



UCL

The potential of hydrogen to fuel international shipping

Carlo Raucci

UCL Energy Institute
University College London

*A thesis submitted in fulfilment of the requirements
for the degree of Doctor of Philosophy*

Supervisor:

Dr. Tristan Smith

Dr. Paul Dodds

February 1, 2017

“to my wife”

UNIVERSITY COLLEGE LONDON

Abstract

Bartlett
Energy Institute

Doctor of Philosophy

The potential of hydrogen to fuel international shipping

by Carlo RAUCCI

Today the way energy is produced and consumed is under debate as it is increasing the atmospheric concentrations of greenhouse gases (GHG), which can cause dangerous anthropogenic interference with the climate system. This means that a de-carbonisation of the global energy system is required. Shipping represents the biggest global low cost international freight transport service, and today it accounts for about 3% of the world's total GHG emissions. Such a percentage is projected to increase by 50% to 250% in the period to 2050. The projected shipping emissions trajectory, therefore, does not seem compatible with the de-carbonisation of the global energy system necessary to meet the internationally agreed goal of reducing the emissions in all sectors and ensure that the temperature rises in 2100 will not be greater than 2°C degree. Since shipping energy demand is mainly satisfied by fuel oil, recent new regulations on efficiency and air pollution have been introduced (EEDI, SEEMP), and instruments that would cut GHG emissions from shipping are under discussion. In the short term (5-10 years) the industry is aiming to reduce its emissions through a combination of technological and operational developments, however in the long term a switch to an alternative fuel may be required. Among the options, hydrogen with fuel cell systems (FCs) is seen by many as one of the long term solutions. Its attraction is not only for its zero operational emissions but also for the higher efficiency that could be achieved on board. Hydrogen and FCs are also seen as promising technologies that can support climate change and energy security goals in several sectors of the energy system. The most attractive uses of hydrogen within the context of a de-carbonization of the energy system are: for storing renewable energy, for heating, and as fuel for the transport sector. Moreover it can increase the operational flexibility as it can connect different energy sectors and energy transmission and distribution networks. The energy and the shipping systems are interrelated, so if the de-carbonisation of the global energy system could be achieved with the use of alternative energy and fuels including hydrogen, the same could be experienced in shipping with a widespread switch to the adoption of hydrogen as alternative fuel within the coming decades.

The purpose of this thesis was to learn more about the potential for hydrogen as a future fuel in shipping. The focus is on a computational modelling approach that is considered to lead to new useful contributions. This study proposes a framework based on a soft-linking technique to examine the potential of using hydrogen in shipping. The framework connects together a global integrated assessment model (TIAM-UCL) and a shipping model (GloTraM). GloTraM is a bottom-up shipping simulation model that is used to evaluate pathways towards a low carbon shipping system; TIAM-UCL is a bottom-up energy system model that is used to investigate possible pathways to reduce the energy and carbon density of the global energy system. The first objective of this study is the development of a new modelling approach that soft-links two existing

models in order to improve the modelling representation of hydrogen take up in shipping. The hypothesis is that the model linkage is more representative for exploring specified scenarios, forecasting investment decisions for hydrogen powered ships in conjunction with the hydrogen infrastructure development than the two separate models. The second objective is the analysis of the possible use of hydrogen under specific scenarios in order to understand at a global level the implications of providing and using hydrogen in shipping. The hypothesis is that the model linkage is able to explore the broader circumstance in which it would be possible to see an uptake of hydrogen in shipping and what it might mean for the contribution of shipping in avoiding 2°C of warming.

Based on this objectives, this research aims to answer the following research questions: Can an integrated framework that combines two different models improves the modelling representation of hydrogen uptake in shipping compared to the current representations found in the literature? What type of results does the integrated framework provide regarding the potential of hydrogen to compete with LNG and current marine fuels to fuel international shipping? Under what circumstance would hydrogen be able to compete with LNG and current marine fuels in shipping and what would be the main economic and environmental implications?

The comparison between the results of the independent and the integrated framework simulations of a specific set of scenarios has highlighted the capability of the framework of modelling the investment decision for ships powered by hydrogen in conjunction with the development of a hydrogen supply infrastructure with a more robust approach compared with the energy and shipping models. Evidence of the modelling improvement was found in: the ability of the model to simulate the equilibrium between marine fuel prices and demands, the ability of the model to capture the dynamics between the carbon price and the shipping fuel mix (how these outputs influence each other), the ability to generate fuel price projections that overcome the limitation of the linear property of the energy system model, the ability of capturing the dynamics between the transport demand among regions and the fuel mix evolution of the global fleet.

Moreover, a number of circumstances for the potential uptake of hydrogen over LNG were found in this thesis; the key circumstances are: the introduction of an emissions cap in shipping, a competitive hydrogen price and investment costs of hydrogen technologies on board ships (fuel cells and hydrogen storage technologies), and finally the supply of hydrogen mainly based on natural gas and biomass with CCS technology or electrolysis in case of an absence of CCS. The main implication of a switch to hydrogen is that shipping emissions would be reduced significantly over time.

This topic was identified as being of importance to assist ship owners and fuel providers in understanding the potential of use of hydrogen in shipping, and to assist policy makers in the development of effective GHG policy for shipping and in understanding

the implications of using hydrogen in shipping within the context of a de-carbonised energy system. It is hoped that information from this study may be useful in creating awareness of the potential that hydrogen might have in shipping and in creating incentives for further research required for exploring this option from different perspective. Moreover this study explores the application of a relative new modelling technique of soft-linking two existing models. The experience engaged in developing such a link could be useful to educators and modellers interested in the soft-linking modelling approach.

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisor Dr. Tristan Smith for the continuous support of my Ph.D study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time. I would also like to thank my second supervisor Dr. Paul Dodds for his insightful comments and encouragement. My sincere thanks also goes to my industrial sponsor Lloyd's Register Marine and the supervisor Kim Tanneberger who provided me the opportunity to join the Ph.D program at UCL. Without this precious support it would not be possible to conduct this research. I thank my colleagues in the shipping group and all Ph.D students for the stimulating discussions, for working hard together before deadlines, and for all the fun we have had in the last four years. Although from many kilometers away, I would like to thank my friends and particularly my family: my parents, my brother and sister and to my nephew, niece and brother in law for supporting me spiritually throughout writing this thesis and my life in general. Finally, and most importantly, I would like to thank Teagan, who became my wife during my Ph.D and who constantly offered her encouragement, patience and love.

Contents

Abstract	ii
Acknowledgements	vi
Contents	vii
List of Figures	xi
List of Tables	xiv
Abbreviations	xv
1 Introduction	1
1.1 Hydrogen to fuel international shipping	2
1.1.1 Shipping emissions	3
1.1.2 Regulatory context	4
1.1.3 Future emissions abatement technologies in shipping	6
1.1.4 Alternative fuels in shipping	7
1.1.5 Other uses of hydrogen	9
1.2 The approach of this study	12
1.2.1 The computational modelling approach	13
1.2.2 The limits of existing models	15
1.2.3 The objectives of the study	16
1.3 The structure of this thesis	17
2 Literature review	20
2.1 Introduction to the literature review	21
2.2 Existing approaches and main conclusions	22
2.3 Studying hydrogen in shipping with a computational modelling approach	26
2.4 Other relevant studies for modelling hydrogen in shipping	28
2.4.1 Existing models for the study of other alternative fuels in shipping	28
2.4.2 Existing models for the study of hydrogen in other sectors	30
2.5 Implications on the modelling representation of hydrogen in shipping	31
3 Methodology and research question refinement	36
3.1 Introduction to the methodology	37
3.2 The representation of the target system in TIAM-UCL	37

3.2.1	The representation of hydrogen infrastructure in TIAM-UCL . . .	38
3.2.2	Hydrogen infrastructure input data	40
3.2.3	Shipping representation in TIAM-UCL	44
3.2.4	Theoretical representational capacity of TIAM-UCL	45
3.3	The representation of the target system in GloTraM	46
3.3.1	Hydrogen ships in GloTraM	48
3.3.2	Hydrogen prices in GloTraM	49
3.3.3	Theoretical representational capacity of GloTraM	50
3.4	The study of hydrogen in shipping with hybrid model	50
3.4.1	Existing approaches of linking models	52
3.4.2	Area of improvements and research questions	54
4	Detailed method development: TIAM-GloTraM	56
4.1	Developing a method for how to soft-link TIAM-UCL and GloTraM . . .	57
4.2	Classification of the linking approaches	57
4.3	Methods for how to soft-link models	59
4.4	Procedures for soft-linking TIAM-UCL and GloTraM	62
4.5	Degree of the linkage	63
4.5.1	Common areas	64
4.5.2	Exchanged variables	66
4.6	Regions definition	69
4.7	Common portfolio of fuel options	70
4.7.1	Hydrogen storage in maritime applications	72
4.7.2	Hydrogen infrastructure for shipping	75
4.8	On board hydrogen technologies	76
4.8.1	Analysis of the specific fuel consumption	78
4.8.2	Analysis of the loss of cargo capacity	80
4.8.3	Analysis of the upfront capital cost	83
4.8.4	Analysis of the through life cost	88
4.9	Modifications to the initial conditions	90
4.10	Transferring information from TIAM-UCL to GloTraM	90
4.10.1	Transport demand of energy commodities	90
4.10.2	Production derived cost as a proxy for fuel price	93
4.10.3	Carbon price	94
4.11	Transferring fuel consumptions from GloTraM to TIAM-UCL	95
4.12	Consistency	101
4.12.1	The objective functions	101
4.12.2	The iterative procedure	103
4.12.3	Assumptions embedded in the soft-linking framework	104
5	Results of the soft-linking framework	106
5.1	Introduction to the results	106
5.2	Key assumptions in TIAM-UCL	108
5.3	Key assumptions in GloTraM	110
5.4	TIAM-UCL independent simulations	114
5.4.1	Scenario 4 Celsius degree with TIAM-UCL	114
5.4.2	Scenario 2 Celsius degree with TIAM-UCL	117

5.5	GloTraM independent simulations	121
5.5.1	Scenario 4 Celsius degree with GloTraM	121
5.5.2	Scenario 2 Celsius degree with GloTraM	122
5.6	TIAM-GloTraM simulations	124
5.6.1	Scenario 4 Celsius degree with TIAM-GloTraM	124
5.6.2	Scenario 2 Celsius degree with TIAM-GloTraM	129
5.7	Comparing the results of the soft-linking framework	133
5.7.1	Transport demand	134
5.7.2	Carbon price	137
5.7.3	Fuel shares and prices	139
5.7.4	An improved modelling representation of the target system	141
6	Exploring the implication of using hydrogen in shipping	145
6.1	Introducing a carbon budget in shipping	146
6.1.1	Implementing a shipping market-based measure in TIAM-GloTraM	149
6.2	The decarbonisation of the shipping sector	151
6.2.1	Shipping with a carbon budget constraint	151
6.2.2	Drivers and choices in a decarbonised shipping sector	153
6.2.3	Hydrogen demand by ship type and size	159
6.3	Environmental implications of using hydrogen in shipping	161
6.3.1	Decarbonisation by ship type	162
6.3.2	The effect on the shipping emissions share	163
6.3.3	Hydrogen supply and consumption in the decarbonised energy sys- tem	169
6.4	Economic implications	172
6.4.1	Hydrogen price	172
6.4.2	Profitability of hydrogen ships	174
6.4.3	Revenue deployment	175
6.5	Testing the viability of hydrogen's potential in shipping	175
6.5.1	Analysis of the input assumptions	178
6.5.2	The robustness of hydrogen's potential in shipping	182
6.5.3	Analysis of the sensitivity scenarios	183
6.5.3.1	The sensitivity of the decarbonisation pathway	183
6.5.3.2	The sensitivity of hydrogen supply	186
6.5.3.3	Economic implications by scenario	188
6.5.4	Variability of hydrogen adoption	191
7	Discussion and concluding remarks	193
7.1	The findings of this thesis	194
7.1.1	Modelling the energy-shipping system	195
7.1.2	The use of hydrogen in shipping	196
7.1.2.1	A shipping emissions regulation	196
7.1.2.2	Hydrogen costs	197
7.1.2.3	The supply of hydrogen	198
7.1.2.4	Main implications	199
7.2	Interpretation and limitations of the results	200
7.2.1	Modelling the interactions between two systems	200

