough methane impacts should be better clarified; benefit-cost ratios of an order of magnitude of almost eight times would require large but unlikely corrections in the quantification and monetization of costs and benefits to offset the NPV of the CBA. As such, the adoption of LNG as an alternative fuel is consistent with real-world efficiency gains.

Under the scenario of a widely decarbonised transport sector in 2050 fossil gas can merely be seen as a bridge technology – to renewable energy sources must be given preference as quick as possible. For a LNG fuelled fleet in the future, governments and European authorities - as well as local authorities - must cooperate and be committed with shipping and energy industries to ensure the transition to a more sustainable fleet. The European Commission supports the introduction of LNG, including by expanding the filling infrastructure. Nevertheless, private and semi-public initiatives are needed and welcome as well. All industrial sectors need to contribute with their share for energy transition. In shipping, it is now demonstrated that LNG can be an efficient end-use fuel to assure that transition; to reduce polluting gases emissions and thus promoting people's health and minimising shipping footprint. People are willing-to-pay for to breathe a better air and are concerned about environmental damages and climate-related challenges. Our questionnaire had the merit to make them aware of and the results are the living proof of their will when facing those challenges. For Portugal as a Nation with such knowledge and experience at sea, LNG as ship fuel, associated technologies and ancillary and subsidiary industries can contribute to the further development of maritime clusters. By another way around, LNG as a substitute fuel contributes for a process of creative destruction in the form this concept was originally enunciated by Schumpeter (Schumpeter, 1942). It means that, and first, at GDP level, this innovation will have a net value added or, at least, a neutral impact since those who work within the traditional bunker supply chain and eventually lose their jobs, can find employment at the new LNG infrastructure, as long as an initial training period is provided. Secondly, for firms, as the LNG turns into a widespread market is assumed that do not bankrupt firms, as they can operate a switch to this new market by itself; the old product as a consumption good simply turns itself obsolete. Finally, if in the future hydrogen technology in the form of fuel cells replaces the LNG, built infrastructure including tanks and pipelines can be used for the storage and transportation of hydrogen due to its adaptability for distribution and transportation of other fluids. LNG can also be used as raw material in the methane steam reforming process (or thermocatalytic decomposition), a method of producing hydrogen from hydrocarbons (Muradov, 2003).

The present thesis identifies a promising perspective for LNG application as an alternative fuel in shipping. The following recommendations address the establishment of a foundation for the introduction of LNG in the Portuguese seaport of Sines:

i) Infrastructure

- Consideration of a LNG fuelling station in the port of Sines, as a starting point for a future wider network of facilities by means of current available modalities (TTS; STS; LTS) in coordination with inland navigation (fluvial navigation);
- Synergies with other modes, e.g. road traffic, terminal vehicles and industrial plants should be persecuted;
- The national authorities should be expeditious with the licensing proceedings and permits as well as with the approval of technical and safety and security plans for LNG handling and bunkering;
- Those projects should be (partially?) European funded.

ii) Ship-owners

- Support of stakeholders in matters of the dissemination of LNG in both technical and operation procedures within the maritime industry;
- Subsidisation of the extra cost for retrofitting/new orders LNG vessels;
- Definition of criteria and conditions for funding;
- Establishment of a national agenda and a LNG-fund supported by carbon (or, otherwise NO_x taxes) and turn the collected taxes back to support measures for LNG as an alternative fuel in maritime transport.

iii) National Development Agenda for LNG

- Likewise, at EU level support for the dissemination of LNG as a marine fuel the adoption of a national development agenda with the same purposes is crucial to inform and contribute to the current debate at national level. Thus, we recommend a joint project for industry, policy makers and stakeholder's group's involvement to increase public awareness of LNG and the drivers and impediments behind it. Openness and transparency are assumed to be essential for public stakeholders such as media, NGOs, local governments, municipalities and the general public to understand basic aspects and considerations about gas industry. This will avoid seeds of discontent to irrupt and will also impede wrong ideas to gain pace (as it happens nowadays against offshore prospection along the Portuguese coast where people associate fracking to deep sea extraction)[90].

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[90] It is worth to say that NG obtained from unconventional methods is extracted onshore while by conventional methods it can be both onshore and offshore. Reservoirs are often located at depths greater than 1,000m; it has not yet been extracted offshore (Scottish Parliament Information Centre - SPICe).

APPENDIX

The LNG bunker market: an opportunity for Portuguese Seaports

Within the LNG industry business an enthralling opportunity for the Portuguese port of Sines is to build LNG bunkering supply facilities. The following piece highlights the business point of view but also include an energy sustainability option that results from the use of a cleaner fuel. As such, the ensuing lines can be seen as part of a position article but yet within the wider scope of the thesis to whom is linked since it covers the three pillars of sustainability: economic, social and environmental.

Why to choose the port of Sines as a first mover in the LNG market?

There are three major Portuguese ports that belong to the European Core Seaports Network: Lisbon, Sines and Leixões. From those, the port of Sines - a natural deep sea port located in the southernmost part of the country (37º 57'N, 08º 53' W) - offers the ideal conditions to receive a "tailor-made" supply infrastructure. In this sense, the following lines are meant to highlight Sines port major comparative advantages within the new energy paradigm era.

The first advantage is the lack of LNG infrastructure in the North-East Atlantic and in particular in the Iberian Peninsula. Although there are some risks: persistent oil prices below $100/barrel and moderate economic growth in Europe together with national budgetary constraints that urges for sound financial management efforts within the allocations agreed, Sines could obtain some advantages as a first-mover. This is a new market and the first comers will get the privileged position over competition and would have better prospects than those who came later.

Secondly, Sines port is the main Portuguese seaport in terms of port throughput within the national port system and it hosts the only Portuguese natural gas terminal, - a benefit in relation to other ports as the investment for LNG import terminal is already in place. In addition to this, the city of Sines also includes in its vicinity a major petro-chemical complex and the port itself has a contiguous area of logistics activities with plenty available land for infrastructure construction and ancillary activities. Therefore, the existing terminal could be expanded to include LNG bunkering and storage facilities following the steps: first made available truck bunkering, next ship-to-ship and finally land-to-ship.

Thirdly, at a regional scale port economic activity reinforces upgrading mechanisms of the maritime operations-based cluster as it favors port diversification. Further, from the standpoint of the Portuguese economy, the increased demand for new LNG fuelled ships can also bring economic benefits through the incremental revival of the national shipbuilding and ship repair industries (e.g. the Lisnave's ship repair yard located some 33 nm from Sines). Also, the geographic location at the crossroads of several east-west, north-south and diagonal shipping at the verge of the Atlantic and the Mediterranean lanes means that there is a potential market for present and future customers. On the other hand, drafts of -15mZH allow larger ship capacity both to unload and to bunker LNG (Figure A-1).

Figure A-1: Sines LNG terminal, storage tanks and terminal location.

Source: Author's collection and Port of Sines Authority.

Finally, even though port economic activity reinforces upgrading mechanisms of maritime operations-based cluster as it favors port diversification, since most of national firms cannot afford to invest in long term profit assets, LNG infrastructure and terminals ensures a basis for the attraction of foreign direct investment. Such port diversification could act as a pivotal force for further natural gas market investment (e.g. expanded facilities to receive U.S. natural gas for distribution within the European network thus diminishing the imports from other less reliable sources).

The EU Directive 2014/94/EU require that major European ports do have in place LNG supply facilities by 2020. Yet, at present there is still little knowledge at national level about LNG as a fuel, its characteristics, benefits and costs. Policy makers are thus in need to be assessed with all the scientific information and also need to be aware of the impacts for society of delaying such decisions. Port Authorities need to be adverted about the price to pay in terms of postponed decisions against competitors. It is most foreseeable that the gap in the supply chain is likely to be filled any time soon with players positioned at critical points of the LNG chain (e.g. with the launch of the EU funding Core LNGas Hive project)[91].

The SWOT analysis below display some weaknesses as well as threats to point out. SWOT analysis allows diagnosing ex-ante internal and conjectural effects produced by an LNG supply installation (Table A-1).

Table A-1: SWOT Analysis for the port of Sines LNG terminal.

Strenghts		Weaknesses	
1	Available land to build the infrastructure	1	South Atlantic and Mediterranean Sea outside an ECA region (presently)
2	Reduces both LNG terminal and pipelines sunk costs	2	Bay of Biscay and Iberian Coast outside an ECA region (presently)
3	Strategic location at the crossroads of major international shipping lanes	3	High initial investment. Payback period can be extensive
4	The LNG (as well as biomethane) as tradable commodities	4	Lack of regulation at national level for LNG bunkering activities
5	Port diversification strategy; contribute for economic decarbonisation	5	Small technical capacity in the manipulation of such an hazardous fuel
Opportunities		**Threats**	
1	Anticipation of SOx and NOx strictest limites from 2020 onwards	1	New alternative fuels (e.g. nuclear, biofuels, hydrogen)
2	Synergies with port and onshore NG market; port vehicles, trucks, buses, etc	2	Sudden interruption in the supply of NG (exogenous threats)
3	Strategic positioning within the LNG supply chain antecipating LTS facilities against near competitors	3	New players in the supply chain (other ports in the vicinity)
4	Access to EU funding within the CEF programme (including others)	4	Hazardous risks for people and materials around port areas
5	Contribution for the revival of national marine industry	5	Market fragmentation generate diseconomies of scale

Source: Author's elaboration.

[91] The aim of the Project is to develop a safe and efficient integrated logistics and supply chain to supply LNG fuel to the transport industry of the Iberian Peninsula.

Although the main purpose of this short assessment is to identify what to do and not so much who should do it, taking into account the Landlord Port[92] management model the intervention of two players is indispensable: the Port of Sines and Algarve Authority (APS) which acting as land owner should be receptive to new concessions to diversify port activities in a way to leverage the business margins from leased terminals and to increase port attractiveness, and; an agent interested to invest and deal in the maritime LNG bunker supply segment. This means that Port Authority would develop and enforce the regulations for LNG bunkering and make the decision as to where and how LNG bunkering operations would be carried out within the port area. Similarly, the operators should invest in infrastructure development – pipelines, storage, bunker delivery modalities and facilities. In this aspect, existing gas terminal can play an important role since major bunker players (it is expected that those firms that are already players in the supply of traditional bunkering fuels might have all the interest in the LNG supply as well) might be more willing to invest where there is already an existing LNG import terminal. In this sense, the investment in additional infrastructure is greatly reduced and might allow investors to have additional confidence in the LNG market. Of course, the existing NG terminal operator is the one who is better positioned to explore this new energy paradigm.