7.2.2	The meaning of the uptake of hydrogen in shipping	202
7.2.2.1	Low carbon fuels in shipping	202
7.2.2.2	Fuels and infrastructure	203
7.2.2.3	Government and industry implications	205
7.2.2.4	Key learning for IMO GHG policy debate	207
7.3	Recommendations for further research	208
7.3.1	Adding features to TIAM-GloTraM	209
7.3.1.1	Soft-linking other transport modes	209
7.3.1.2	The estimate of the carbon price	209
7.3.1.3	Other fuels	210
7.3.1.4	Including the changes of transport cost	210
7.3.1.5	The bunkering infrastructure and the trade of hydrogen	210
7.3.2	Exploring uncertainty	210
7.3.3	Ship design	212
7.3.4	Other relevant topics of research	212

List of Figures

1.1	Comparison of 16 GHG scenarios from the IMO and the RCP marker scenarios for a range of climate outcomes	4
1.2	Approved ECA regions and IMO agreement to reduce atmospheric pollution from ships	5
3.1	Hydrogen as in TIAM-UCL	40
3.2	The global transport system as conceptualised in GloTraM	47
4.1	TIAM-GloTraM: Links between TIAM-UCL and GloTraM	63
4.2	Regions as defined in TIAM-GloTraM	69
4.3	Hydrogen infrastructure in TIAM-UCL	76
4.4	Loss of cargo carrying capacity	84
4.5	Projected fuel cell costs	86
4.6	Liquid Hydrogen storage costs by ship type and size	89
4.7	Illustrative example of converting regional trade from TIAM-UCL to trade by country level in GloTraM	92
4.8	Fuel oil (HFO) sales to fuel ships 2010 in million tonnes	97
4.9	Historical shares of marine fuel oil sales aggregated by TIAM-GloTraM region	98
4.10	Historical shares of marine gas diesel sales aggregated by TIAM-GloTraM region	99
4.11	Variance of the regional shares for fuel oil on the right, and for gas diesel on the left	100
4.12	Supply-demand equilibrium in TIAM-UCL	101
4.13	Iterative process between TIAM-UCL and GloTraM	104
5.1	Exogenous regional shipping energy demand. On the left international shipping energy demands by region. On the right domestic shipping energy demands by region	110
5.2	Sulphur regulations in the reference scenarios	111
5.3	Exogenous total trade of energy commodities assumed in GloTraM	112
5.4	TIAM-UCL trade of energy commodities between different regions IT4D scenario	116
5.5	TIAM-UCL emissions and marine fuel consumptions IT4D scenario. On the left emissions, on the right, fuel consumptions	117
5.6	TIAM-UCL fuels prices IT4D scenario in \$/tonnes (left) and \$ /GJ (right)	117
5.7	TIAM-UCL trade of energy commodities between different regions IT2D scenario	118
5.8	TIAM-UCL emissions and marine fuel consumptions IT2D scenario	119

5.9	Carbon prices IT4D and IT2D scenarios in TIAM-UCL	120
5.10	TIAM-UCL fuels prices IT4D scenario in \$/tonnes (left) and \$ /GJ (right)	120
5.11	GloTraM emissions and fuel consumptions IG4D scenario	122
5.12	GloTraM emissions and fuel consumptions IG2D scenario	123
5.13	Convergence of energy commodities trade TG4D scenario	125
5.14	Convergence of fuel shares in shipping TG4D scenario	127
5.15	Convergence of fuel prices TG4D scenario	128
5.16	TIAM-GloTraM fuels shares TG4D scenario	129
5.17	Convergence of energy commodities trade TG2D scenario	130
5.18	Carbon prices TG4D and TG2D scenarios in TIAM-GloTraM	131
5.19	Convergence of fuel shares in shipping TG2D scenario	132
5.20	Convergence of fuel prices TG2D scenario	133
5.21	TIAM-GloTraM fuels shares TG2D scenario	134
5.22	Transport demand by scenarios	135
5.23	Carbon prices for each simulations with TIAM-UCL and TIAM-GloTraM	138
5.24	Fuel shares and prices 4°C scenarios	140
5.25	Fuel shares and prices 2°C scenarios	142
6.1	World's total CO_2 emission (top); shipping CO_2 emissions and shares (as percentages of the word's total emissions) (bottom dotted line) and target trajectory (bottom red line)	149
6.2	Decarbonisation of the shipping sector in TG2D_CB scenario	152
6.3	Fuel mix in TG2D_CB scenario by ship type.	154
6.4	Transport demand by ship type (top), energy demand by fuel type (bottom) - scenario TG2D_CB	155
6.5	Comparison between shipping carbon price and global carbon price in TG2D_CB scenario	156
6.6	Fuel prices in TG2D_CB scenario	157
6.7	Competitiveness of fuel/machinery options	159
6.8	Hydrogen share per ship type by size category ranging from the smallest size 1 to the largest size 8 in wet crude	160
6.9	CO_2 emissions by ship type category in the TG2D_CB scenario	162
6.10	Average carbon factor by ship type (top), EEOI by ship type (bottom) . .	164
6.11	Shipping CO_2 emissions and annual shares of the total CO_2 for TG2D and TG2D_CB scenarios	165
6.12	Shipping operational CO_2 emissions by fuel type in TG2D_CB scenario .	166
6.13	Emissions by sectors in TG2D_CB scenario(top). Annual CO_2 emissions for all transport modes indexed to their value in 2010 (bottom)	167
6.14	Hydrogen share by mode in TG2D_CB scenario	169
6.15	Hydrogen production and consumption in TG2D_CB scenario	170
6.16	Hydrogen and other marine fuels upstream CO_2 emissions in TG2D_CB scenario	171
6.17	Weighted average and regional hydrogen price (top). Hydrogen price by sector (bottom)	173
6.18	Profitability of fuel/machinery options	174
6.19	Carbon pricing and revenue deployment	176
6.20	Fuel mix in shipping by scenario over the period 2010 to 2050	182

6.21 Shipping's operational emissions trajectory by scenario (top). Offsets of CO_2 emissions trajectory by scenario (bottom)	185
6.22 Fuel mix trends by scenario	186
6.23 Shipping emissions as share of total world emissions	187
6.24 Cumulative hydrogen production technologies by scenario	188
6.25 Cumulative hydrogen end-user consumptions by scenario	189
6.26 Shipping carbon prices trends by scenario (top). Hydrogen prices for shipping by scenario (bottom).	190

List of Tables

2.1	Specifications for the representation of hydrogen as a fuel in shipping and required model feature	33
3.1	Capital investment costs of hydrogen infrastructure components in \$(2010)/(GJ/yr)	41
3.2	Operational costs of hydrogen infrastructure components in \$(2010)/(GJ/yr)	42
3.3	Energy efficiency of hydrogen infrastructure components (%)	43
3.4	CO ₂ emissions factors of hydrogen infrastructure components (kt(CO ₂)/PJ)	44
3.5	CH ₄ emissions factors of hydrogen infrastructure components (kt(CH ₄)/PJ)	44
3.6	N ₂ O emissions factors of hydrogen infrastructure components (kt(N ₂ O)/PJ)	45
3.7	Ship type by size category	48
4.1	Fuel options in TIAM-UCL and GloTraM and common portfolio in TIAM-GloTraM	70
4.2	Gravimetric and volumetric hydrogen density in various materials and systems. The density is estimated for systems and in parenthesis is the theoretical limit of the material given. Source:(Züttel et. al., 2010)	75
4.3	Main engine and fuel type combinations	77
4.4	Specific fuel consumptions of the main machinery options	79
4.5	Assumed engine mode and the engine load condition during a voyage that would consume the full tank	82
4.6	Assumptions and estimates of dwt_loss for LNG and Hydrogen storage systems on board	83
4.7	Energy commodities as defined in TIAM-UCL and the associated group commodity as defined in GloTraM	91
5.1	Simulations	107
5.2	Variables examined	107
5.3	Main engine options	114
5.4	Fuel options	114
6.1	Assumed proportions of the revenue deployment due to the carbon pricing	150
6.2	Parameter robustness analysis (PRA)	179
6.3	Simulations for the parameter and structural robustness analysis	181

Abbreviations

AFR	Africa
APU	Auxiliary Power Unit
AUS	Australia
BG	Biomass Gasification
BIOCR	Bio crops
BIODST	Bio diesel
BIOJTK	Bio jet kerosene
BIOKER	Bio kerosene
BIONAP	Bio naphta
BIOSLD	Solid biomass
CAN	Canada
CCS	Carbon Capture Storage
CG	Coal Gasification
CHI	China
COAHCO	Hard coal
CSA	Central and South America
dwt_loss	Dead weight tonnes loss
ECA	Emissions Control Area
EEOI	Energy Efficiency Operational Indicator
EEU	Eastern Europe
EGCS	Exhaust Gas Cleaning Systems
EU	European Union
FC	Fuel cell
FSU	Former Soviet Union
GASLNG	LNG in TIAM-UCL
GHG	GreenHouse Gas

GloTraM	Global Transport Model
H24SI	4 stroke spark ign. (hydrogen)
H2HFC	Reformer with fuel cells and electric motor (hydrogen)
H2ICE	Hydrogen Internal Combustion Engine
HFCEV	Hydrogen Fuel Cell Electric Vehicles
HFO	Heavy Fuel Oil
HFO2S	2 stroke diesel with HFO
HFOdEle	diesel electric with HFO
HGV	Heavy Goods Vehicle
ICE	internal combustion engine
ICS	International Chamber of Shipping
IEA	International Energy Agency
IG2D	Independent GloTraM 2°C scenario
IG4D	Independent GloTraM 4°C scenario
IMO	International Maritime Organization
IND	India
IPCC	Intergovernmental Panel on Climate Change
IT2D	Independent TIAM-UCL 2°C scenario
IT4D	Independent TIAM-UCL 4°C scenario
JPN	Japan
LCA	Life Cycle Assessment
LGV	Light Goods Vehicle
LNG	Liquefied Natural Gas
LNG4SI	4 stroke spark ign with LNG
LNRFRC	Reformer with fuel cells and electric motor (LNG)
LSHFO	Low Sulphur Heavy Fuel Oil
MBM	Market-Based Measures
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MDO2S	2 stroke diesel with MDO
MDO4S	4 stroke diesel with MDO
MDOdEle	diesel electric with MDO
MEA	Middle East

MEPC	Marine Environment Protection Committee
MEX	Mexico
MILP	Mixed Integer Linear Programming
MRV	Monitoring, Reporting and Verification
NSTR	Standard goods classification for transport statistics
ODA	Other developing Asia
OILCRD	Crude oil
OILDST	Distillates
OILGSL	Gasoline
OILHFO	Heavy fuel oil
OILNAP	Naphta
OILNGL	Natural gas liquids
RCP	Representative Concentration Pathways
SCC	Shipping in Changing Climates
SEEMP	Ship Energy Efficiency Management Plan
sfc	Specific Fuel Consumption
SKO	South Korea
SMR	Steam Methane Reforming
TENM	Tonnes per nautical mile
TG2D	TIAM-GloTraM 2°C scenario
TG2D_BioC	Investment cost of hydrogen production plants from biomass scenario
TG2D_CB	Carbon budget scenario
TG2D_Fc	Fuel cell cost scenario
TG2D_Ff	Fuel cell efficiency scenario
TG2D_IT	Carbon budget scenario
TG2D_nCCS	CCS technology scenario
TG2D_Sc	Hydrogen storage cost on board scenario
TG2D_VI	Volumetric density H2 storage scenario
TG4D	TIAM-GloTraM 4°C scenario
TIAM-UCL	TIMES Integrated Assessment Model University College London
TLC	Through life cost
TRACOA	Coal
TRADSL	Diesel ,

TRAGSL	Gasoline
TRAHFO	Heavy fuel oil in TIAM-UCL
TWD	Domestic shipping energy demands
TWI	International shipping energy demands
UK	United Kingdom
UKERC	UK Energy Research Centre
UKTM-UCL	UK TIAM model
UNFCCC	United Nations Framework Convention on Climate Change
UPC	Unit Procurement Cost
USA	United State of America
WEU	Western Europe

Chapter 1

Introduction

Will hydrogen fuel international shipping? Shipping emissions could increase significantly in the future and a new regulatory context is likely to enter into force to reduce shipping emissions. Future emissions abatement technologies might not ensure satisfactory results, therefore alternative fuels for shipping have come into the spotlight in the last few years. Although liquefied natural gas (LNG) is by far the most promoted alternative fuel in shipping, hydrogen could play an important role in the future. The use of hydrogen in combination with fuel cell systems on board ships could theoretically lower to zero the carbon intensity of shipping fleets. In addition hydrogen could emerge significantly in the road transport sector, and the introduction of hydrogen in shipping would be an additional market that has not been studied extensively so far.

In such complex context it becomes very difficult to predict the possible use of hydrogen to fuel international shipping. Due to the complexity of the target system, many factors need to be taken into account. Although the studies that have assessed the potential use of hydrogen in shipping have provided already useful insights, their conclusions appear contrasting and weak. The debate, therefore, still seems to be open and there appears to be a need for a more rigorous approach.

1.1 Hydrogen to fuel international shipping

There are a number of factors that could influence the future use of hydrogen in shipping. As will be shown in chapter 5, one of the main advantages of using hydrogen in shipping is that it could lower shipping emissions. As consequence, it becomes very important the interest to achieve this goal and the possible regulatory framework. How plausible will be the use of any alternative fuels in shipping is also a very important factor, especially if there would be competing abatement technology options on the market (ICS, 2009). Moreover, hydrogen as an energy carrier has been investigated extensively in the past (Winter and Nitsch, 2012; Mazloomi and Gomes, 2012), and in a context of sustainable development many authors envisage a transition to a hydrogen economy (Ekins, 2010; Züttel et. al., 2010). Its potential role in the energy system is, therefore, another important factor.

Based on these elements, the first step is to look into each of these areas in further detail to understand the current state of the art and any gaps. Hence, the following sections are divided in: shipping emissions, regulatory context, future emissions abatement

technologies in shipping, alternative fuels in shipping, and other uses of hydrogen.

1.1.1 Shipping emissions

Shipping is responsible for a wide range of global and local environmental concerns. Currently, particular attention is on the ships' emissions ([Endresen et. al., 2008](#)). Ships commonly use oil-derived liquid fossil fuels that emit numerous pollutants such as carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen oxide (NO_X). In 2014 the International Maritime Organization (IMO) carried out a study to provide an inventory and future scenarios for GHG and non-GHG emissions from ships. Such a study ([Smith et. al., 2015](#)) updates a previous study undertaken in 2009 ([Buhaug et. al., 2009](#)). One conclusion of the [Smith et. al. \(2015\)](#) study is that shipping CO_2 emissions are projected to increase by 50% to 250% in the period to 2050 from the base year 2010.

The contribution of shipping CO_2 emissions to the world's total could increase significantly in the future, especially if a decarbonisation of the energy system is taken into account. According to [Smith et. al. \(2015\)](#) in 2012 the world's total CO_2 emissions was estimated to be 35.640 million tonnes, of which 938 were emitted from ships representing about 2.6% of the total. The scenarios for the projected shipping emissions provided in [Smith et. al. \(2015\)](#) do not see a downward trend. Shipping is forecast to constitute between 6% and 14% of total anthropogenic carbon dioxide emissions in 2050 according to [MEPC.1/Circ.6851 \(2015\)](#), although it has forecast the introduction of energy efficiency technologies and the use of alternative fuels. This trend does not seem compatible with the low-carbon development of the global energy system.

The decarbonisation of the global energy system is recognised as an indispensable strategy to reduce the global GHG emissions. According to the [IPCC \(2013b\)](#)'s Fifth Assessment Report (AR5) findings this strategy will limit the global temperature to rise above 2°C from pre-industrial level which will avoid dangerous climate change. In December 2015 an historic agreement was undertaken by 195 nations in Paris. Such an agreement brings all nations into a common cause to keep the global temperature rise this century well below 2°C and to limit the temperature increase even further to 1.5°C above pre-industrial levels.

The possible increase of shipping emissions becomes a concern under the context of global sustainable development, although shipping was not included in the Paris agreement. This concern is well described in [Bows-Larkin et. al. \(2015\)](#); figure 1.1 shows

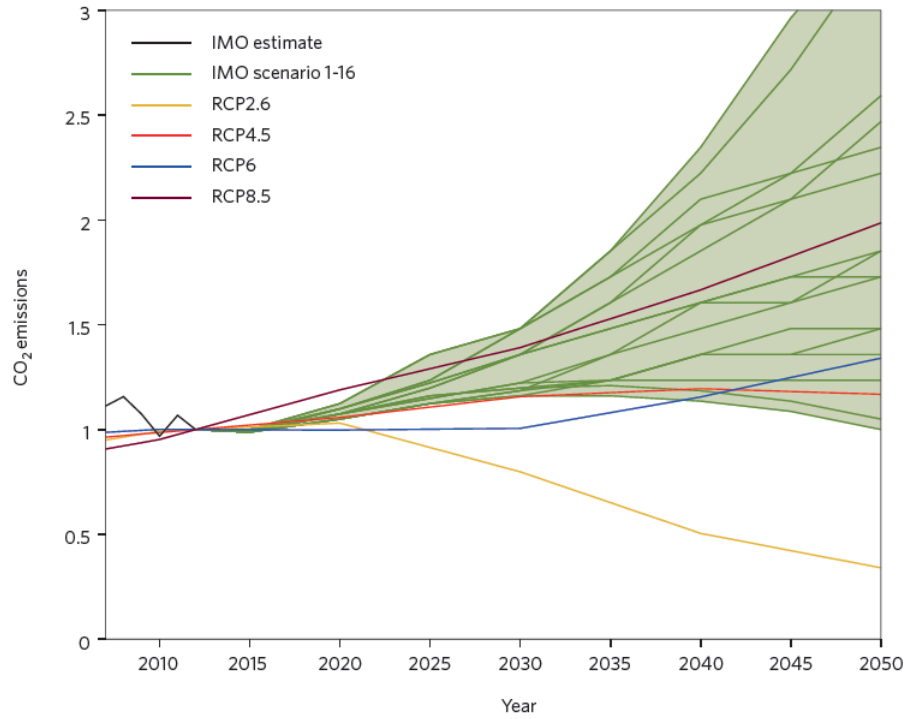


FIGURE 1.1: Comparison of 16 GHG scenarios from the IMO and the RCP marker scenarios for a range of climate outcomes. All scenarios are indexed to 2012 emissions.
Source: (Bows-Larkin et. al., 2015)

a chart from this study that compares the shipping emissions scenarios from [Smith et. al. \(2015\)](#) with four representative concentration pathways (RCPs). As explained in [Bows-Larkin et. al. \(2015\)](#), each pathway has been estimated so that it corresponds to a different climate outcome; for example, RCP2.6 pathway has an estimated 0.9–2.3°C of warming by 2100, while on the other side RCP8.5 has an estimated 3.2–5.4°C. The main conclusion was that none of the anticipated shipping scenarios is close to the pathway RCP2.6 which ensures a proportionate contribution for shipping to avoid 2°C of warming. Therefore the sustainability of the shipping system has become very important in order to bridge this gap, which highlights the need to investigate new policy and technology solutions, particularly in the mid-to-long term, after 2020.

1.1.2 Regulatory context

A particular focus on ships' emissions is demonstrated by tighter regulations on efficiency and air pollution provided by IMO in Annex VI of The International Convention on the Prevention of Pollution by Ships (MARPOL). In 2010 the revised Annex VI introduced a phasing in a progressive reduction in SO_X emissions from ships and further reductions in

NO_X emissions from ships. Figure 1.2 shows the approved emission control area (ECA) regions and the progressive reduction in SO_X emissions. By 2015 all ships entering ECA regions are allowed to use a fuel with a maximum sulphur content of 0.1% by weight or these ships can use technologies that ensure such limitations on SO_X emissions. A study on the availability of low sulphur fuels for shipping has been commissioned by IMO and it will be used as a base to decide when the further limit of maximum sulphur content of 0.5% will be extended to all outside ECA regions. These regulations are very important as they might incentivise the introduction of new, cleaner fuels in shipping, although the focus is only on SO_X emissions. New ECA regions could be introduced in the future. China, for example, has just approved a regulation that limits fuels with high sulphur content in its major ports.

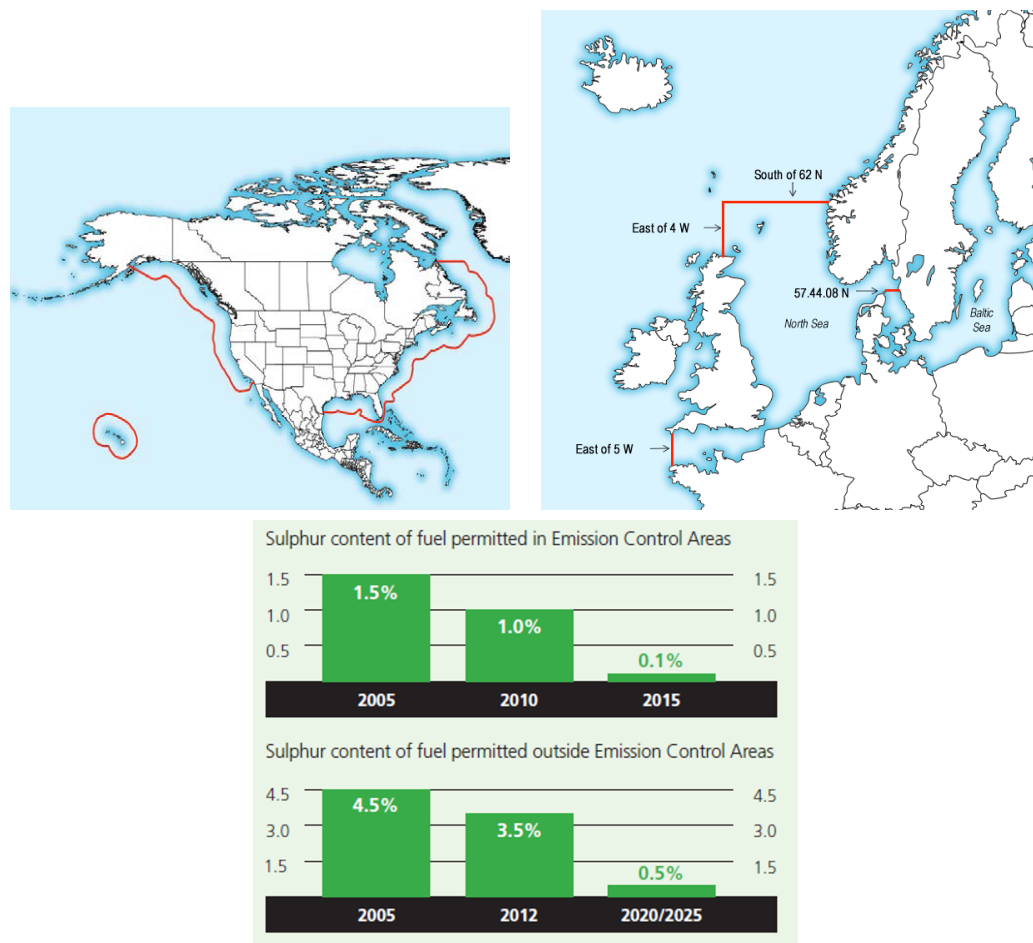


FIGURE 1.2: Approved ECA regions and IMO agreement to reduce atmospheric pollution from ships. Adapted from [ICS \(2009\)](#) and [INTERTANKO \(2012\)](#).

In 2013 amendments of the Annex VI were adopted by Parties to MARPOL Annex VI represented in the Marine Environment Protection Committee (MEPC), which set

mandatory measures to reduce emissions of GHG in international shipping. The new chapter 4 of Annex VI made it mandatory for new ships to respect the limit imposed of an Energy Efficiency Design Index (EEDI), and all ship were rewired to follow the Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2015). According to ICS (2009), the EEDI should lead to about a 25%-30% reduction in emissions by 2030 compared to business-as-usual', and the SEEMP, instead, should ensure the monitoring and the improvement of several factors that can contribute to CO_2 emissions.