According to the Lloyd's Register (2012) study and despite being an industry that is still taking its first steps, the LNG as an alternative fuel for marine purposes opens a window of opportunities for ports. Yet, gas providers and bunker suppliers are unwilling to invest in the necessary infrastructure until there is sufficient demand. This is an egg-and-chicken problem and someone needs to give the first step: if the suppliers do not establish supply infrastructures, ships owners will not ordered or convert their fleets if there are no consolidated bunkering stations. Of course, if someone has to take the first step it seems right to be from the supply side. However, in order to have a gas network infrastructure and storage tanks to make possible LNG bunker operations they have to be built and money needs to be put up front. Initial projects for the development to support a supply network of LNG require the overhaul of infrastructure and will require National/European funding to offset some of the cost of LNG infrastructure.

[92] In the Landlord Port model the port authority owns the land and provides the superstructure; i.e. road networks, quay walls and jetties. The infrastructures, the terminals, are leased to terminal operators. The operator in turn invests in cargo handling equipment, hire port workers and negotiate contracts with ship-owners.

Investment risks

Recognizing the egg-and-chicken problem, demand will only fully materialize if adequate supply exists. Conversely the supply will only materialize if developers of the supply infrastructure are sure that the demand will materialize. This conundrum means that for investors, should they be public or private, significant investment risks will be faced. Yet, there are some mitigation procedures to face risks. For instance, construction risk where a project is built to time, cost and specifications, an EPC contract for engineering, procurement and construction that transfers all the cost and performance risks of constructing a plant to a contractor can be adopted[93]. In the case of the LNG supply back to back contracts could be a solution. Back to back contracts are contracts entered into by a party for the purchase of LNG from a supplier and its sale to a customer or customers such that the terms of each contract are carefully matched and the party in the middle then carries little or no risk. For the LNG be sold at a price that cover costs, for example, long term contracts indexed to HFO and MGO prices can be signed. As for the operational risks, i.e. the costs to maintain and operate an LNG supply terminal, the operator can opt by an O&M contract, that is, a contract for the operation and maintenance that transfers all risks of operating and maintaining a plant to a contractor (The Danish Maritime Authority, 2012). As for institutional risks and to name only few, taxation for instance is a matter of the utmost importance since marine fuels are exempt within the EU fiscal framework but there is uncertainty in including marine use of LNG as such. Another issue is that for LNG procurement, the market is characterised by long term contracts with thin liquidity, so further study is needed on the extent to which this prove a constraint to the development of medium and small terminals.

It is important to stress that it is not intended with this working document to present a comprehensive financial assessment to determine the economic interest for Portuguese ports of the LNG as maritime bunker *per se*, it is rather to reflect expectations of its possible realization. However, and knowing that between the time mediating the transposition of the European legislation for LNG bunkering into national legislation and specific suitability to port procedures - and time required for investment approval and

[93] An EPC contract is a particular form of contracting arrangement used in some industries where the EPC Contractor is made responsible for all the activities from design, procurement, construction, to commissioning and handover of the project to the End-User or Owner.

conclusion of civil works -, it is worth to say that for the port of Sines work in progress should have had already started long ago.

Market potential and economic feasibility

The overall number of ships powered by LNG is still limited but the vessels confirmed for delivery by the end of 2018 indicate a doubling of the fleet over the period 2013-2018. Although the number of units in service is still laughable compared to the world fleet this number is expected to grow significantly. Sines is located on the Atlantic façade where an important part of world maritime traffic gives potential demand as primary market for LNG bunkering whose growth forecasts around 75% between 2020 and 2030 only for European SECA region. The Danish Maritime Authority foresees that in order to meet this demand, more than 40 small scale LNG terminals will have to be established throughout the European SECA in 2015.

The viability and cost structure of a multilevel project like this is strongly correlated with current and potential demand. The traffic passing along the coast is however, a good indicator and serves as a proxy for market potential. On the side of acquisition price the supply cost is much lower compared to traditional fuels, which impacts the resale price and offers a comfortable margin to the dealer agent. Relying on global values for LNG compared with other fuels, we conclude that acquisition costs are expected to be much lower than the acquisition costs equilibrium for project's feasibility. The average IRR of investments should be below 12%, which corresponds to a payback time of about eight years, for achieving a competitive retail price (Danish Maritime Authority, 2012). On the side of the current and potential demand and with regard to mainland ports, Sines displays the higher number of ships/gross tonnage ratio amongst national ports, i.e. greater rotation of ships and capacity of tanks. Yet, and in order to deepen the knowledge of such innovative technology, a comprehensive study analyzing the economic, financial and commercial aspects, technical implications, legal action framework and operational requirements, risk analysis, demand forecast and environmental impact for such a project including possible synergies with land-based demand is in need[94]. The development of potential demand scenarios lacks a proper study for a long-time horizon. Knowing that there are no such studies, quantitative or cost-effective analyses must rely on EU funds,

[94] Indeed, port vehicles and land-based activities can be added up to geographically allocated demand.

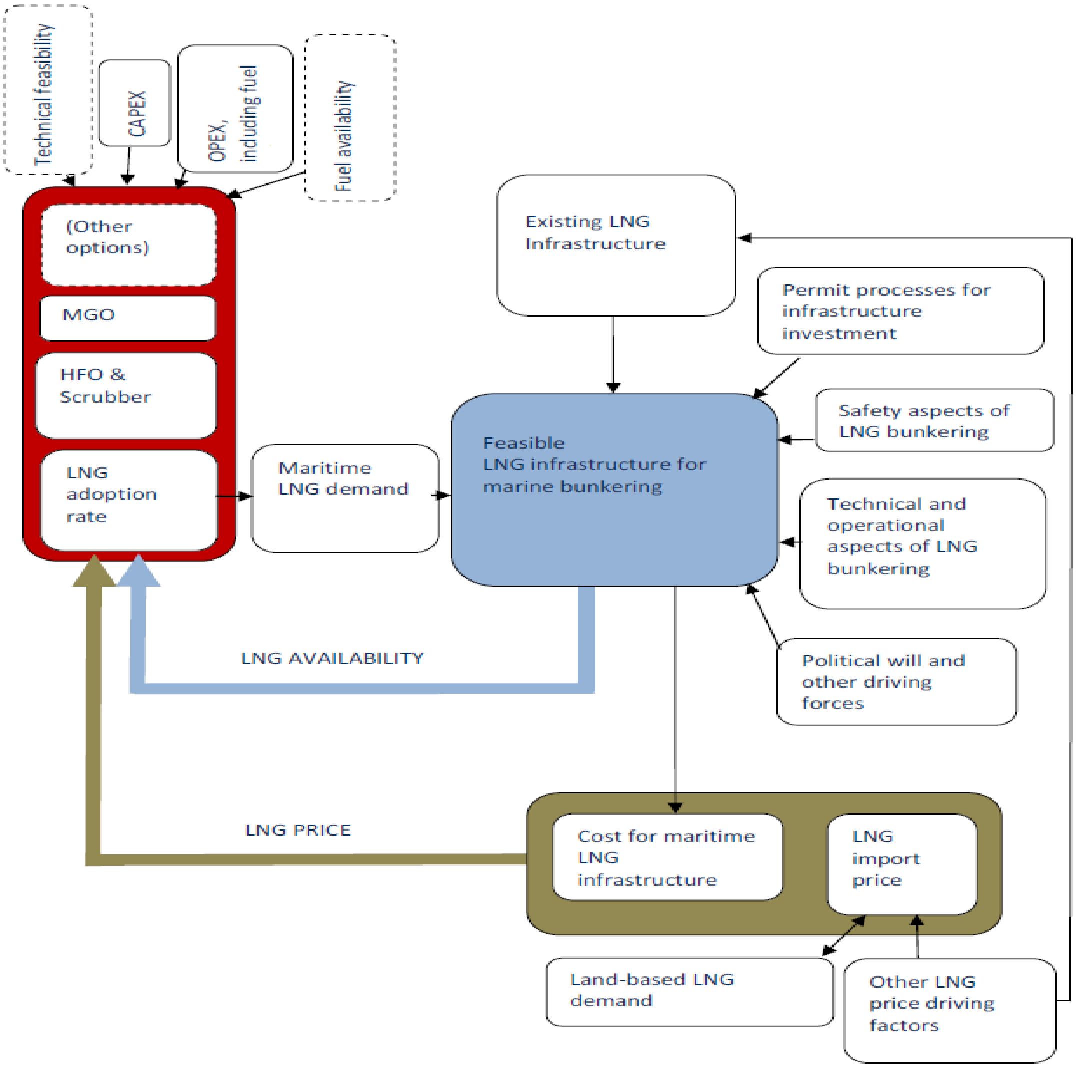
such as some others already did, (e.g. Brofjorden port on the west coast of Sweden, which call for proposal to the TEN-T funds have granted the amount of 23.1 M€ covering 30% of project costs). The feasibility study itself can receive financial support from the EU. The operational capacity and market potential will be further explored as the correlation between the know-how and business portfolio rises. The degree of achievement will be higher as the participation of the players surmount. Investment in LNG bunkering infrastructure is expected to be private sector financed in the main although some port authorities are expected to initiate projects and there is a case for public financial support in the early stages of network development. While private investors (e.g. terminal operators and gas suppliers) will be needed, for a LNG bunkering process business model be considered, and in order to mitigate the principal risks those investors face, institutional barriers shall be removed. Accordingly, as it was stated earlier, National/European help for the implementation is a key question to be addressed. Other stakeholders whatsoever should be included: Sines municipality, ONGs and general public must accompany the process in a transparent way.

The LNG infrastructure business plan

The LNG business plan can be analysed in two interlinked parts: the maritime demand and the maritime supply chain infrastructure. According to the Danish Maritime Authority (2012) study which procedures we adopt here, there will be “hard” aspects such as terminals and bunker vessels and “soft” aspects such as regulatory and industry standards. Hard aspects are, for example, the costs for maritime LNG infrastructure, assumed to be those that constitute the larger share of the overall costs. Other major costs are those for the ship supply (increasing costs are expected in the case of pipeline flexible hoses for land-to-ship supply) and transport costs largely determined as a function of the distance between the export terminal and the receiving terminal. Soft aspects regarding different rules and regulations applying for hinterland perspective and sea perspective, laws, by-laws, guides, standards and procedures for design, construction, operation and maintenance can be more likely to be time consuming. The border between maritime and onshore regulations often lies at the quayside, where the vessel and equipment fall under sea-based restrictions while other processes fall under hinterland regulations (DMA, 2012). Soft aspects also include the care need to be taken to avoid interference with other activities in port areas.

From the ship-owners' point of view and how LNG can become a vital option for them, the red box in the left upper corner of Figure A-2 represents the ship-owners' compliance strategies. The feasibility study must be centred on balancing demand and supply of LNG as is illustrated by the figure. Two most important factors determining the demand is the cost and availability, also compared to other options than LNG. A brown and a blue arrow illustrate these two aspects.

Figure A-2: Methodological approach for an LNG project feasibility study.