Other instruments that would cut GHG emissions from the international maritime transport sector are being discussed. For example, a number of market-based measures (MBM) proposals are objectives of a feasibility study and impact assessment (MEPC.1/Circ.61/INF2, 2010). In addition, in June 2013 the European Commission set out a strategy for reducing domestic shipping GHG emissions. The strategy includes the monitoring, reporting and verification (MRV) of CO_2 emissions from large ships using EU ports. Finally, the IMO has recently agreed in principle to the development of a global data collection system to measure CO_2 emissions from individual ships (ICS, 2009).

How the regulatory framework will evolve will be very important in view of creating new incentives towards the decarbonisation of the shipping industry. The IMO appears to lead on this topic, although regional regulations on efficiency and air pollution from ships are also becoming tighter.

1.1.3 Future emissions abatement technologies in shipping

The global shipping industry aims to reduce by 20% CO_2 emissions by the end of 2020 and to comply with all MARPOL Annex VI regulations through a combination of technological and operational developments (ICS, 2009). Such a combination includes for example improvements to hull, engine and propeller design, but also better speed management. This is considered a valuable option in the short term, however, what would be the strategy for a more significant emissions reduction long term will depend on the technological developments (ICS, 2009). These technological developments in shipping are currently under discussion. A completed examination of the transformative impact of 18 technologies in ship design and marine engineering, and on the use of ocean space in 2030 has been provided in a report made available by Lloyd's Register Argyros

[et. al. \(2014\)](#). An additional review of alternative sources of energy in shipping can be found in [Fernández Soto et. al. \(2010\)](#).

Among the technological solutions for the reduction of shipping emissions, there are exhaust gas cleaning systems (EGCS), also called scrubbers, renewable energy based technology such as wind and solar power systems on board ships, and fuel cells as a main propulsion system. Ships with scrubbers on board will still be using traditional marine fossil fuel as this scrubber technology can ensure only a lower amount of SO_X emissions. As consequence scrubbers are not seen as a long-term solution for a significant CO_2 emissions reduction. Wind power is not a new solution for shipping as it has been used for centuries. Wind technologies for today's ships are being investigated by a number of studies such as [Rojon \(2013\)](#). Solar power, instead, seems to be less attractive on board ships as it would be difficult to provide sufficient power. Fuel cells as a main propulsion system could be a possibility for new ships as they can be used in combination with a reformer with a number of hydrocarbons such as LNG and methanol ([Erkko, 2011](#)). However, their environmental benefits could be higher when they are used in combination with hydrogen ([Argyros et. al., 2014](#)). The development of such technology is still at an early stage for maritime applications, but there already exist prototypes of auxiliary power unit (APUs) operating on board ships ([McConnell, 2010](#)).

The investigation on further technological developments is an important factor that will influence the way future ships are developed. The uptake of hydrogen as fuel for shipping will also depend on such developments.

1.1.4 Alternative fuels in shipping

Alternative fuels could be a different option for significant shipping emissions reductions in the long-term. The most pronounced alternative fuels for shipping are: LNG, methanol, biofuels (including bio-methanol) and hydrogen (including bio-hydrogen), LPG (Liquid Propane Gas), DME (Dimethyl Ether) and ammonia, although only the first four appear to be the most promising in accordance with [Ruud Verbeek \(2011\)](#) and [Argyros et. al. \(2014\)](#). An additional motivation in exploring alternative fuels in shipping is that compliance with the global introduction of the maximum sulphur content in marine fuels by 2020 might increase the prices of low sulphur fuels which, as a consequence, could create an extra economical incentive to switch to competitive cleaner fuels.

LNG is by far the most promoted alternative fuel in shipping as shown in the many projects and programmes that are trying to demonstrate its advantages. It has been claimed that LNG is a fossil fuel option that has a low sulphur content and produces lower CO_2 emissions than the current marine fuels (Verbeek et al., 2011; GL, 2011; Lloyds Register, 2012). Methanol is also commonly seen as a future fuel in shipping, and advanced biofuels (bio-methanol included) are often mentioned as a viable alternative. Hydrogen with fuel cells, however, is seen as the most long-term solution; its attraction is not only for its zero operational emissions but also for the higher thermal efficiency that could be achieved on ship (Ruud Verbeek, 2011; Argyros et al., 2014). LPG, DME and ammonia are potential marine fuel candidates, although there is limited information available on their viability on board ships. A number of studies such as Bengtsson (2011) and Brynolf et al. (2014), have applied a life cycle assessment (LCA) to assess the environmental impact of alternative marine fuel. However, it seems that there is not a strong consensus on which of these alternative fuels would provide a viable solution, although LNG has found concord among many (Ruud Verbeek, 2011; DNV, 2010; GL, 2012; Wartsila, 2012; DNV GL, 2014)

Generally, the use of any alternative fuels in shipping shares common concerns. First, their storage on board ships causes technical challenges including safety and space requirements. Second, the initial costs required for the supply chain infrastructure are generally higher than for petroleum-based fuels due to the lack of initial economies of scale. Finally, a number of other concerns must be addressed, for example the economical longevity, future price and availability, the upstream emissions and net effect reduction of CO_2 equivalent associated with each of the alternative fuels. Many of these concerns are not completely understood and are not strictly linked with the shipping industry. For example, future prices and the upstream emissions are associated with the multiple choices of production pathways that can arise from joining the different elements of the energy system; the future amount of alternative fuels required to satisfy the shipping demand would compete with the amount of such fuels required to satisfy the demands from other sectors.

The supply chain of existing marine fuels involves an international network of organisational and trade relationships. A technological transition such as alternative fuels in shipping would involve changes not only in the technology itself but also in practices, and regulations in such networks (Geels, 2002). In shipping, a transition from sailing

ships to steamships in the nineteenth century is a classic example of a technological transition which is described empirically in [Geels \(2002\)](#). In general it is concluded that a massive technological transition is the outcome of a series of adaptations and changes over time that involve a broader scope. The evaluation of alternative fuels in shipping, therefore, is not a simple technological comparative analysis, but involve the transition of a whole system.

If the technical and operational measures will not be enough for a drastic emissions reduction, then alternative fuels with the use of a more efficient propulsion system could be the most plausible response for a more significant long-term emission reduction in shipping. If alternative fuels will take up in shipping it would be through a series of adaptations and changes. The use of any of these fuels shares common concerns and not all are exclusively linked with the shipping industry, therefore the deployment of any alternative fuel in shipping will also be associated with their role in the future energy system.

1.1.5 Other uses of hydrogen

Since hydrogen was first separated and identified in the second half of the 18th century, its role as an energy carrier has been under extensive investigation. Many authors envisage a transition to a hydrogen economy as the a solution for a zero-carbon energy system. According with them, due to hydrogen physical and thermodynamic properties, hydrogen-based technologies could find many applications within a decarbonised global energy system, and it is expected that hydrogen would have a key role in the near future ([Winter and Nitsch, 2012](#); [Andrews and Shabani, 2012](#); [Barreto et.al., 2003](#); [Ekins, 2010](#)). Today the main use of hydrogen is in refineries as an upgrader to lower the sulphur content of oil-derived fuels or as a commodity in the industrial process ([Züttel et.al., 2010](#)). However, the most attractive uses of hydrogen would be: for storing renewable energy, for heating, and as fuel for the transport sector ([SBA, 2014](#)).

The need to balance the energy network from the increasing intermittency of renewable energies raise questions about the development of energy storage systems. According to the study [SBA \(2014\)](#), hydrogen-based storage technologies may be the best way in providing back-up power when renewables are not producing energy and in avoiding wastage during peaks in renewable electricity supply. In a recent study [Ehteshami and Chan \(2014\)](#) claimed that hydrogen is the most promising option for storing renewable

energy; by comparing different options based on a set of criteria, it was claimed that the most promising option resulted to be storing renewable energy sources in the form of hydrogen through the electrolysis process. Also [JRC \(2007\)](#) declared that in order to ensure high penetrations of renewable electricity in the short to medium term, hydrogen can be used as a storage media to cope with stochastic power generation. However concern, were expressed about the hydrogen re-electrification, which may not be the most energy efficient and cost-competitive storage technology.

Another attractive use of hydrogen is its use as an alternative to natural gas for space heating, water heating and for gas cooking. In a recent study [Dodds and Hawkes \(2014\)](#) declared that hydrogen can be burned directly in boilers or used in fuel cells and has higher efficiencies and no fundamental difference compared to the natural gas equivalents. According to this study hydrogen could be injected into the gas system but this could accommodate only a small percentage of hydrogen by volume, while a widespread use of hydrogen gas would mean a new dedicated transmission network would have to be constructed.

Perhaps the most investigated use of hydrogen within the context of a decarbonisation of the energy system is its use as fuel for the transport sector. During the recent decades much attention has been devoted to road transportation, and also more recently numerous papers have focused on hydrogen as a fuel, including [Mansilla et. al. \(2012\)](#), [Rosenberg et. al. \(2010\)](#), [Konda et. al. \(2011\)](#), [Veldhuis et. al. \(2007\)](#) and [Boudries \(2014\)](#). In addition, private industry and public programmes have announced the development of hydrogen mobility. One example is the HyTEC project which aims to create three new European hydrogen passenger vehicle deployment centres in London, Copenhagen and Oslo ([HYTEC, 2015](#)). Another example is the H2Mobility project which is a collaboration between car manufacturers, utility companies and government departments to evaluate the potential role for hydrogen in road transport.

Many of these studies have concluded that in the near term, hydrogen fuel cell electric vehicles (HFCEVs) suffer from higher purchase prices compared to competitors such as plug-in electric vehicles. Moreover, there are numerous challenges associated with the full-scale infrastructure for low-carbon production, transportation and storage of hydrogen. The cost of a refuelling infrastructure was found to be one of the biggest barriers ([CCC, 2013](#)). In the longer term, however, HFCEVs have the potential to reduce emissions and be competitive against or complementary to other alternatives

(CCC, 2013). The volume required for on board hydrogen storage tanks has an effect on the cost of owning HFCEV, however according with Anandarajah et. al. (2013), if the developments overcome challenges around hydrogen storage technologies then hydrogen vehicles could be useful for the long-term decarbonisation of the road transport sector, in particular for buses and HGVs, where battery electric vehicles may be unsuitable.

The study Anandarajah et. al. (2013) analysed the role of hydrogen and electricity to decarbonise the transport sector using a global energy system model, and found that hydrogen and electricity are complementary transport fuels in the short and medium term. In all scenarios the model deploys hydrogen vehicles from 2030 and fuel cell technology becomes cost-effective first in the relatively high-mileage modes of buses and LGVs. This study showed also that the timing of the deployment of hydrogen vehicles is strongly dependent not only on vehicle cost, but also on biomass resource and CCS technology availability, and on global marginal abatement cost. Another study, SBA (2014) claimed that although HFCEVs need to resolve challenges such as refuelling time, mileage range, cost and hydrogen distributions they seem to be the preferable solution for hydrogen mobility compared to hydrogen used in an internal combustion engine (H2ICE) as the latter has a lower efficiency and is more sensitive to the hydrogen cost.

Whether hydrogen will be used for heating or as fuel for the transport sector, a key concern mentioned in many studies is regarding how hydrogen would be produced. JRC (2007) claimed that hydrogen production with natural gas is the cheapest option; electrolysis has by far the highest potential, while the potential for biomass is more limited. The study declared that hydrogen produced from renewable electricity requires less land than using biomass to satisfy the same demand for transport. Coal to hydrogen pathways with CCS could play an important role, however such a switch in the use of coal is an alternative that is not currently backed up by the power sector industry. In conclusion, it is recognised that there are different methods of producing hydrogen and each of these methods have different implications for costs and emissions savings.

Based on the discussion above, it can be concluded that there is diversity in the possible uses of hydrogen. In the medium and long term, however, its use as a fuel in the road transport sector is the main possible role of hydrogen within a decarbonised global energy system. A number of technical issues are recognised in all studies, however one of the main challenges seems to be economic and evidence of emissions savings. Policy and

other mechanisms that encourage incentives for low carbon solutions would be important for hydrogen, and it is envisaged that niche market for hydrogen could soon emerge (for example, applications in remote areas and islands) (SBA, 2014). Further areas of research that would help investors, policymakers and decision makers in better understanding the role of hydrogen in the future energy system are identified in many studies; for example SBA (2014) emphasised the need to develop multidimensional optimisation tools. Such tools should take into account the numerous inputs and outputs that exist, the roll up of revenue streams to demonstrate the profitability of the hydrogen, and the comparison of hydrogen solution with the alternatives in the context of local application specific conditions (SBA, 2014).

1.2 The approach of this study

There are few studies regarding hydrogen in international shipping and they can be divided into three categories: studies specifically focused on hydrogen as a fuel in shipping, studies with a focus on fuel cells in marine applications that have considered hydrogen in combination with fuel cells, and finally, studies with a focus on alternative fuels in shipping with hydrogen among the options. All of these studies have used different approaches which have led to different conclusions. Some studies declared that hydrogen is not suitable for ships for practical, economic and energy efficiency reasons (Ruud Verbeek, 2011), while others see hydrogen as the most distant future alternative marine fuels depending on the associated costs, on the evidence that it helps to reduce GHG emissions, and on future emissions policy (Taljegard et. al., 2014; Argyros et. al., 2014; DNV GL, 2014). More details on those studies will be provided in section 2.2.

The studies that have used a computational modelling approach appear to be more suitable when a large number of factors need to be considered. Using an energy system model, the study Taljegard et. al. (2014) assessed the most cost-effective fuel choice taking into account the dynamics that would occur in the global energy system (e.g. LNG total supply limit) and at some level of detail the type of ship and its technical characteristics (fuel tank system on board). Using a shipping model instead, the study Argyros et. al. (2014) assessed the most profitable fuel choice in shipping taking into account at a great level of detail the technical and operational characteristics of a fleet (by ship type and size categories), the sectoral regulatory framework and the fuel price and

transport demand projections. Although the use of computational modelling approach have provided important and useful insights regarding the potential of hydrogen in shipping, their conclusions appear often contrasting. For example, [Taljegard et.al. \(2014\)](#) claimed that hydrogen would be used in coast-going shipping after 2060, while [Argyros et.al. \(2014\)](#) claimed that an aggressive carbon policy combined with a moderate hydrogen price may lead to a considerable uptake of hydrogen from 2030 in international shipping. More details on those types of studies will be provided in section 2.3.

The way hydrogen has been studied does not appear to satisfy a complete and comprehensive understanding of all factors involved for the exploration of the possible use of hydrogen to fuel international shipping. There is, therefore, the potential for different research techniques that include the ‘whole system’ understanding (both the energy and the shipping systems), with appropriate technological and economic details. Consequently, the following sections are a summary of the state of the art of the two relevant areas: computational modelling in general, the limits of existing models. Finally, the objectives of this study will be identified.

1.2.1 The computational modelling approach

Some authors define computer simulations, others define the computational models used to compute a simulation. A definition of computer simulation is given in [Winsberg \(2013\)](#): *it is a program that is run on a computer and that uses step by step methods to explore the approximate behaviour of a mathematical model of a real-world system (existing or hypothetical)*. A broader definition is also given: a computer simulation is a comprehensive method for studying a system, so it refers to the entire process of choosing a model, implementing, calculating the output, and visualising and analysing the resultant data in order to make inferences about the target system. The latter definition is closer to the definition in [Weisberg \(2012\)](#), which defined the indirect study of real-world systems via the construction and analysis of the model as a case of scientific problem solving. According to the author modelling is not always aimed at purely veridical representation of the target system, rather it aims to identify the features of the system that are most salient to the investigation. In particular, when a computational model is used to explain a phenomenon, generally transition rules or algorithms are used. In this case neither the sequence of the model’s states nor the final equilibrium

state of the model carries the explanatory force but it is the algorithm itself that it is needed to explain a phenomenon.

According to [Winsberg \(2013\)](#), it is possible to divide computer simulations into two main categories: equation-based simulations and agent-based simulations. Simulations that belong to the former are based on global equations that are associated with the theories about how a system works. Simulations that belong to the latter category are based on local rules of evolutions associated with the behaviour of single elements of a system. On the other hand, [Weisberg \(2012\)](#) offered a distinction between mathematical models and computational models stating that the main difference between them is that the computational models *are procedural in the sense that they represent causal properties of their targets by relating these causes to procedures. They can be conditional or probabilistic, all of which are difficult to represent using non procedural structure* unlike in mathematical models. In this study, the computational modelling approach refers to the use of a computational model as defined in [Weisberg \(2012\)](#), such a model is used to compute equation-based simulations as defined in [Winsberg \(2013\)](#).

Regardless of how it is defined, a computational modelling approach is often used for forecasting, in other words it is a simulation of how it is expected that a system in the real world would behave under a particular set of circumstances. For example, in our case the purpose of a computational modelling approach could be stated as the simulation of how the shipping system would behave if hydrogen and fuel cell technologies were available at a certain cost and with some specific technical characteristics. Another example could be the simulation of how the global energy system would behave if it is constrained to meet a certain emission target using a set of technologies (including hydrogen based technologies) to satisfy a number of energy demands.

It is important to note that there are mechanisms that can affect the outcome in real life that is difficult to capture in a model (e.g behaviour aspects or convenience aspects), which requires further analysis.

Many authors seem to agree that all models are made of a structure and an interpretation, so as an interpreted structure [Weisberg \(2012\)](#), [Godfrey-Smith \(2006\)](#), [Pincock \(2012\)](#). A classic example is the Schelling model, which is an agent-based model used to represent movements in the city; in this model the structure is a set of states and transitions rules in a computational space and the interpretation is that there is a similarity between transitions rules instantiated by the agents in the model and the thought

process of actual residents in a city.

In conclusion, appropriately developed computational models can be used to explore a wide range of research questions. The model structure and the interpretation are the key components that are required to be identified in order to rigorously study the intended target system.

1.2.2 The limits of existing models

Modelling frameworks have recently been used to evaluate pathways towards a low carbon shipping system taking into account a number of different factors where different solutions are technically and economically evaluated, such as hydrogen with fuel cells (e.g. [Argyros et. al. \(2014\)](#); [DNV \(2012\)](#)). Similarly, models are also used to investigate possible pathways to reduce the energy and carbon density of the global energy system. Generally, they are used to analyse the cost efficiency of energy technologies such as hydrogen related technologies and conditions that may impact on such technologies under specific CO_2 constraints (e.g. [Taljegard et. al. \(2014\)](#); [Anandarajah et. al. \(2013\)](#)).

The former type of models simulate the evolution of the shipping system. The interpretation is that the technology on board ships would be selected in the real world based on the profit maximisation of the shipowner and shipping regulatory compliance. The latter type of models simulate the evolutions of the global energy system, maximising the social welfare (consumer surplus plus producer surplus) under specific CO_2 constraints. The interpretation is that energy technologies would be selected in the real world based on the theory that the most cost-effective technology would be used.

If a “shipping model” is used to investigate hydrogen as an alternative marine fuel, it is possible to analyse the interactions that occur within the shipping system. For example, hydrogen powered ships are technically and economically evaluated taking into account several factors such as the weight, volume and cost of hydrogen fuel storage on board, and the profitability for different ship type and ship size in comparison with other options. However, the limit in this type of model is that a number of exogenous assumptions are used to include the signals from the global energy and economic system such as the fuel prices. Often the results are very sensitive to these types of assumptions and the dynamics of hydrogen supply and demand in shipping are external to the model.

If an energy system model is used to investigate hydrogen as an alternative marine fuel, it is possible to capture to a certain level of detail the competition for primary energy resources to produce hydrogen, the spatial factors, and the effects of global economic and climate policy drivers. However, the shipping system is generally poorly represented, and the model is not able to capture the interaction between the technical and operational specifications of hydrogen powered ships.

Both types of models appear to fail to take into account the combined effect of the supply and demand balance of hydrogen as an alternative marine fuel. This suggests that a more rigorous approach is needed with a more complex representation of hydrogen uptake in shipping. More details on the modelling representation of hydrogen uptake in shipping for two existing models will be provided in chapter 3.

1.2.3 The objectives of the study

There are contrasting agreements on the possibility to use hydrogen to fuel international shipping. The use of a modelling approach has helped to better understand such topic. Two existing types of models have been used, however there is a methodological disagreement in how to model the uptake of hydrogen in shipping; the first type of model is driven by the least cost to reach a global CO_2 reduction target, the other type of model is driven by the profitability for the ship owner of using hydrogen powered ships. The literature generated from the use of such models is considered inadequate because the dynamics of the supply-demand balance of hydrogen as an alternative marine fuel has been ignored or there is little information available on the balance in both modelling methods. By soft-linking these types of models the strengths of both can be used to overcome the lack of a robust method to investigate the potential of hydrogen to fuel international shipping.

The research questions of this thesis are:

1. Can an integrated framework that combines two different models improves the modelling representation of hydrogen uptake in shipping compared to the current representations found in the literature?
2. What type of results does the integrated framework provide regarding the potential of hydrogen to compete with LNG and current marine fuels to fuel international shipping? Under what circumstance would hydrogen be able to compete with LNG

and current marine fuels in shipping and what would be the main economic and environmental implications

This thesis has two main objectives: the first objective is the development of a new modelling approach that soft-links two existing types of model in order to improve the modelling representation of hydrogen uptake in shipping. More details on existing literature on how to soft-link two models will be provided in chapter 4. The hypothesis is that the model linkage is able to explore specified scenarios, forecasting investment decisions for hydrogen powered ships, in conjunction with hydrogen infrastructure development.

The second objective is the analysis of the possible use of hydrogen under specific scenarios in order to understand at a global level the implications of providing and using hydrogen in shipping. The hypothesis is that the model linkage is able to explore the broader circumstances in which it would be possible to see an uptake of hydrogen in shipping and what this means for the contribution of shipping in avoiding 2°C of increased temperature compared to the industrial level.

The purpose of this thesis is to learn more on hydrogen as a future fuel in shipping taking into account the big picture. This thesis is identified as being of importance to assist ship owners and fuel providers in understanding the potential of hydrogen in shipping, and to assist policymakers in the development of effective GHG policy for shipping, providing a comprehensive understanding of the implications of using hydrogen in shipping within the context of a decarbonised energy system. It is hoped that information from this thesis may be useful in creating awareness of the potential that hydrogen might have in shipping and create incentives in exploring these options at different levels in order to demonstrate that hydrogen could be the means for a large reduction in shipping emissions. Moreover, this thesis explores the application of a relatively new modelling technique of soft-linking two existing models. The experience engaged in developing such a link could be useful to educators and modellers interested in the soft-linking modelling approach.

1.3 The structure of this thesis

The remaining chapters are organised as following: chapter 2 comprises of a literature review of the main studies concerning the use of hydrogen as a fuel in shipping. The purpose of this chapter is the identification of the gaps in the literature that leads to

the research questions. Existing approaches are evaluated and a particular focus is on the computational modelling methods.

In chapter 3 the modelling representation of hydrogen uptake in shipping is examined in order to identify the specifications required for a complete and adequate representation. The bottom-up energy model TIAM-UCL and the bottom-up shipping model GloTraM are analysed in this chapter with their relative representational capacity of the target system. The studies that have linked two different models are also reviewed. Finally the gaps in the literature are identified as well as the research questions.

Chapter 4 identifies an appropriate method that can be used to answer the identified research questions, and then develops the method used to soft-link two existing models (TIAM-UCL and GloTraM). Linking two computational models is a relatively new method, therefore this chapter starts by critically analyses existing studies that have applied soft-linking methods. A number of steps are identified in order to soft-link the two models. Each step is developed in greater detail along with the associated assumptions.

Chapter 5 explores the evidence as to whether the soft-linking framework improves the modelling representation of hydrogen uptake in shipping. This chapter is intended to address the first research question by describing and comparing the results of independent simulations of TIAM-UCL and GloTraM and the results of TIAM-GloTraM. Two different scenarios are examined. They explore the evolution of the global energy system in conjunction with the shipping system under two different emissions reduction targets.

Chapter 6 examines the potential of hydrogen to be an alternative marine fuel. This chapter is intended to address the second research question. A different scenario is explored with diverse circumstances to explore what may lead to the adoption of hydrogen as a fuel in shipping. The results from this scenario are described in detail, analysing the implications in both the energy and the shipping systems. This chapter comprises also of a robustness analysis where the resulting inferences are tested by exploring a number of scenarios. This analysis is carried out in order to understand the relationship between given uncertain input factors and the model output. The robustness analysis highlights the relationship between specific input factors and the possible uptake of hydrogen in shipping. It also identifies specific dynamics between the energy and the shipping systems that can influence the potential of hydrogen to be an alternative marine fuel.