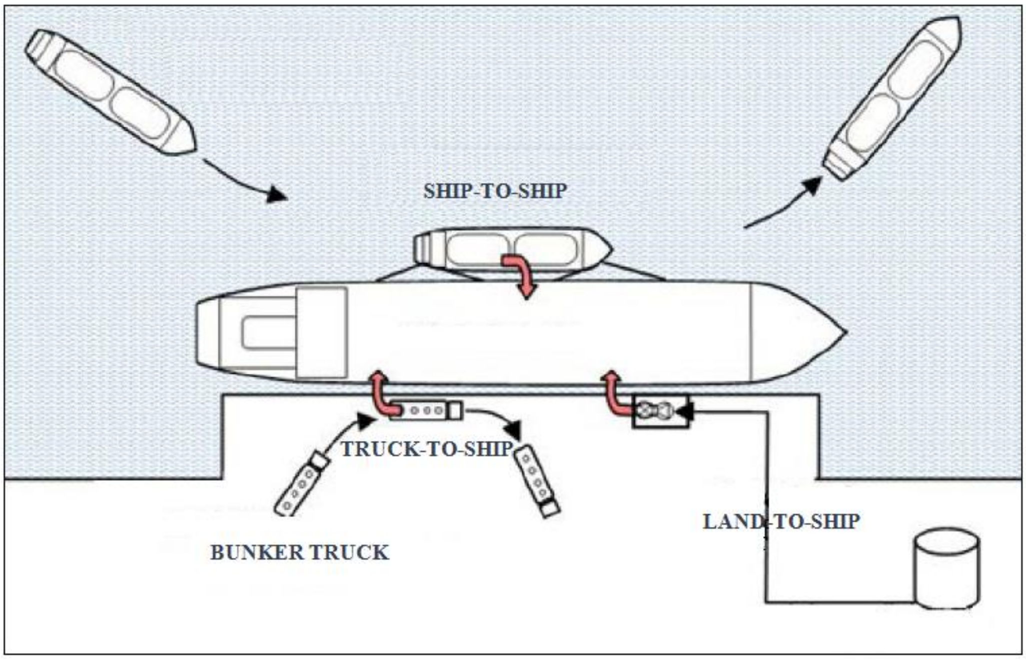


Source: The Danish Maritime Authority – DMA (2012).

Modalities and operations

The LNG supply chain for land terminals implies the existence of infrastructures such as a port terminal, storage tanks and vessels supply. For vessels supply there are various solutions that can be used in parallel and are complementary in situations where, for example, there is a peak in LNG demand in the terminal or various types of vessels to supply: Truck-To-Ship (TTS up to 200m3); Ship-to-ship (STS for capabilities above 100m3) and Land-To-Ship (LTS, pipeline for large volumes). The pathway for LNG implementation at the port of Sines should to progressively expand the range of LNG bunkering modalities as the market grows, i.e. the steps would be the following: first made available truck bunkering, next ship-to-ship and finally land-to-ship. However, land-to-ship operations, although likely to occur when ships load/unload requires a comprehensive assessment of operations security risk. LNG containers delivered on-board to be used as fuel supply or used as a fuel tank or used for intermediary storage and transport may also become an important solution for on-vessel consumption and as a complement for LNG market investors (The Danish Maritime Authority, 2012).

Figure A-3: LNG bunkering modalities.



Source: Adapted from The Danish Maritime Authority – DMA (2012).

Competition in close proximity: wait to see?

The Working Group of the International Association of Ports and Harbours - World Ports Climate Initiative (WPCI), has launched a website that provides detailed information on the use of LNG as a marine fuel, technical conditions, fuel facilities, and LNG tankers and how to write a business plan. The main results of the working group are a set of bunkering checklists in order to benefit the ships within the LNG supply chain in different ports. Thanks to these harmonized lists, owners calling at various ports will no longer be confronted with different rules and regulations for LNG. From those Port Authorities adhering to this initiative, Portuguese ports are all absent (Figure A-4). At present, the construction of LNG bunker infrastructure are being considered or planned by close competitors: Spanish ports like Ferrol, Gijón and Santander, are already preparing to receive such installations even though they are small/medium scale facilities. It is most foreseeable that the gap in the supply chain is likely to be filled any time soon with players positioned at critical points of the LNG chain.

Figure A-4: LNG planned facilities in the Iberian Peninsula.

Source: Adapted from WPCI.

Although Atlantic Iberian waters and ports are not included in an ECA, such region is likely to be defined in the near future. This will force ship-owners to choose between mitigation technologies, marine diesel/gasoil or LNG in order to comply with sulphur and nitrogen oxide regulations. If Atlantic ports do not have by that time any LNG filling facilities, it is most expected that the northern range ports will once more improve their comparative advantages compared with those from the south. Once the LNG filling station network is established then it can be expected that some degree of competition will be established between filling stations, and that competition will happen outside Iberian waters. Thus the urgency from the business viewpoint to promote LNG at national level in order to take advantage of the limited choice of LNG fuelling points. But a small scale facility in Sines is not a truly option. In fact, for an individual port, it is in very few cases feasible to invest in LNG terminals based on solely the LNG demand from ships specifically calling at that port. If there is land-based demand, and if ships from other nearby ports can be served via bunker vessels or trucks, feasibility is more likely (Danish Maritime Authority, 2012). Thus, the recommendation is that if an LNG infrastructure is planned to be set on place at Sines, the business plan should contemplate a more ambitious investment as part of an effort to reach customers from nearby ports and thus creating the conditions for external economies of scale to happen. Otherwise if the vision is a short sighted, rising costs and decreasing output could rather origin diseconomies of scale instead.

Final remarks

The Trans-European Transport Network (TEN-T) launched a challenge to the core 83 European ports to made available maritime LNG bunker facilities until 2020: "*The 83 maritime ports of the TEN-T Core Network are the primary locations for the use of LNG in shipping*" (EC-SWD (2013) 6 final). The port of Sines is part of this core network. On the other hand, European funds are available through the Connecting Europe Facility (CEF) whose "call for proposals" (applications for project proposals) published in September 2014 grant to public and private promoters that want to start using LNG be eligible to apply for financial support under specific conditions. The financial envelope under the TEN-T, Connecting Europe, comprises more than 26 billion€ to be allocated to multi-year projects between 2014 and 2020. 250 million will be earmarked to projects that fall within MoS (Motorways of the Seas), which includes among others, the development of alternative fuels to ships, in particular but not limited to LNG, and including fuel infrastructure (EC-C(2014) 1921 final, Section 3.3.4). According to the EC, the estimated investment value for each marine bunker installation in those 83 core ports varies between 36,8M€ and 76,3M€ depending on the option of intervention policy (EC-SWD (2013) 6 final). Still, in paragraph 4 policy option the comparison between the benefits of choosing the deployment of the infrastructure and the costs of other possible policy results in ratios above 1.5 in all Member States, yet it does not take into account benefits on oil reducing dependence, increased competitiveness or the better functioning of the internal market.

The introduction of LNG as a marine bunker in the port of Sines can act as a pivotal for regional development promoting port attractiveness and contributing for the creation of a new innovative market, while reducing the environmental impacts from conventional fuel oils. LNG as a marine bunker constitutes at this very moment a niche market. Not excluding any of the other Portuguese core ports from the introduction of small/medium-scale installations, this study highlights the favourable conditions the port of Sines has to receive maritime bunker facilities - works of art, equipment and bunkering procedures. In fact, the existence of an LNG terminal with -15mZH draft allowing the berthing of large LNG carriers makes the difference between its counterparts for the installation of bunkering modalities. Sines LNG jetty terminal allow berth for ships up to 300m long and totals capacity to up 390.000m^3 (177,000 tonnes). Thus, the port of Sines, can reinforce its key position as a national energy hub port enhancing its pivotal nature for regional economic development. Moreover, there is plenty land available to build the necessary infrastructure and other due complementary and ancillary areas, perhaps the best comparative asset this port has to offer regarding other national and even Iberian ports. Thus, if a tendering procedure for a terminal operator concession is to be launched the incumbent should follow the concept of energy hub where in addition to LNG bunker, station for filling trucks, buses and cars should be contemplated.

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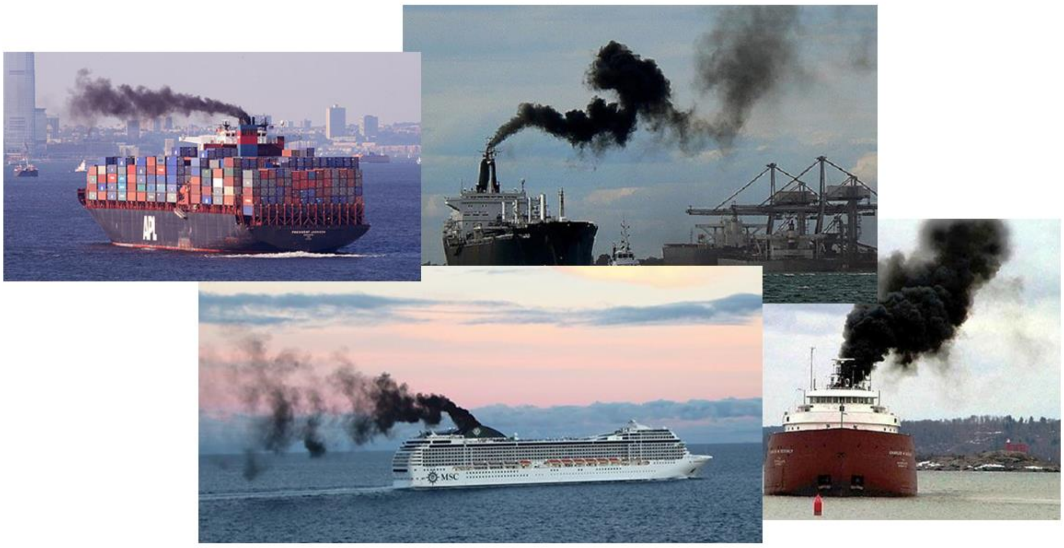
ANNEXES

ANNEX 1

The pre-test/pilot study (ancillary aids)

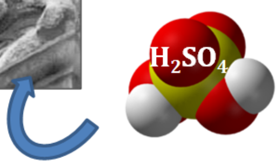
Combustíveis Marítimos Tradicionais (Fuelóleo e Diesel)

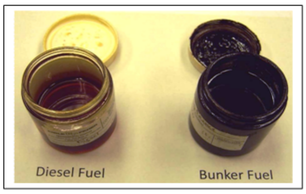


Combustíveis Marítimos Tradicionais

Dióxido carbono (CO_2) Gás Efeito Estufa (GEE);
Dióxido enxofre (SO_2) precursor de chuvas ácidas;
Óxido azoto (NOx) precursor do Ozono;
Micropartículas inaláveis e Metais pesados

Efeitos causados em estátuas de mármore devido às chuvas ácidas.