Finally, discussion and conclusions are provided in chapter [7](#) .

Chapter 2

Literature review

2.1 Introduction to the literature review

This chapter provides a literature review of the main studies concerning the use of hydrogen as a fuel in shipping. The aim is to identify possible gaps in the literature and therefore the needs for further investigations. The idea of hydrogen in shipping is associated with the portfolio of technology solutions that the shipping industry has in order to improve its energy efficiency, and to reduce its carbon intensity. Different scopes have been investigated for such technology solutions in shipping. The efficiency of hydrogen powered ships, for example, is under investigation with the analysis of operating prototypes. The potential efficiency of hydrogen in combination with fuel cell systems on board ships has also been investigated by studies that have focused on maritime applications of fuel cell systems. Other scopes have included environmental and economic factors to drive the possible adoption of hydrogen in shipping, taking into account the supply of hydrogen. A number of approaches have been used such as the analysis of empirical data, the cost-benefit analysis, cross-modal comparison, life cycle assessment, general assessment, simulations of a ship's main engine, and the use of computational models to simulate the shipping system or the energy system. In this thesis particular focus will be given to the studies that have used a computational modelling approach, although it is recognised that other approaches have already provided a number of useful insights.

The modelling approach has been applied with different purposes; for example, some studies have discussed on the potential of hydrogen in shipping but with the broader scope of studying alternative fuels in shipping. Other studies have focused on hydrogen as fuel but without considering shipping among the possible users. The implications for the modelling representation of the use of hydrogen in shipping will be reviewed in this chapter. The purpose of such a review is the identification of the required specifications that need to be considered for hydrogen's modelling representation in shipping.

This chapter is organised as follows: section 2.2 provides a review of existing approaches evaluating methods used and conclusions. In section 2.3 the existing approaches are evaluated for being the most suitable method to investigate the potential use of hydrogen in shipping. Section 2.4 provides a review of other relevant studies to analyse the background theory and identify implications on the modelling representation of the use of hydrogen in shipping. Finally, the identified implications are discussed in section

2.5, which also provides an examination of how hydrogen has been modelled and how such representations fit with the identified implications.

2.2 Existing approaches and main conclusions

The literature on hydrogen for marine applications is not extensive compared to what is available on hydrogen for other transport sectors. It is possible to divide this literature into three categories: studies specifically focused on hydrogen as a fuel in shipping, studies with a focus on fuel cells in marine applications that have considered hydrogen in combination with fuel cells and, finally, studies with a focus on alternative fuels in shipping with hydrogen among the options.

Few studies were found in the first category that particularly focused on hydrogen as fuel for shipping. [Bevan et.al. \(2011\)](#) and [Bulletin \(2013\)](#) have described the construction of prototypes which have been built to demonstrate the technical feasibility on board a ship, on a canal boat and a small cruise boat respectively. Both examples are successfully operating. The installation on board submarines is also another successful example of the practical implementation of hydrogen technology on board, as described in [Sattler \(1998\)](#) and [Psoma and Sattler \(2002\)](#). Other studies have provided possible concept designs on board specific ships. [Veldhuis et.al. \(2007\)](#), for example, studied the potential for hydrogen considering a high speed catamaran serving specific routes. [Upadhyay et.al. \(2011\)](#) proposed an integrated multiple modular hydrogen fuel cell drive, and [Mulder and Mulligan \(2010\)](#) proposed a hybrid electric tug powered for 80% of the operational hours with fuel cell/battery hybrid and hydrogen and the remaining 20% with a diesel generator/battery hybrid. Two other studies have been carried out discussing the idea of using hydrogen as fuel in shipping. [Farrell et.al. \(2003\)](#) suggested as the best strategy to introduce hydrogen as a transportation fuel is to use it in international cargo shipping. The study used a cross-modal comparison in order to determine the best strategy. [Koeffman \(2012\)](#) provided an interesting assessment of all main implications of using hydrogen as fuel for shipping such as: the sourcing of hydrogen, the comparison with other fuel competitors, the loading and storing of such fuel on board ships, the most suitable type of prime mover and the implications for the ships' architecture.

In the second category there are the studies that have focused primarily on fuel cells in maritime applications and that have made considerations regarding hydrogen on

board ships. They are [Vogler \(2010\)](#), [Sattler \(2000\)](#), [Ludvigsen and Ovrum \(2012\)](#), [Han et. al. \(2012\)](#). While discussing the fuel cells applications on board ships, these studies have highlighted a number of key factors where fuel cells are used in combination with hydrogen. Mainly the discussion is about the type of hydrogen storage system that would be used on board and other requirements that would be needed to handle this type of fuel.

Studies with a focus on alternative fuels in shipping with hydrogen among the options are included in the third category. It is possible to further divide these studies into two subcategories. The former includes two studies that have compared alternative fuels against several technical, economic and environmental criteria to drive possible future adoptions in the shipping industry. [Ruud Verbeek \(2011\)](#) used different sources to discuss the production, the short and long term potential and the cost of each alternative fuel, while [DNV GL \(2014\)](#) discussed the technological challenges and potential benefits from each alternative fuel and provided a life cycle assessment (well-to-propeller analysis).

The latter subcategory includes studies that have used computational models to assess the introduction of alternative fuels in shipping. [Taljegard et. al. \(2014\)](#) used a cost optimisation energy systems model (Global Energy Transitions - GET RC 6.2) to analyse the cost-effective fuel choices in shipping under stringent CO_2 emissions reduction targets. While [Argyros et. al. \(2014\)](#) used the Global Transport Model (GloTraM) to analyse the role and demand for different fuels and energy efficiency technologies. This model simulated the global fleet activity and its technological and operational evolution in response to external drivers such as fuel prices, transport demand, regulations and technology availability. Details of the hydrogen representation for this model are given in section 3.3 and in chapter 4.

A number of considerations can be highlighted from such a variety of approaches concerning the use of hydrogen as fuel in shipping. On one hand the experiences gained with the practical installations on board lead to the conclusion that it is technically feasible to accommodate hydrogen and fuel cells systems on ships. On the other hand it is difficult from this type of approach to drive conclusions on the potential of hydrogen to fuel international shipping. A number of studies have dedicated their attention to possible concept design options for several types of ships, highlighting that for applications on board large ships different design challenges still need to be addressed. In general, many authors seem to agree that these key factors for the technical and economic analysis of

hydrogen as a fuel in shipping are: the weight and volume impacts of the hydrogen fuel storage system used on board, the capital and operational costs associated with both the storage system and the combined main propulsion machinery, and the associated efficiency of the main propulsion engine (Upadhyay et.al., 2011; Veldhuis et.al., 2007; Ludvigsen and Ovrum, 2012; Han et.al., 2012).

Particular attention has been given to the hydrogen storage systems. The maximisation of the volumetric and the gravimetric energy density of the stored fuel is an important challenge. Although today the most commonly used hydrogen storage system is high-pressure gas cylinders, the low volumetric density is considered a key limitation for application on board ships. In accordance with several studies, large storage cylinders are estimated to be 4-7 times in volume the traditional fuel oil tanks (Taljegard et.al., 2014; DNV GL, 2014; Vogler, 2010). Liquid hydrogen stored in a cryogenic state has been considered in Veldhuis et.al. (2007), Han et.al. (2012) and DNV GL (2014). The main concerns are the low temperatures, the large energy losses, and the space required for very well insulated fuel tanks DNV GL (2014). Moreover, if liquid hydrogen is stored in a cryogenic state, it requires a refrigeration unit which adds extra cost Han et.al. (2012). Another promising hydrogen storage option that was investigated for marine applications is the metal hydrides hydrogen storage system, which has been tested successfully in submarines. The main disadvantage of metal hydrides hydrogen storage for merchant ships is the low weight percentage of hydrogen (Han et.al., 2012; Sattler, 1998). Others future options would be a carbon nano-fibres system or the generation of hydrogen on board from easy-to-store hydrocarbons Sattler (1998). In the latter case the efficiency of a reformer has to be taken into account in the overall efficiency of the tank to propeller system. Besides the type of hydrogen storage system chosen, special safety considerations have to be taken into account when hydrogen is stored on board ships due to its low flammability limits. New requirements would be needed such as ventilation, alarm systems and fire protection, as well as the introduction of other measures to limit the likelihood and consequences of hydrogen leakage (Ludvigsen and Ovrum, 2012).

The main engine choices for a hydrogen fuelled ship are: fuel cells and gas turbines. Few information was found on hydrogen used in gas turbine for ships, while a specific topic of interest in many of the studies is the use of fuel cells as a propulsion device associated with hydrogen, therefore it is important to consider some of the main challenges for this type of system in marine applications. The power requirement is a challenge as fuel

cell systems with at least 500kW of power would be needed. In general fuel cells will need to achieve from 1 to 5 MW to be considered a substitution for the electrical power. Other challenges are: the high investment costs, the dimensions and weight of fuel cell systems, their expected lifetime, their response at transient loads, and the energy and emissions associated with their life cycle. It is recognised that these issues need more investigations ([Vogler, 2010](#); [DNV GL, 2014](#)).

Fuel cell systems on board ships also have a number of advantages; first, the potential reduction of fuel consumption through improved efficiency, second, the consequent reduction of emissions. Other advantages can be the insignificant noise and vibration levels, the potential design flexibility and lower maintenance requirements. Because of these advantages [DNV GL \(2014\)](#) claimed that fuel cells can become a part of the future shipping power systems portfolio and that the recent commercialisation of certain land-based fuel cells applications can facilitate their use in shipping in the future.

Fuel availability and price are very important factors too for the use of hydrogen in shipping. It is recognised that hydrogen as a fuel can be difficult and costly to produce, transport and store. On the other hand, hydrogen is considered competitive when it can be produced using the surplus of energy from solar or wind energy that the grid cannot take ([Ruud Verbeek, 2011](#)), although it depends on the capacity factor of the electrolyzers. The distribution network for hydrogen and for any other new alternative fuel is currently limited ([Ludvigsen and Ovrum, 2012](#)), which raises a high level of uncertainty regarding the long-term availability of such fuel. These issues are associated with the upstream process, which should be taken into account also in terms of emissions emitted. The impacts of upstream emissions caused from fuels that appear attractive on the basis of their potential low operational emissions are not yet completely understood. The effects of bringing alternative fuels into port terminals are often studied with LCA, however more investigations are needed as it is difficult to find robust results that define such types of effects.

Conclusions regarding the potential hydrogen uptake in shipping from the studies that have been reviewed in this study are contrasting. On one hand there are studies that have predicted hydrogen as being unsuitable for ships for practical, economic and energy efficiency reasons, suggesting that traditional marine fuels will remain the preferred marine fuels. LNG appears to be the first alternative, depending on two main factors: the price and evidence that it helps to reduce GHG emissions ([Ruud Verbeek, 2011](#)),

and the cost of the storage tank (Taljegard et al., 2014). Hydrogen is seen as the most distant future alternative to the marine fuels together with synthetic fuels and biofuels depending on the characteristic of the ship (Taljegard et al., 2014). On the other hand there are studies that have envisaged a more diverse fuel mix in the future where LNG, biofuels, renewable electricity and hydrogen all play important roles (DNV GL, 2014). It is also suggested that a more aggressive emissions reduction policy combined with a moderate hydrogen price may lead to a considerable uptake of hydrogen (Argyros et al., 2014).

Other conclusions come from considerations regarding the characteristics of the markets. DNV GL (2014), for example, claimed that for some shipping segments there are not incentives for owners to explore any alternative fuel as fuel costs are paid by the charterer. Farrell et al. (2003) claimed that historically there has been a slow adoption in innovations in the maritime industry. Whereas Ludvigsen and Ovrum (2012) claimed that the increased availability of alternative fuels in other sectors may also accelerate the introduction in shipping, while Farrell et al. (2003) claimed that the introduction of hydrogen in shipping would be a more effective way to advance hydrogen-related technologies.

This section highlights the fact that there are different approaches for the study of the use of hydrogen in shipping. It is difficult to drive robust conclusions due to the numerous factors that need to be considered. The possible advantages and disadvantages or benefits and barriers are all well described, however the conclusions regarding the potential of hydrogen to fuel international shipping are contrasting.

2.3 Studying hydrogen in shipping with a computational modelling approach

As discussed in the previous section there are different approaches for the study of hydrogen as a fuel in shipping. In general they differ on the type of method used and the specific questions that can be answered. Often, different approaches lead to different conclusions. The boundaries in each approach can help to define the limitations and the robustness of the relative conclusion. In this section, the existing approaches are evaluated for being the most suitable method to investigate the potential use of hydrogen

in shipping. By doing this, techno-economic modelling and social-technical transition methods are also compared under a broader view.

The first existing approach is the construction of prototypes of hydrogen powered ships. Although they are very important to overcome technical obstacles and to explore the technical feasibility, they are not sufficient for answering questions about the future potential use of hydrogen on a large scale. So it is too for the studies that have focused on the concept designs of a hydrogen powered ship including the studies with a focus on the installation on board of hydrogen in combination with fuel cell systems. They are very useful to identify technical challenges, but they are generally limited to a techno-economic analysis of one specific ship, sometimes taking into account few serving routes as, for example, in [Veldhuis et. al. \(2007\)](#). The boundaries of these studies are depicted to have as a core either the ship itself or a type of ship, and they generally exclude the dynamics of the shipping system.

The second approach is the assessment based on technical, economical and environmental criteria as in [Farrell et. al. \(2003\)](#), [Koefman \(2012\)](#), [Ruud Verbeek \(2011\)](#), and [DNV GL \(2014\)](#). This type of approach can be categorised under the social-technical transition methods. They deal with technological transitions identifying patterns and mechanisms in the transition process. They can be very useful to identify socio-technical drivers that are difficult to capture such as market barriers, political development, and other global economic factors. Despite that, the conclusions reached with this type of approach rely on assumptions that are very uncertain, sometimes not supported by a reliable quality of empirical data, therefore they appear insufficient robust.

As mentioned, hydrogen is part of the solution that can reduce the energy and carbon intensities of the shipping industry; the energy intensity of the shipping system has been studied with the computational modelling approach such as that used in [Taljegard et. al. \(2014\)](#) and [Argyros et. al. \(2014\)](#). They have used a modelling framework that is generally implemented to investigate possible pathways to reduce the energy and carbon intensities of the specific shipping sector or several sectors together.

Energy system models are one example. This type of model is used to analyse the cost efficiency of energy technologies and conditions that may have an impact on such technologies under specific CO_2 emissions reduction constraints. They can be very useful to assess the effect of new policies, although they are not able to generate scenarios of the evolution of the energy system. Sectoral models such as shipping models are

another example. They are suitable for evaluating pathways towards a future shipping system taking into account a number of different factors such as the scale effect of a ship's size, the ship's technical design and the ship's operational specification under different shipping policy scenarios. In a sectoral model energy efficiency solutions can be technically and economically evaluated.

Different approaches can answer questions to a certain level of detail from different perspectives; the computational modelling approach seems to be the most appropriate tool when a large number of factors need to be taken into account. The uptake of hydrogen in shipping depends not only on its implementation on board ships but also on other factors that describe sectoral and global pathways of energy and carbon intensities reduction. In this thesis, therefore, the focus is on the computational modelling approach as it is considered to lead to new useful contributions regarding the potential of hydrogen to fuel international shipping.

2.4 Other relevant studies for modelling hydrogen in shipping

The focus of the following literature review will be on the computational modelling approach, therefore the modelling representation of hydrogen in shipping becomes of significant importance. In this section two other categories of study that are interesting for the discussion of the modelling representation of hydrogen in shipping are broadly examined. The first category includes the studies that have used computational models for investigating other alternative fuels in shipping rather than hydrogen, while the second category includes the studies that have modelled hydrogen as a future energy carrier in other sectors. Both of these types of study are important for our study because by analysing the background theory it is possible to identify implications on the modelling representation of the use of hydrogen in shipping.

2.4.1 Existing models for the study of other alternative fuels in shipping

There are a number of studies that have used models to investigate the uptake of other alternative fuels in shipping in which hydrogen is not included. Some models take into consideration several fuel options, many others consider only LNG as an alternative.

A complete review is not in the scope of this thesis, rather the focus is only on the specifications embedded in the models used. Such specifications are useful to identify factors that are considered significant when modelling hydrogen uptake in shipping.

Among those models that explore other fuel options there is one used in [DNV \(2012\)](#). This study was carried out using a simulation model very similar to the one used in [Argyros et. al. \(2014\)](#). This model simulates how ship owners seek to comply with regulations and increased energy efficiency requirements by investing in new technologies. It is very similar in structure to the model used in [Argyros et. al. \(2014\)](#), however it is less rich in technological details. Environmental and energy efficiency regulations are included in the model. These specifications highlight the need to take into account the effect of such regulations both in the investment decision process and in terms of environmental impacts. In this study LSHFO, MGO and LNG are taken into account as alternative fuels to HFO. A key assumption is LNG price projections, which can be obtained in two different ways: linked to crude oil price or as an independent gas market. Historical prices are used to parametrise the model. As in [Argyros et. al. \(2014\)](#), fuel prices are exogenous to the model and this sophistication on LNG price projection highlights the need to link fuel price assumptions with the dynamics that belong to the supply of such fuel. [DNV \(2012\)](#) concluded that in the future the viability of many emission reduction technologies depends heavily on various fuel prices and their relative price differences.

The study carried out by the Environmental Protection Agency [EPA \(2008a\)](#) developed a framework to examine the petroleum refining industry and the marine fuels market. In this study a model of shipping activity was used to estimate regional and worldwide projections of future marine fuels demand. The model of shipping activity estimated future fuel consumptions based on trade commodity projections, ship characteristics and voyage characteristics. Then these consumption projections provided a baseline for the WORLD model, a bottom-up model of the downstream oil sector, which was used to establish projections of future refining activities. These specifications highlight two main implications: the first is the need to represent the characterisations of ships and voyages in greater detail to capture the dynamics inherent to the shipping system. The second is the need to use the information from the shipping model in a more sophisticated model that is able to represent the supply side; in this case limited to the supply of oil products.

There are other studies that have looked only at LNG as an alternative fuel for shipping, addressing different technical challenges on board and offshore. [Semolinos \(2013\)](#) and [Verbeek et. al. \(2011\)](#) have provided an economic account for the development of LNG as a marine fuel. In these studies the techno-economic analysis have used assumptions on investment costs on board ships and logistic costs of LNG port terminals. It is important to note that both models distinguished different types of aggregation. Particularly, [Semolinos \(2013\)](#) made considerations to represent the possible LNG supply chains for small and large ports at first and later phases of development, while [Verbeek et. al. \(2011\)](#) considered three types of ships: a short sea ship, a port ship and an inland ship. These specifications highlight the need to take into account the constraints and implications associated to the refuelling process at a greater level of resolution.

Another study is [GL \(2011\)](#) which provided a cost and benefits analysis of LNG as a fuel for container ships taking into account specific costs for LNG technologies on board different size ships and with varying fuel prices scenarios. This implies the need to include the cost differences among ship types and sizes. A final example is [Lloyds Register \(2012\)](#) which used a top down approach to provide a perspective on future LNG fuel demand looking at trading patterns, refuelling demand and LNG supply availability issues. A model was used to forecast LNG demand as a function of regulations, availability of LNG at key ports and deployment of new buildings on selected trade routes. Input data was collected through a survey of shipowners and port authorities. This method highlights the need to assess the likely adoption of LNG or any other alternative fuel taking into account both the shipowners' and fuel suppliers' perspectives.

As discussed, other alternative fuels in shipping have been studied with techno-economic modelling methods. Such methods have particular specifications that are useful to identify significant factors that a model should consider when modelling the uptake of hydrogen in shipping. Such factors are: the environmental and energy efficiency regulations, the fuel prices and availability as a function of factors associated to the supply of such fuel, an adequate resolution of the representation of the supply and refuelling process, and an adequate characterisation of ships and voyages.

2.4.2 Existing models for the study of hydrogen in other sectors

There are a large number of studies that have used models to analyse hydrogen as a future energy carrier. A complete review is not in the scope of this thesis, and it can

be found in [Dagdougui \(2012\)](#), [Joffe and Strachan \(2007\)](#) and [Agnolucci and McDowall \(2013\)](#). Hydrogen in energy models has been approached in different ways. One classification of models and approaches is proposed in [Dagdougui \(2012\)](#), and it includes mathematical optimisation methods, decision support system based on a geographic information system, and assessment plans for a better transition to hydrogen economy. Another categorisation can be found in [Joffe and Strachan \(2007\)](#), which identifies modelling approaches such as the following: optimisation models with or without spatial models, scenario-based models with or without spatial models. Furthermore, [Agnolucci and McDowall \(2013\)](#) discussed optimisation techniques that have used Mixed Integer Linear Programming (MILP) models with explicit spatial representation of the hydrogen network on regional and local scales. Despite the fact that these studies have not considered hydrogen in shipping, a number of useful insights regarding the modelling representation of hydrogen can be obtained. In particular, the focus here is on the challenges involved in modelling hydrogen in such models.

In order to provide a reasonable analysis of the possible pathways for hydrogen development within the modelling approach, there are a number of challenges that need to be considered. They are: the representation of the competition for primary energy resources, the representation of the spatial factors of the hydrogen infrastructure development, and the level of technical detail required to appropriately represent the various hydrogen pathways. Essentially these challenges are model specifications that are required respectively for: including the impact of the resource competition on future energy demands, representing the geographical dependencies of hydrogen infrastructure on the use of local resources and on the distribution distance and flow rate, and including the technological characterisation of different resolutions ([Joffe and Strachan, 2007](#)).

2.5 Implications on the modelling representation of hydrogen in shipping

Existing studies regarding hydrogen in shipping have been examined focusing on the techno-economic modelling methods. Other relevant models have been discussed highlighting factors and implications for the representation of alternative fuels in shipping and hydrogen in models. The target system in this thesis is the hydrogen uptake in

shipping. According to [Weisberg \(2012\)](#), before accounting for the representational capacity of a model it is important to establish the relationship between the target system and the model. Such a relationship can be analysed looking at the background theory of the existing studies examined above. If we assume that this background theory is rich enough, then we are able to highlight the feature set that is needed in a model to be representative of our target system.

Hydrogen on board ships implies the representation within a model of the technological concept design of hydrogen and the associated main propulsion system in a certain level of detail. For example, if hydrogen was to be used with fuel cells, all implications associated with the technological components should be represented, such as efficiency of fuel cells, power density, required safety systems, effect on the cargo capacity and range, capital and operational costs.

A hydrogen powered ship would operate within the shipping system, and it would compete with other alternative and conventional ships in different shipping markets characterised by specific voyage, operational specifications, ship type and size. Moreover, other factors can influence the viability of a hydrogen powered ship such as the shipping regulatory framework and changes in the transport demand. This implies also that the representation of the shipping system within a model should be included in a certain level of detail.

Hydrogen needs to be available at port refuelling terminals, therefore the representation within a model of the hydrogen supply chain for shipping should be included. Hydrogen production, transportation and storage should be modelled in a certain level of resolution. Hydrogen supply chain would interact with the rest of the global energy system, competing for primary energy resources, and satisfying the demand of other sectors. This implies also that the representation of the energy system within a model should be included in a certain level of detail.

Finally, the price of producing hydrogen would affect the demand for such fuel and at the same time the demand would affect the hydrogen price. A need to capture the balance of supply and demand is required in a model such as in the approach used in [EPA \(2008a\)](#).

Table 2.1 summarises the feature set of an ideal model that we assume to be representative of the hydrogen uptake in shipping. These specifications define the feature set of an ideal model that is assumed to be representative of the hydrogen uptake in

shipping.