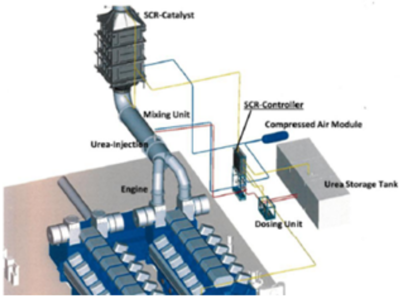
Apenas o asfalto e o betume para impermeabilização são mais espessos do que o bunker oil

Emissões potenciam acidificação, eutrofização, danos na saúde humana e formação de ozono fotoquímico.

As emissões dos navios estão previstas aumentar entre **102%** a **193%** em relação aos níveis de 2000 até 2050.

Tecnologias de Mitigação de Emissões

Scrubbers são dispositivos mecânicos que reduzem o SO_x e as micropartículas emitidas pelos motores dos navios
.
Mas as reduções de NOx são negligenciáveis e é necessária a instalação de um dispositivo de **redução catalítica**



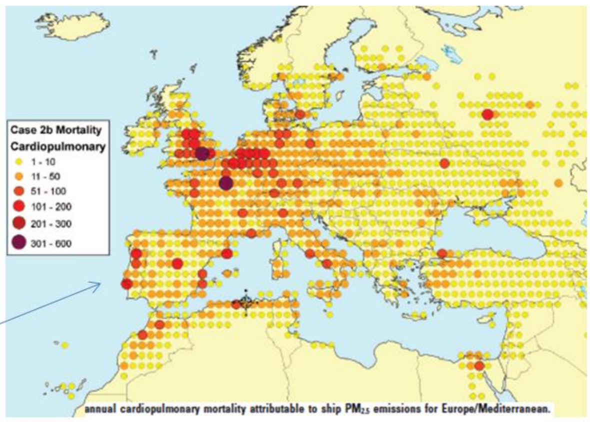
Mas estes dispositivos não são alternativas para uma economia de baixo-carbono e podem impulsionar o "business-as-usual!

PHASING-OUT das Economias baseadas no Petróleo

Principais contributos do GNL Marítimo

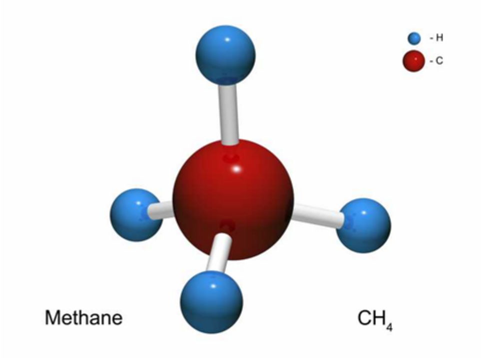
- Redução dos **GEE**
- Gradual **descarbonização das economias**
- Redução das doenças **crónicas** e **agudas**
- Redução da **mortalidade prematura**

Estima-se que as micropartículas produzidas pelos navios sejam responsáveis por **60.000 mortes/ano** por doenças cardiopulmonares na Europa



Milhares de navios cruzam anualmente a costa portuguesa. Embora as emissões sejam produzidas em mar alto, os seus efeitos são sentidos em terra devido aos ventos predominantes

O Gás Natural Liquefeito (GNL)



O principal componente é o **metano** (CH4);
É um combustível mais limpo que os tradicionais.

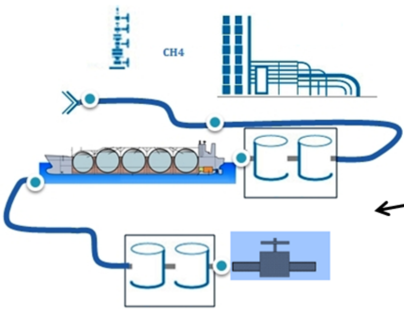
Nos navios, o GNL é o GN armazenado como líquido a **-162 ° C** em tanques criogénicos

O **enxofre** e as **micropartículas** são eliminadas a 100%;
CO_2 a c. 25% e o **óxido azoto** c. 90%.

É abundante, barato e a tecnologia está provada.

tivado o seu uso como combustível marítimo alternativo, por parte da **Comissão Europeia**.

As **infraestruturas** de armazenagem, liquefação, regaseificação e transporte do GNL podem ser futuramente usadas para o Hidrogénio



Sem alternativas no curto-médio prazo ao GNL como combustível marítimo

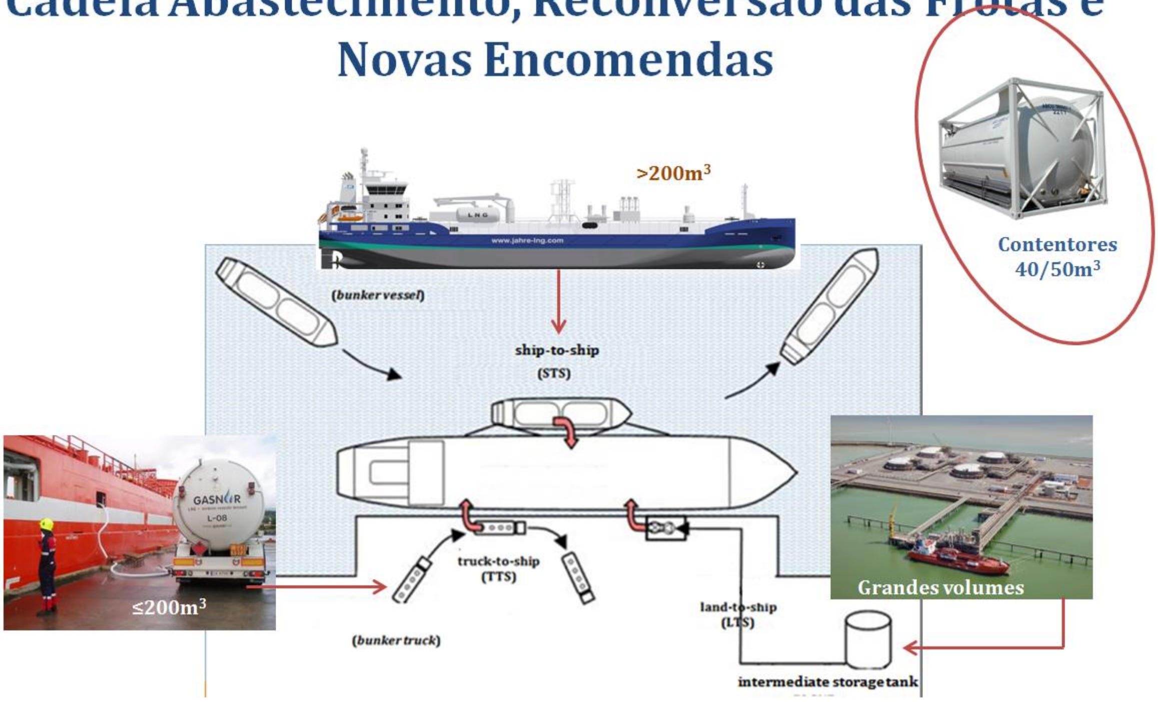
Nuclear *(perigoso)*

Biofuels *(exigem largas parcelas de terra cultivada)*

Hidrogénio: *(fraca capacidade armazenamento células elétricas)*

-Methane slip (emissões de metano não queimado são aprox. **25 x mais elevadas em termos de Gases Efeito Estufa**)

Cadeia Abastecimento, Reconversão das Frotas e Novas Encomendas



O esforço financeiro do investimento a realizar é considerável, no entanto os *benefícios* são esperados serem muito superiores aos custos!

ANNEX 2

The pre-test/pilot normalised questionnaire filled out by the interviewees

AbERTA
www.uab.pt

SHIPPING AND SUSTAINABILITY
LIQUEFIED NATURAL GAS AS AN ALTERNATIVE FUEL:
SOCIAL COST-BENEFIT ANALYSIS

Paulo Jorge Pires Moreira
Ph.D. Thesis in Social Sustainability and Development

PRE-TEST/PILOT SURVEY

Name (*Nome*):________________________________

Age (*Idade*): [18-34] [35-54] [55-69]

Academic qualifications (*Habilitações académicas*): [Até 9.º] [9.º-12.º] [Sup.]

Occupation (*Profissão*):________________________

Residence from Ocean (km) (*residência a km do Oceano*): _________________

Gross <u>monthly</u> income group, if it applies (*remuneração bruta* mensal, *se aplicável*):

€500,00 - €1000,00 [1] € 1000,00 - € 2000,00 [2] > € 2000,00 [3]

Question:
The respondent is willing to pay hypothetically, a 3 (three) year **annual** tax for a better air quality in accordance with what has been explained in this study?
*(O entrevistado estaria disposto a pagar <u>hipoteticamente</u> uma taxa/imposto **anual**, durante 3 (três anos) por uma melhor qualidade do ar em conformidade com o que foi explanado neste estudo?)*

Yes *(Sim)* [ ] No *(Não)* [ ]

If "Yes", how much would you willing to pay (in Euros)?
(Se respondeu "Sim", diga quanto estaria disposto a pagar (em Euros)

€ _____ , 00

Thank you very much (Muito obrigado)

Date (*Data*):

ANNEX 3

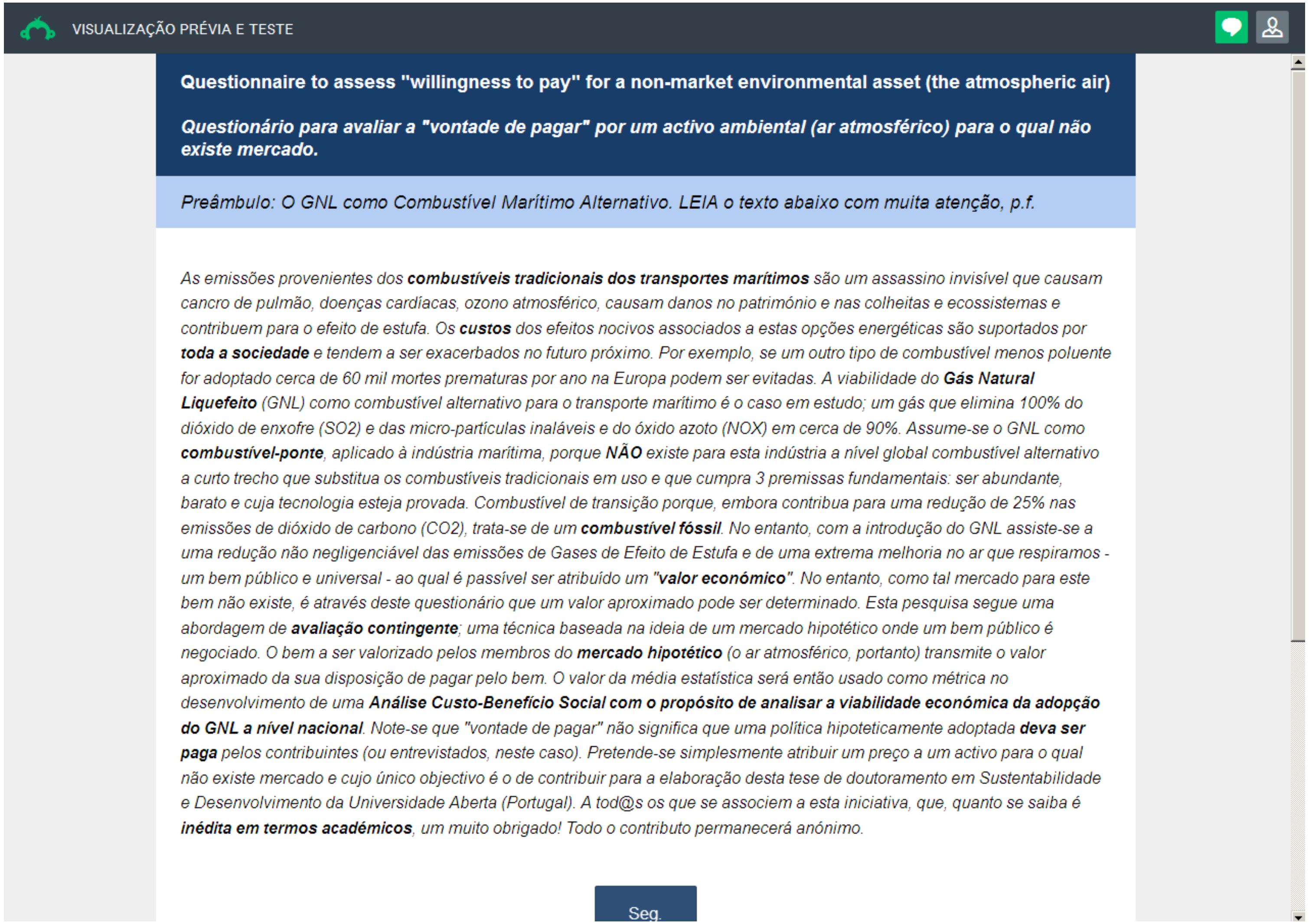
Sample representativeness vis-à-vis Population

		Sample (%)	PORDATA (%)
Gender	Male	47.9%	48.0%
	Female	52.1%	52.0%
		n= 261	*N= 7016000*
Age	18-34	23.8%	28,3%
	36-54	43.3%	44.0%
	55-69	33.0%	27,6%
Education	Incomplet.	20.3%	20.4%
	Compl.	23.0%	20.4%
	Grad.	38.7%	10.5%
	MSc/PhD	18.0%	6.0%
Occupation	Student	13.0%	7.4%
	Unempl.	8.0%	10.0%
	Employed	67.4%	70.0%
	Retired	11.5%	9.4%
Income*	500-1000	26.8%	39.0%
	1000-2000	33.7%	26.0%
	>2000	25.3%	11.1%
Location	North	25.7%	35.6%
	Center	39.5%	41.2%
	South	29.1%	23.2%
	Other	-	-

* 37 of the respondents (14%) didn't answered this question.
Therefore it is not possible to ascertain the true values.

ANNEX 4

Questionnaire to elicit WTP



VISUALIZAÇÃO PRÉVIA E TESTE

Questionnaire to assess "willingness to pay" for a non-market environmental asset (the atmospheric air)

Questionário para avaliar a "vontade de pagar" por um activo ambiental (ar atmosférico) para o qual não existe mercado.

Preâmbulo: O GNL como Combustível Marítimo Alternativo. LEIA o texto abaixo com muita atenção, p.f.

*As emissões provenientes dos **combustíveis tradicionais dos transportes marítimos** são um assassino invisível que causam cancro de pulmão, doenças cardíacas, ozono atmosférico, causam danos no património e nas colheitas e ecossistemas e contribuem para o efeito de estufa. Os **custos** dos efeitos nocivos associados a estas opções energéticas são suportados por **toda a sociedade** e tendem a ser exacerbados no futuro próximo. Por exemplo, se um outro tipo de combustível menos poluente for adoptado cerca de 60 mil mortes prematuras por ano na Europa podem ser evitadas. A viabilidade do **Gás Natural Liquefeito** (GNL) como combustível alternativo para o transporte marítimo é o caso em estudo; um gás que elimina 100% do dióxido de enxofre (SO2) e das micro-partículas inaláveis e do óxido azoto (NOX) em cerca de 90%. Assume-se o GNL como **combustível-ponte**, aplicado à indústria marítima, porque **NÃO** existe para esta indústria a nível global combustível alternativo a curto trecho que substitua os combustíveis tradicionais em uso e que cumpra 3 premissas fundamentais: ser abundante, barato e cuja tecnologia esteja provada. Combustível de transição porque, embora contribua para uma redução de 25% nas emissões de dióxido de carbono (CO2), trata-se de um **combustível fóssil**. No entanto, com a introdução do GNL assiste-se a uma redução não negligenciável das emissões de Gases de Efeito de Estufa e de uma extrema melhoria no ar que respiramos - um bem público e universal - ao qual é passível ser atribuído um "**valor económico**". No entanto, como tal mercado para este bem não existe, é através deste questionário que um valor aproximado pode ser determinado. Esta pesquisa segue uma abordagem de **avaliação contingente**; uma técnica baseada na ideia de um mercado hipotético onde um bem público é negociado. O bem a ser valorizado pelos membros do **mercado hipotético** (o ar atmosférico, portanto) transmite o valor aproximado da sua disposição de pagar pelo bem. O valor da média estatística será então usado como métrica no desenvolvimento de uma **Análise Custo-Benefício Social com o propósito de analisar a viabilidade económica da adopção do GNL a nível nacional**. Note-se que "vontade de pagar" não significa que uma política hipoteticamente adoptada **deva ser paga** pelos contribuintes (ou entrevistados, neste caso). Pretende-se simplesmente atribuir um preço a um activo para o qual não existe mercado e cujo único objectivo é o de contribuir para a elaboração desta tese de doutoramento em Sustentabilidade e Desenvolvimento da Universidade Aberta (Portugal). A tod@s os que se associem a esta iniciativa, que, quanto se saiba é **inédita em termos académicos**, um muito obrigado! Todo o contributo permanecerá anónimo.*

Seg.

VISUALIZAÇÃO PRÉVIA E TESTE

Questionário para avaliar a "vontade de pagar" por um activo ambiental (ar atmosférico) para o qual não existe mercado.

Question 1 - *Questão 1*

Rationale: To achieve a better air quality by reducing ships emissions, new engines and new ships are needed. The costs for retrofitting or for new orders from the European maritime fleet should be borne equitably by all stakeholders: governments, ship owners, taxpayers. In this sense, if funds are not granted by the European Union or by national governments and, for example, the maritime industry is forced to proceed to the adoption of new fuels through coercive measures, these costs will eventually be reflected in the price of freights and at the end, on the cost of goods on supermarket shelves. One way or another, taxpayers would end up having to pay for the improvement of air quality.

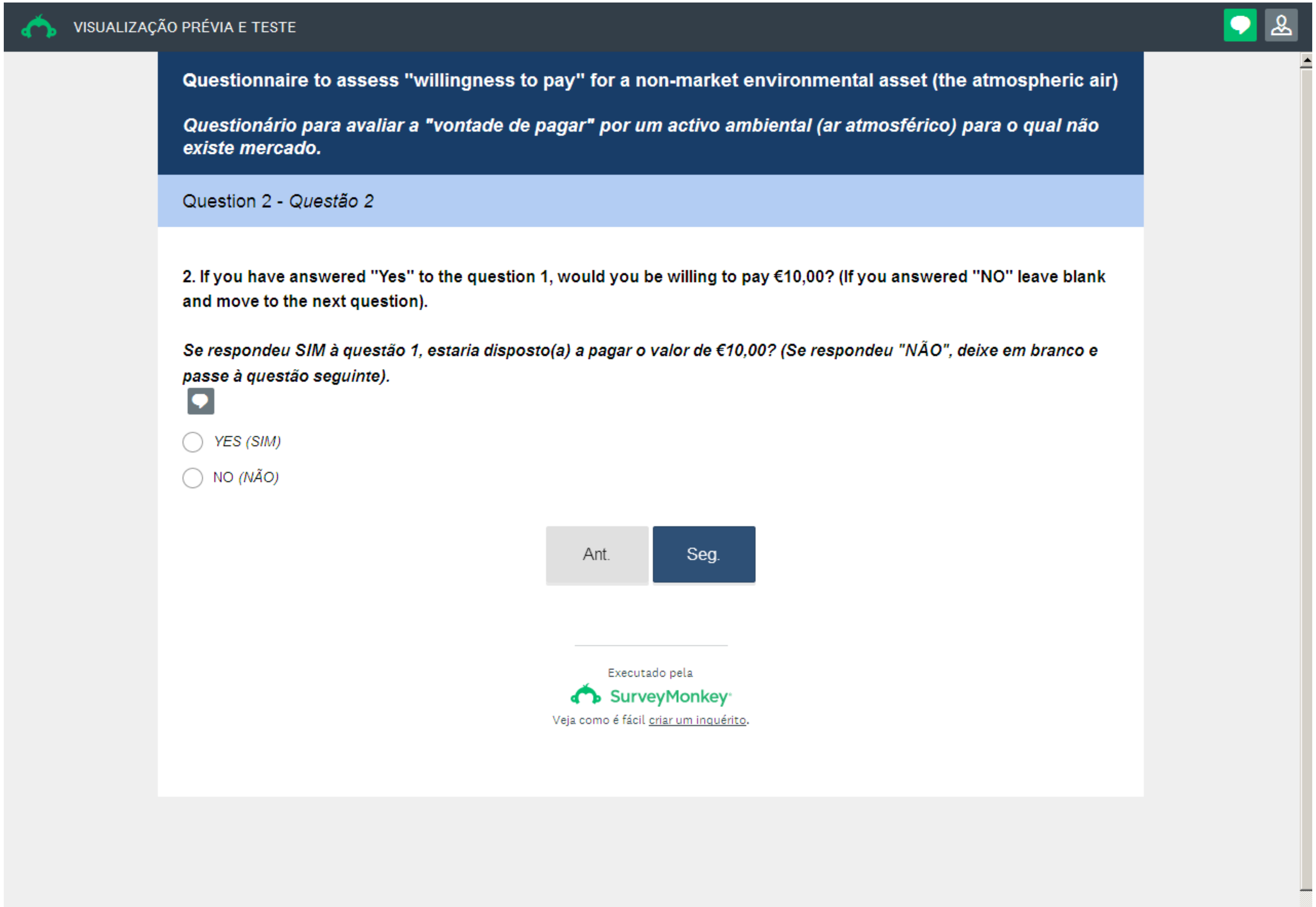
Razão lógica: Para alcançar uma melhor qualidade do ar reduzindo as emissões dos navios são necessários novos motores e novos navios.Os custos com a reconversão ou com novas encomendas da frota marítima europeia devem ser suportados, equitativamente, por todos os stakeholders: governos, armadores, contribuintes. Se não forem alocados fundos disponibilizados via União Europeia ou por parte dos governos nacionais e se, por exemplo a indústria marítima for forçada a proceder à adopção de novos combustíveis através de medidas coercivas, esses custos acabarão por se repercutir no preço dos fretes e, ao final, no custo dos bens nas prateleiras dos supermercados. De uma forma ou de outra, os contribuintes acabariam por ter que pagar pela melhoria da qualidade do ar.

*** 1. Would you be willing to pay an *annual* €3.00 tax during 3 (three) years as a counterpart for the introduction of Liquefied Natural Gas as a marine fuel in order to preserve / improve the quality of the air we breathe, in the manner described in this questionnaire, which rationale is given by the preamble of this Question?**

Estaria disposto(a) a pagar um imposto no valor anual de €3,00 durante 3 (três) anos como contrapartida para a introdução do Gás Natural Liquefeito de uso marítimo como forma de preservar/melhorar a qualidade do ar que respiramos, nos moldes descritos neste questionário, cuja base lógica é dada pelo preâmbulo desta Questão?

- YES (SIM)
- NO (NÃO)

Ant. Seg.



VISUALIZAÇÃO PRÉVIA E TESTE

Questionnaire to assess "willingness to pay" for a non-market environmental asset (the atmospheric air)

Questionário para avaliar a "vontade de pagar" por um activo ambiental (ar atmosférico) para o qual não existe mercado.

Question 2 - *Questão 2*

2. If you have answered "Yes" to the question 1, would you be willing to pay €10,00? (If you answered "NO" leave blank and move to the next question).

Se respondeu SIM à questão 1, estaria disposto(a) a pagar o valor de €10,00? (Se respondeu "NÃO", deixe em branco e passe à questão seguinte).

- *YES (SIM)*
- NO *(NÃO)*

Ant. Seg.

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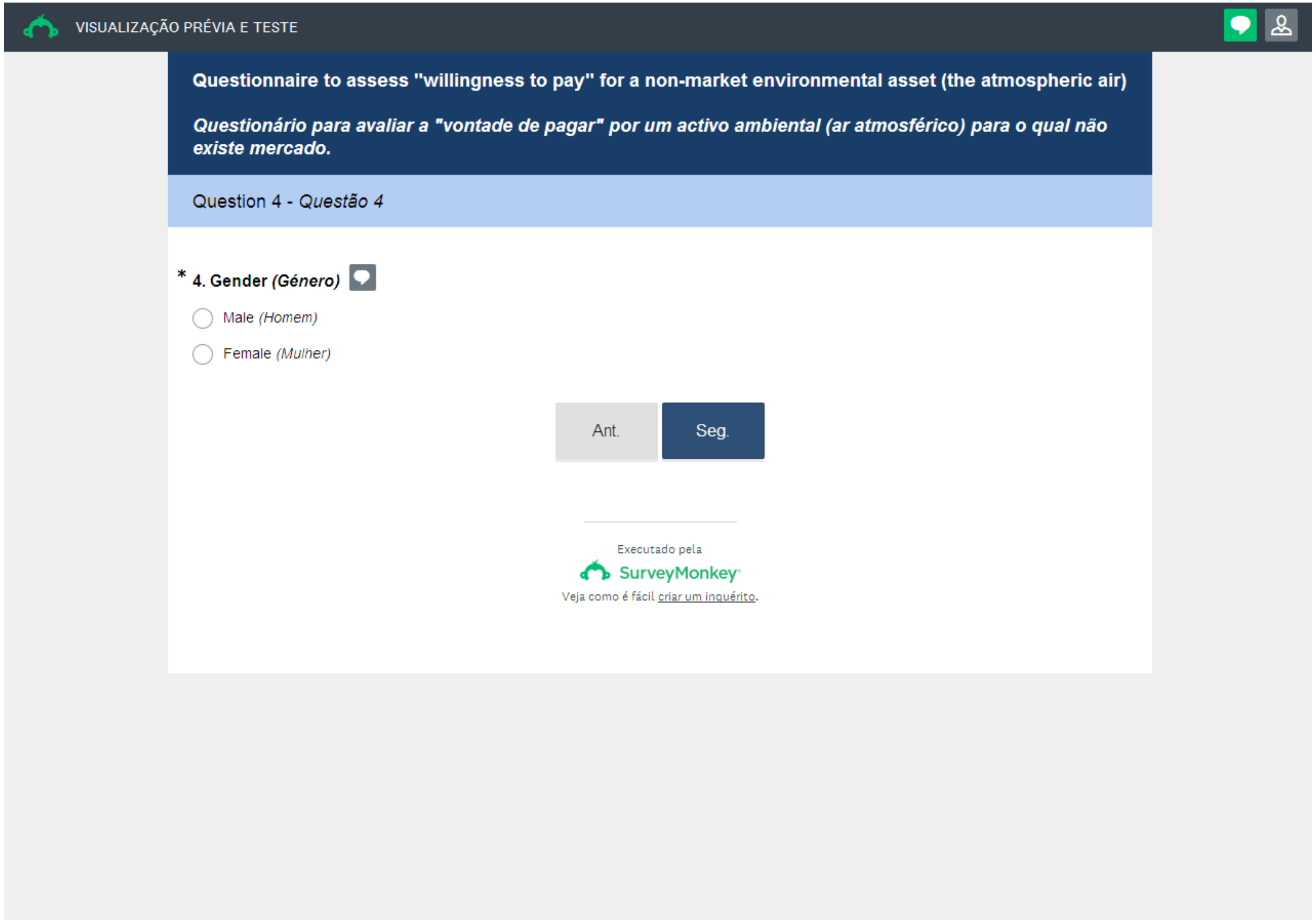

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Questionnaire to assess "willingness to pay" for a non-market environmental asset (the atmospheric air)

Questionário para avaliar a "vontade de pagar" por um activo ambiental (ar atmosférico) para o qual não existe mercado.

Question 4 - *Questão 4*

* **4. Gender *(Género)***

- Male *(Homem)*
- Female *(Mulher)*

Ant. Seg.

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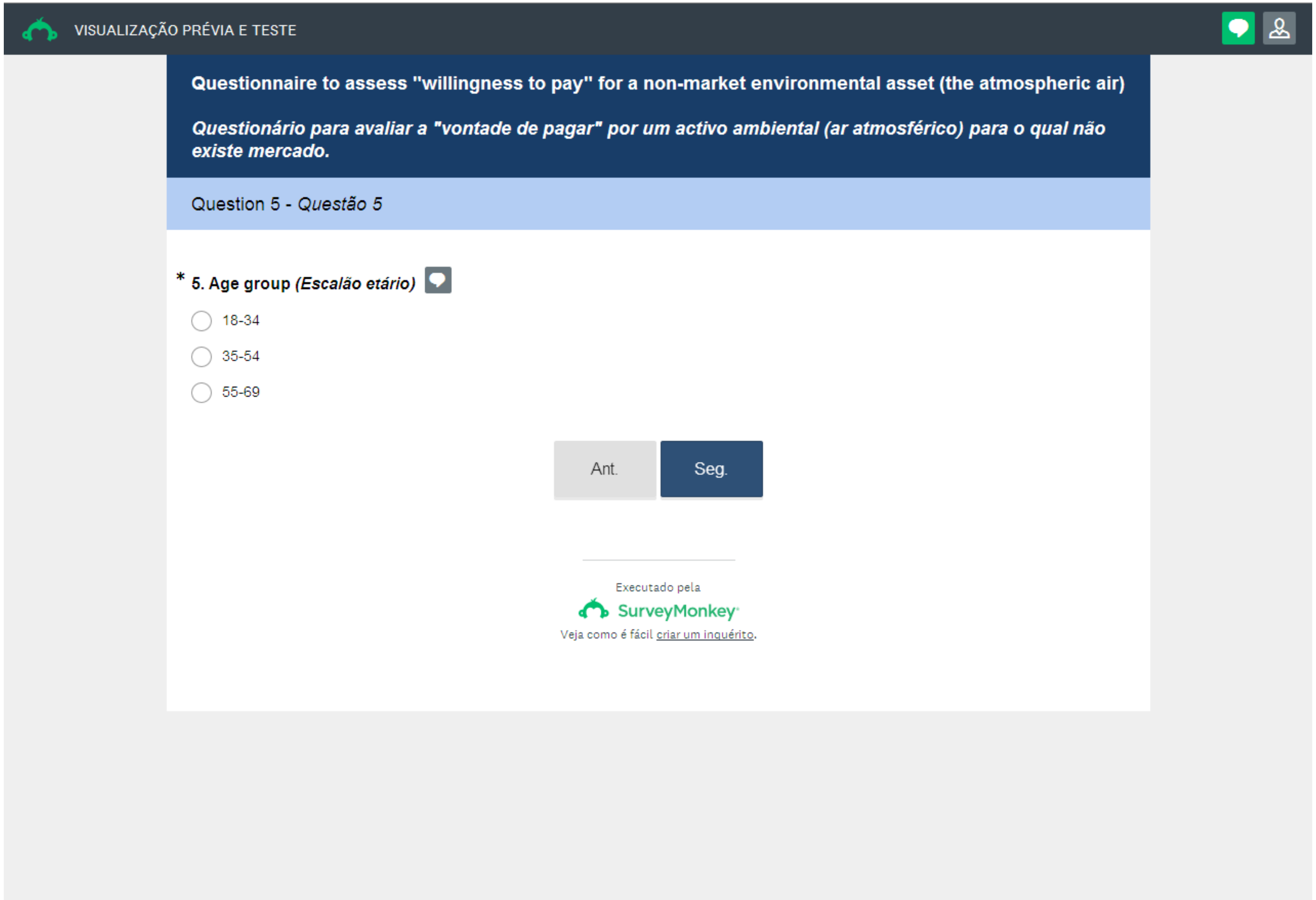

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Questionário para avaliar a "vontade de pagar" por um activo ambiental (ar atmosférico) para o qual não existe mercado.

Question 5 - *Questão 5*

* **5. Age group *(Escalão etário)***

- 18-34
- 35-54
- 55-69

Ant. Seg.

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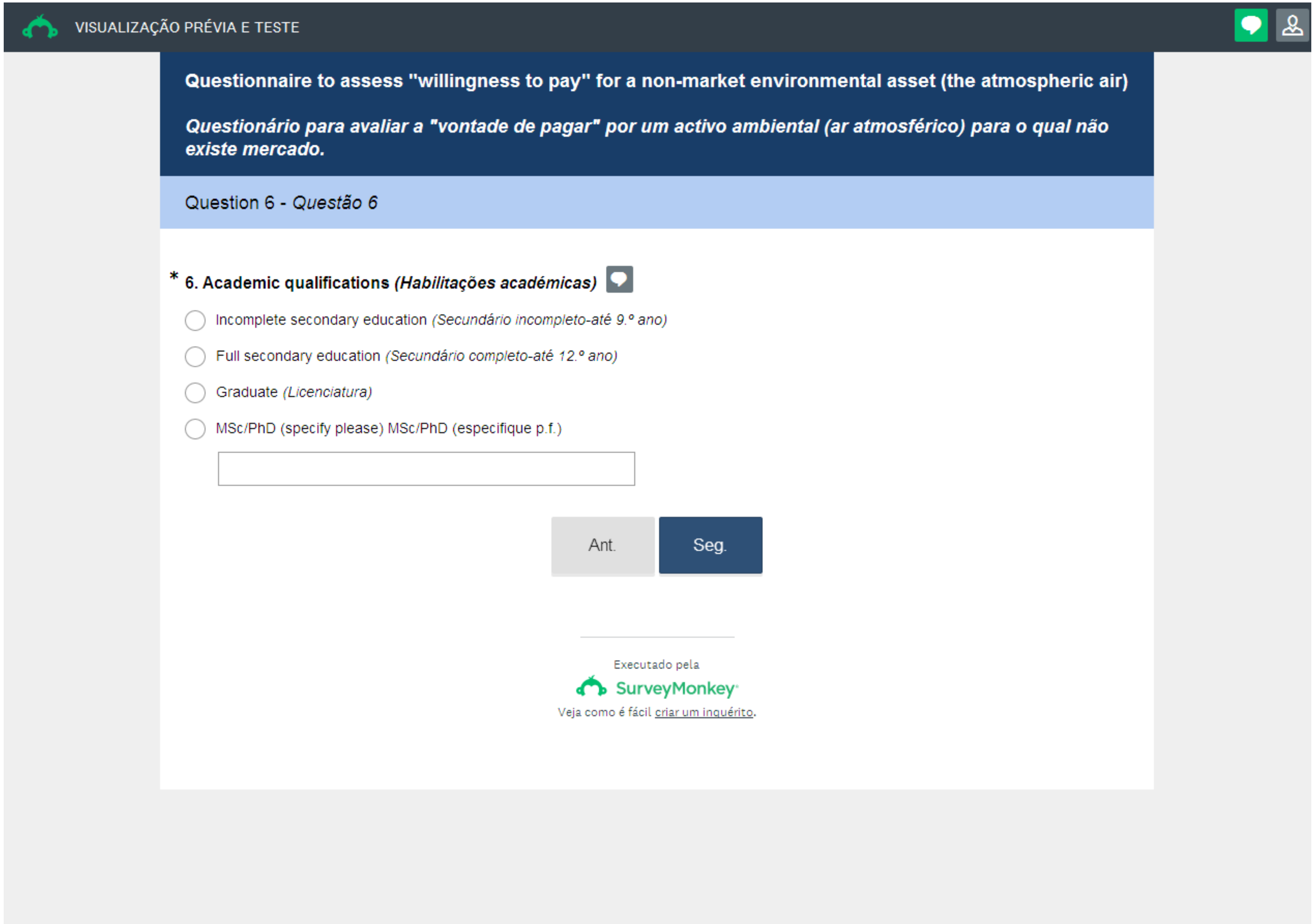

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Questionnaire to assess "willingness to pay" for a non-market environmental asset (the atmospheric air)

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Question 6 - *Questão 6*

* **6. Academic qualifications *(Habilitações académicas)***

- Incomplete secondary education *(Secundário incompleto-até 9.º ano)*
- Full secondary education *(Secundário completo-até 12.º ano)*
- Graduate *(Licenciatura)*
- MSc/PhD (specify please) MSc/PhD (especifique p.f.)

Ant. Seg.

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Veja como é fácil criar um inquérito.

VISUALIZAÇÃO PRÉVIA E TESTE

Questionnaire to assess "willingness to pay" for a non-market environmental asset (the atmospheric air)

Questionário para avaliar a "vontade de pagar" por um activo ambiental (ar atmosférico) para o qual não existe mercado.

Questions 7/8 - *Questões 7/8*

7. Occupation *(Profissão/ocupação)*

- Student *(Estudante)*
- Employee *(Empregado)*
- Unemployed *(Desempregado)*
- Other (Retired) Outra (Pensionista)

8. Please, let me know about your gross *monthly* income group (if it applies). *Por favor, indique a sua remuneração bruta mensal (caso seja aplicável)*

- € 500,00 - € 1000,00
- € 1000,00 - €2000,00
- Above (acima de) € 2000,00

Ant. Seg.

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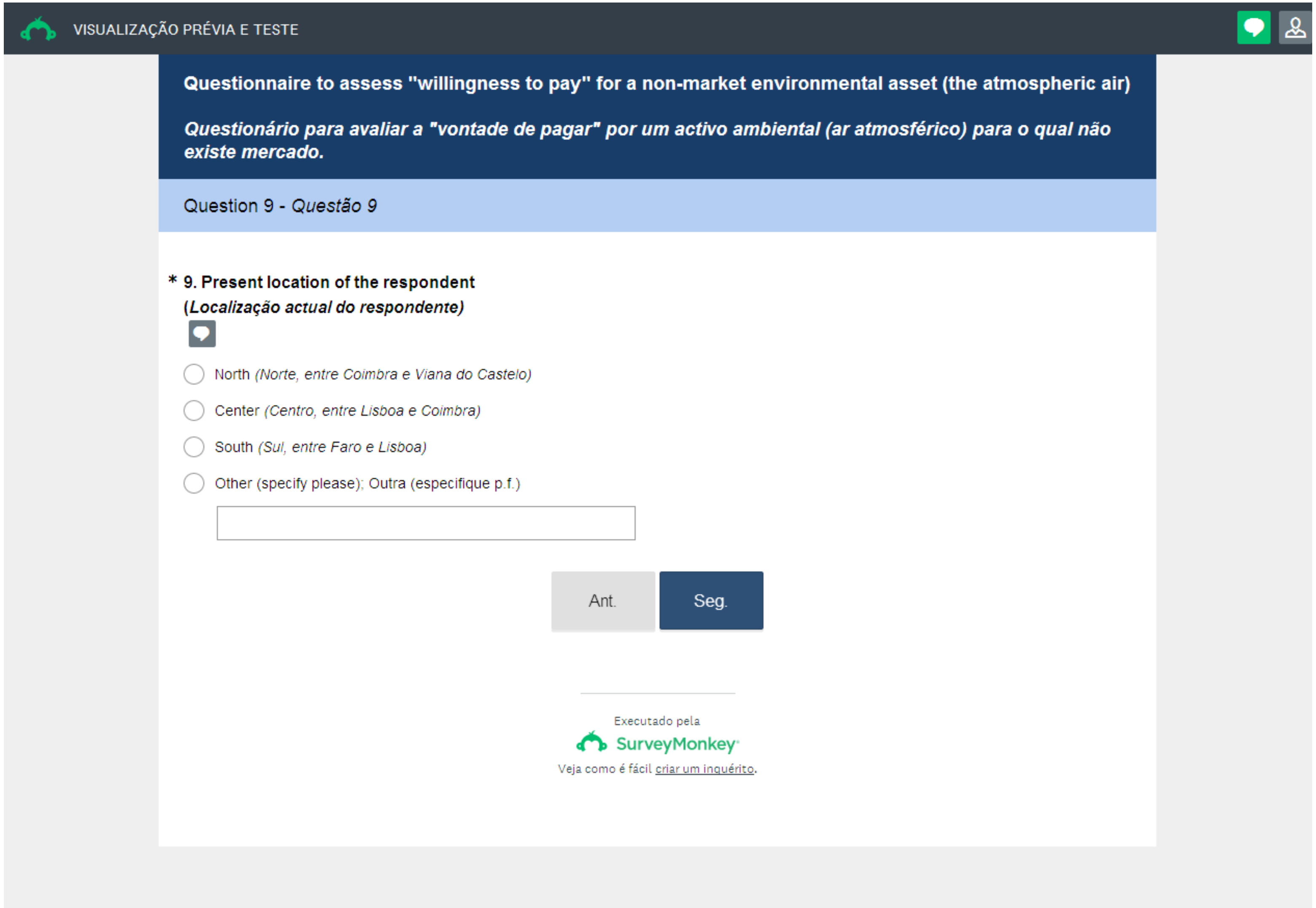
Veja como é fácil criar um inquérito.



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Questionnaire to assess "willingness to pay" for a non-market environmental asset (the atmospheric air)

Questionário para avaliar a "vontade de pagar" por um activo ambiental (ar atmosférico) para o qual não existe mercado.

Question 9 - *Questão 9*

* **9. Present location of the respondent**
(*Localização actual do respondente*)

- North *(Norte, entre Coimbra e Viana do Castelo)*
- Center *(Centro, entre Lisboa e Coimbra)*
- South *(Sul, entre Faro e Lisboa)*
- Other (specify please); Outra (especifique p.f.)

Ant. Seg.

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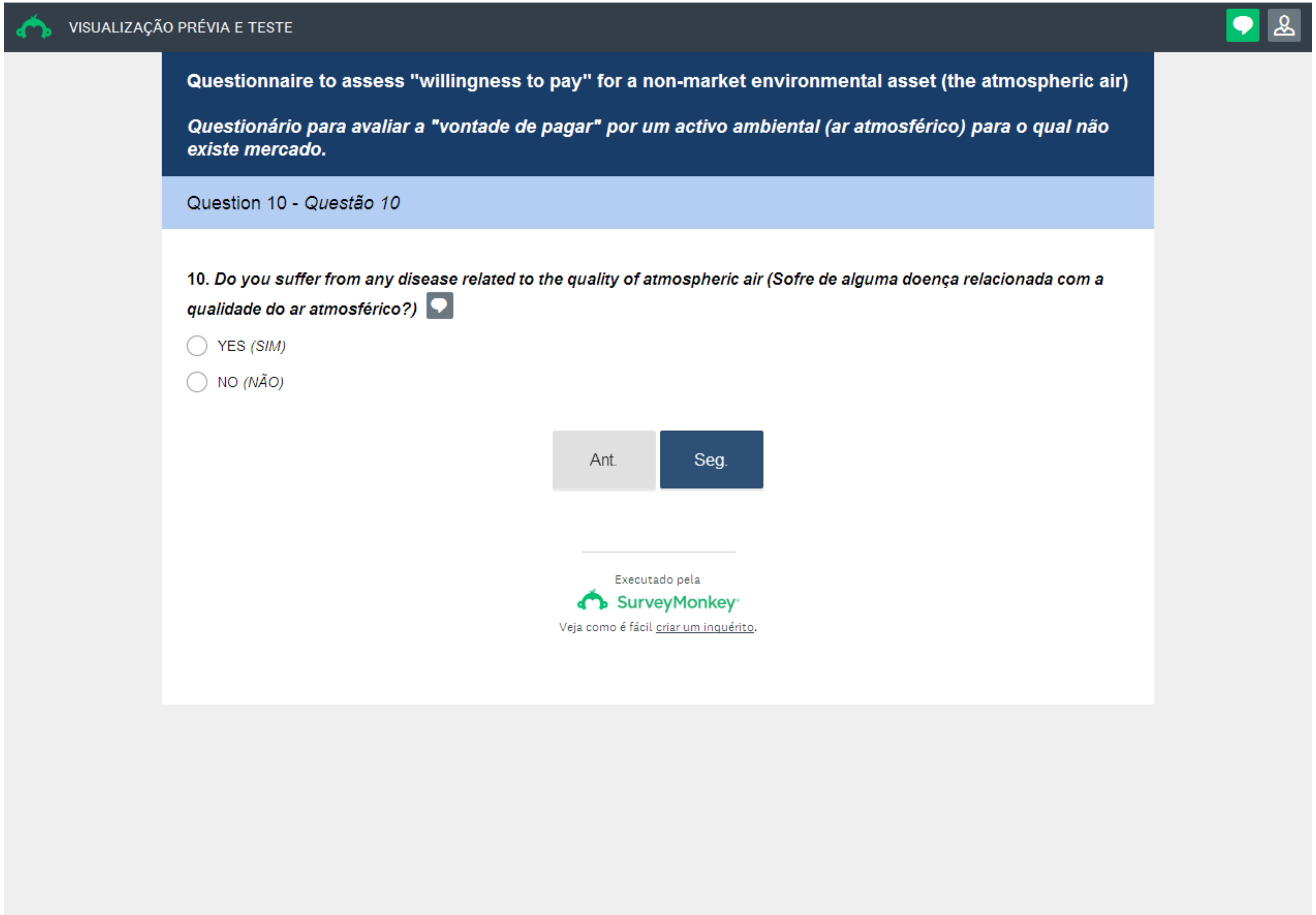
Veja como é fácil criar um inquérito.



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Questionnaire to assess "willingness to pay" for a non-market environmental asset (the atmospheric air)

Questionário para avaliar a "vontade de pagar" por um activo ambiental (ar atmosférico) para o qual não existe mercado.

Question 10 - *Questão 10*

10. ***Do you suffer from any disease related to the quality of atmospheric air (Sofre de alguma doença relacionada com a qualidade do ar atmosférico?)***

- YES *(SIM)*
- NO *(NÃO)*

Ant. Seg.

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Veja como é fácil criar um inquérito.

ANNEX 5

Time series for Portugal 2014 (adapted from Holland, 2014)

Aggregated health damage (M€/year)	
2010	**5,130**
2011	5,000
2012	4,871
2013	4,742
2014	**4,612**
2015	4,483

Net health benefits (M€/year)	
2010	**357**
2011	339
2012	327
2013	303
2014	**285**
2015	267

Life years from PM (number/years)	
2010	**65,106**
2011	63,330
2012	61,554
2013	59,778
2014	**58,000**
2015	56,226

Deaths from PM (number/year)	
2010	**6,113**
2011	6,041
2012	5,969
2013	5,897
2014	**5,825**
2015	5,753

Deaths from Ozone (number/year)	
2010	534
2011	529
2012	523
2013	518
2014	**512**
2015	507

Lost working days (number/year)	
2010	1,704,116
2011	1,664,155
2012	1,624,194
2013	1,584,233
2014	**1,544,272**
2015	1,504,311

Lost working days (M€/year)	
2010	222
2011	217
2012	212
2013	206
2014	**201**
2015	196

ANNEX 6

Ship data for the case-study

	Ship data (container ship)	Units	Default values	Alternative 1	Alternative 2
2	Container capacity	TEU	800	800	800
3	Feeder ship - type 1 (<2900 TEU) - Panamax - type 2 (1900 - 5300 TEU) or Post Panamax - type 3 (>4000 TEU)	(-)	1	1	1
4	Elongation in percent	%	0	0.0	0.0
5	Length between pp	m	126.88	126.88	126.88
6	Length in waterline incl. bulbous bow (= 1.01 Lpp)	m	128.15	128.15	128.15
7	Length over all	m	136.21	136.21	136.21
8	Breadth mld.	m	21.54	21.54	21.54
9	Depth	m	10.68	10.68	10.68
10	Design draught	m	7.67	7.67	7.67
11	Maximum draught	m	7.82	7.82	7.82
12	Maximum draught - design draught	m	0.15	0.15	0.15
13	Design deadweight/Maximum deadweight	%	97	97	97
14	Design deadweight	tons	10569	10569	10569
15	Maximum deadweight	tons	10920	10920	10920
16	Maximum deadweight/TEU	tons/TEU	13.65	13.65	13.65
17	Lightweight coefficient	t/m^3	0.142	0.142	0.142
18	Steel weight correction	%	0	0	0
19	Calculated machinery weight change due to engine change	tons	0	1	1
20	Specified machinery weight change (= the calculated value)	tons	0	0	0
21	Lightweight	tons	4135	4135	4135
22	Steel weight	tons	2931	2931	2931
23	Displacement at design draught	tons	14705	14705	14705
24	Displacement at maximum draught	tons	15055	15055	15055
25	Block coefficient (based on Lpp) at design draught	-	0.684	0.684	0.684
26	Block coefficient (based on Lpp) at maximum draught	-	0.688	0.688	0.688
27	Lpp/Displ.vol.$^{1/3}$ at design draught	-	5.22	5.22	5.22
28	Lpp/Displ.vol.$^{1/3}$ at maximum draught	-	5.18	5.18	5.18
29	Midship section coefficient	-	0.98	0.98	0.98
30	Prismatic coefficient at design draught	-	0.698	0.698	0.698
31	Prismatic coefficient at maximum draught	-	0.702	0.702	0.702
32	Waterplane area coefficient based on Lpp	-	0.859	0.859	0.859
33	Wetted surface at design draught	m^2	3711	3711	3711
34	Wetted surface at maximum draught	m^2	3763	3763	3763
35	Service speed at design draught	knots	16.7	16.7	16.7
36	Froude Number at service speed	-	0.242	0.242	0.242
37	Scantling trial speed at 100 % deadweight at 75 % MCR	knots	16.6	16.6	16.6
38	Froude Number at 'reference speed'	-	0.240	0.240	0.240
39	Service allowance on resistance	pct.	15	15	15
40	Beaufort No.	-	0	0	0
41	Calculated wind speed acc. to Beaufort No.	m/s	0.0	0.0	0.0
42	Longitudinal wind resistance coefficient, Cx	-	0.80	0.80	0.80
43	Wind speed to be used for separate wind resistance	m/s	0.0	0.0	0.0
44	Wind resistance fraction of trial resistance	pct.	0	0	0
45	Transmission efficiency	pct.	96	96	96

46	General improved propeller efficiency	pct.	0.0	0.0	0.0
47	Main engine power (MCR)	kW	8086	8105	8105
48	Auxiliary power at sea at design draught	kW	404	405	405
49	Auxiliary power in harbor	kW	381	381	381
50	Single screw (1) or twin screw propulsion (2)	-	1	1	1
51	Conventional hull form (1) or twin skeg hull form (2)	-	1	1	1
52	Propeller diameter	m	4.71	4.71	4.71
53	Propeller type (1 = conventional - 2 = ducted)	(-)	1	1	1
54	Propeller loading (MCR)	kW/m^2	464	465	465
55	Speed dependency exponent n (Power = constant V^n)	-	4.9	4.9	4.9
56	IMO Energy Efficiency Design Index at 100 % Dw	g/dwt/nm	22.95	21.83	15.28
57	**ENGINE TYPE & TECHNOLOGY**				
58	Main engine type (slow speed = 1, medium speed = 2)	(-)	2	2	2
59	Main engine service rating (for non derated engine only)	pct. MCR	90	90	90
60	Fuel type (HFO = 1, MD/GO = 2, LNG = 3, Dual fuel = 4)	-	1	2	3
61	SFOC at 75 % MCR in normal ME mode (If default press 1)	g/kW/hour	1	1	1
62	If normal tuning press 1 - if low load tuning press 2	-	1	1	1
63	Sulphur content in heavy fuel (HFO)	pct.	3.5	0.0	0.0
64	Sulphur content in diesel oil or gas oil (DO/GO)	pct.	0.1	0.1	0.0
65	Derated 2 stroke main engine? (NO = 0, YES = 1)	-	0	0	0
66	Fuel optimised main engine? (NO = 0, YES = 1)	-	0	0	0
67	TIER 1, 2 or 3 engine? (1 - 3)	-	3	3	3
68	Specify NOx reduction technology: EGR (Exhaust Gas Recirculation) =1, SCR (Selective Catalyic Reduction) = 2 or other technology = 3	-	2	2	0
69	Use of scrubbers if oil is used (NO = 0, YES=1)	-	1	0	0
70	**ACTUAL CONDITION**				
71	Payload/deadweight at design draught	%	66.4		
72	Capacity utilization (100 % ~ design condition)	%	58	58	58
73	Actual deadweight	tons	7644	7644	7644
74	Actual payload	tons	4088	4088	4088
75	Actual displacement	tons	11779	11779	11779
76	Waterplane area coefficient based on Lpp	-	0.829	0.829	0.829
77	Actual draught	m	6.41	6.41	6.41
78	Wetted surface at actual draught	m^2	3259	3259	3259
79	Service speed at actual draught	knots	16.7	16.7	16.7
80	Service allowance on resistance	%	0	0	0
81	Speed dependency exponent n (Power = constant V^n)	-	4.4	4.4	4.4
82	Necessary mian engine power at actual deadweight	kW	4956	4966	4966
83	Engine rating in actual condition (Cont. Service Rating = CSR)	% MCR	61	61	61
84	SFOC at CSR	g/kW/hour	207.1	190.7	155.6
85	Oil consumption per hour (auxiliary engines at sea)	t/hour	0.08	0.08	0.06
86	Oil consumption per hour (auxiliary engines in harbor)	t/hour	0.07	0.07	0.06
87	Oil consumption per hour (main engine)	t/hour	1.03	0.95	0.77
88	Oil consumption per hour (main and auxiliary engines at	t/hour	1.11	1.02	0.84
89	**EEDI deadweight (per cent)**		70	70	70
90	Scantling deadweight	tons	10920	10920	10920
91	70 % of maximum deadweight	tons	7644	7644	7644
92	Actual displacement	tons	11779	11779	11779
93	Block coefficient based on Lpp	-	0.656	0.656	0.656
94	Waterplane area coefficient based on Lpp	-	0.829	0.829	0.829
95	Actual draught	m	6.41	6.41	6.41
96	Wetted surface at EEDI draught	m^2	3259	3259	3259
97	70 % DW trial speed at 75 % MCR ('reference speed')	knots	17.45	17.45	17.45