TABLE 2.1: Specifications for the representation of hydrogen as a fuel in shipping and required model feature

Specifications	Required model's feature
Technological details of the concept design options for hydrogen and main machinery systems on board ships	Accounting for the key technological components, their energy and emissions factors Technical compatibility of hydrogen technologies and other energy efficiency technologies Impact of weight and volume of hydrogen storage systems on board Accounting for the costs of hydrogen storage systems, costs of the associated main machinery and costs of maintenance of hydrogen-main machinery option, and other associated costs
Economic analysis of hydrogen-main machinery option	Simulation of the investment evaluation process of hydrogen technologies along with all the other alternative options
Details of the shipping system specifications	Segmentation by ship type and size Characterisation of voyages, operational data and routes Accounting for current and main alternative fuels competitor Accounting for current and future environmental and energy efficiency shipping regulations
Technological details of the hydrogen supply chains for port terminals	Accounting of different hydrogen infrastructure pathways Costs of producing, transporting and storing hydrogen Accounting for the emission effects of bringing hydrogen to port terminals
Details of the energy system specifications	Interaction of hydrogen supply chains for shipping with the rest of the global energy system Accounting of competition for primary energy resources Accounting of spatial factors Influence of the changes in transport demand of energy commodities Accounting of regulations on global CO_2 emissions reduction targets
Hydrogen price for shipping	Balance of supply and demand for hydrogen in shipping

In general, hydrogen modelling representation can be found in the literature in two different types of models: in energy models in which the focus is on the representation of the hydrogen supply chain, and in sectoral models in which the focus is on the representation of hydrogen end-user technologies. Such models differ from each other in

their aims, system boundary and geographical scale, and in theory they are all suitable to represent hydrogen in shipping but in a different manner.

Some of these models focus on the hydrogen supply infrastructure at a local or national scale, answering questions regarding the best configuration that optimises a specific object function. In these studies a greater level of technological detail on the hydrogen supply chain is provided, however many inputs such as energy resource availability and demand are exogenous to the models. These types of models are suitable for assessing the deployment of hydrogen supply chain technologies on a local scale, for the assessment of the refuelling process of hydrogen in a particular area, for example. Due to the international nature of the shipping industry, an aggregation at global level of resolution is considered more appropriate. Moreover, these models generally lack the appropriate technological details of hydrogen end-user technologies, for example hydrogen powered ships are rarely included. Moreover, they lack an economic analysis to assess the market penetration of hydrogen end-user technologies, and the interactions with the rest of the energy system are not modelled.

In contrast, other models have a complete representation of the energy system, in which the hydrogen supply chains and hydrogen end-user technologies are both modelled. The level of resolution of such models depends on the system boundary (e.g. only one sector, the whole energy system), and on the geographical scale (e.g. local, regional, global). Such models have a common aim, which is the simulation of consistent scenarios of change in the energy system under specific emissions reduction constraints ([Schafer, 2012](#)). The impacts of hydrogen technologies on the energy system can be assessed through the analysis of such scenarios. On one hand these types of models have a good representation of the energy system and an appropriate level of technological detail on the hydrogen supply chain. On the other hand they have a poor level of technological detail of hydrogen end-user technologies and energy service demand. An example of this type of model is described in [Taljegard et. al. \(2014\)](#), where a bottom-up energy model was used, and in which the entire shipping fleet was divided into only three categories: container, coast and ocean-going ships.

In contrast to the energy model discussed above, hydrogen can be represented also in models that aim to represent a specific sector. Generally, in these types of models the focus is on the hydrogen end-user technologies rather than on the supply chain technologies. These models can have a good level of technological detail of hydrogen

end-user technologies, and are often used to analyse the market penetration with specific economic evaluations. The literature is rich of models for hydrogen in the road transportation system, and few examples can be found for hydrogen in shipping. These types of models generally lack a proper level of technological detail of the hydrogen supply chain and the energy system.

In conclusion, based on the identified specifications there is no existing model that can be considered representative of the hydrogen uptake in shipping. Energy models include some factors and shipping models include other factors. Rarely are they used in conjunction to explore the balance of supply and demand. The bottom-up energy system model TIAM-UCL and the bottom-up simulation model of the shipping system GloTraM are examples of these types of models. A close look at these specific models can help to identify how the representation of the target system may be improved.

Chapter 3

Methodology and research question refinement

3.1 Introduction to the methodology

The conclusion from the previous chapter is that an existing model that can be considered being fully representative of the hydrogen's uptake in shipping does not exist. Energy system models and shipping models can partially be considered representative as they do not include all specified specifications. In this chapter, a possible framework for a complete representation of our target system is examined. The framework is composed of the bottom-up energy system model TIAM-UCL and the bottom-up shipping system model GloTraM. The representation of hydrogen in both models is assessed against the required specifications with the purpose of identifying shortcomings and areas of improvement. Hybrid models that link together two different models are also examined in order to evaluate if they are an appropriate method to resolve the gap identified in the literature. This analysis will motivate the two the research questions.

This chapter is organised as follows: the theoretical representational capacity of the shipping model TIAM-UCL is assessed in section 3.2, while section 3.3 assess the theoretical representational capacity of the energy system model GloTraM. Finally, section 3.4 justifies why a linking approach can be an appropriate method for the study of hydrogen as a fuel in international shipping, and identifies the gap in the literature and the research questions.

3.2 The representation of the target system in TIAM-UCL

The 16-region TIAM-UCL global energy system model has been developed at UCL through the UK Energy Research Centre (UKERC). It is a linear programming cost optimisation model which minimises total discounted energy system cost in the standard version and maximises social welfare (consumer surplus plus producer surplus) in the elastic demand version over the modelling period (Loulou and Labriet, 2008). TIAM-UCL models all primary energy sources (oil, gas, coal, nuclear, biomass and renewables) from production through to their conversion, infrastructure requirements and, finally, to sectoral end use. In each region, resources and costs of all primary energy production are defined. After a number of processes, several energy commodities can be used directly within the region or can be traded (McGlade and Ekins, 2015). Hard coal, crude oil, refined products including heavy fuel oil, natural gas, both in pipelines and as liquefied natural gas can be traded between different regions. The trade of hydrogen is

not allowed. Energy service demands are initially based upon energy balances in 2005 and are projected using drivers such as GDP, population, number of households, sector output, etc. ([Anandarajah et. al., 2011](#)). The climate module of TIAM-UCL, which converts emissions to atmospheric concentrations to radiative forcing to temperature rises, constrains the model to a certain average global temperature rise. It is assumed that the model has a perfect foresight. The start year is 2005 and the end year is 2100 with 5 years time-step, however, the results are generally shown only for the period from 2010 to 2050. A detailed description of input assumptions, approaches and data sources for TIAM-UCL can be found in [Anandarajah et. al. \(2011\)](#).

TIAM-UCL has been used in a number of studies and it is continuously developed and maintained by UCL. Particularly, it has been used in [Anandarajah et. al. \(2013\)](#) for developing long-term scenarios of the energy system to analyse the role of hydrogen and electricity to decarbonise the transport sector, and in [McGlade and Ekins \(2015\)](#) to explore the implications of a certain emissions limit for fossil fuel production in different regions. TIAM-UCL includes the representation of hydrogen infrastructure, and the representation of the shipping system.

3.2.1 The representation of hydrogen infrastructure in TIAM-UCL

The representation of hydrogen infrastructure in TIAM-UCL consists of different pathways in the supply side of the model ([Anandarajah et. al., 2013](#)). Each pathway can be divided into several components: production, transportation, liquefaction, distribution, refuelling stations and end-use sector.

The production technologies are categorised into three classes: centralised large, centralised medium, and decentralised plants. The centralised plants can be steam methane reforming (SMR), coal gasification (CG) and biomass gasification (BG) and they can be equipped with carbon capture and storage (CCS), although at additional cost and with an efficiency penalty. Centralised medium size hydrogen plants can instead be SMR, BG, and electrolysis. Finally, decentralised plants can be SMR, BG, electrolysis with decentralised electricity production and with centralised electricity production. A number of other production technologies such as biomass IGCC, biomass oil SMR, waste gasification, nuclear, thermolysis, photocatalytic could become important in the future and should be included for an accurate representation of hydrogen production. They are not present in this version of TIAM-UCL as they are more immature technologies

and generally with higher production costs in comparison with the ones included in the model, so they would not add much to the representation of the hydrogen production.

Generally hydrogen transportation depends on the type of production plants. Hydrogen produced from large scale plants can be transported in liquefaction plants that can be built at the production site or close to demand sites or can be transported through pipelines in gaseous form. Hydrogen produced from medium scale plants is assumed to be located closer to demand sites, which imply short distance transportation through pipelines or by truck as liquid hydrogen. Hydrogen produced from decentralised small scale plants does not have any transportation cost and differs from the previous production plants because it can be produced with electricity generated by decentralised wind and solar plants.

Once hydrogen is transported the distribution can take place. Liquid hydrogen can be distributed to the transport sector by the means of refuelling stations. The latter includes the re-gasification process as it is assumed that vehicles would adopt only high-pressure gas cylinder hydrogen storage systems on board. Gaseous hydrogen can be distributed to transport and industry sectors, or it can be blended with gas and supplied to end-use sectors. Decentralised small scale plants include liquefaction and refuelling stations and can be distributed directly to transport and other sectors or blended with gas.

The majority of the end users vehicle technology in the transport sector in TIAM-UCL can be hydrogen fuelled in combination with fuel cells technology. Other hydrogen based technologies are modelled to meet demand in other sectors (residential, commercial and industry).

The existing representation of hydrogen infrastructure in TIAM-UCL is provided in figure 3.1. In this thesis all hydrogen data is based on [Dodds and McDowall \(2012\)](#) with the exception of SMR, CG and BG production technologies investment cost data which was updated with the values derived from [Agnolucci et.al. \(2013\)](#). Also, centralised electrolysis production investment costs data was updated with the values found in [Decourt et.al. \(2014\)](#). A discussion of the hydrogen data and its assumptions can be found in [Dodds and McDowall \(2012\)](#), [Agnolucci et.al. \(2013\)](#) and [Anandarajah et.al. \(2013\)](#).

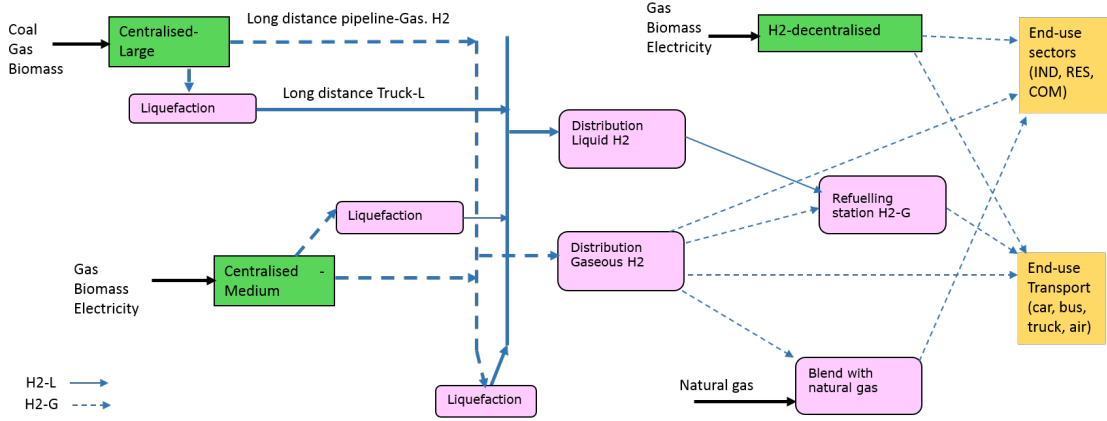


FIGURE 3.1: Hydrogen infrastructure in TIAM-UCL before this study. Adapted from [Anandarajah et. al. \(2013\)](#)

3.2.2 Hydrogen infrastructure input data

This section provides a brief summary of all input data regarding the hydrogen infrastructure in TIAM-UCL. In particular, the following input assumptions are presented: the capital investment costs, the operational costs, efficiencies and emissions factors. The sources of this input data as found in the model TIAM-UCL are provided in [Anandarajah et. al. \(2011\)](#).

Table 3.1 provides the investment costs of hydrogen infrastructure components represented in figure 3.1, while table 3.2 provides the operational costs. SMR plants are divided into centralised large and medium, and decentralised small plants. SMR centralised large plants are considered a mature technology with negligible reduction costs during the time, while a slight improvement is applied for SMR centralised medium plants. SMR decentralised plants are the most expensive at the beginning, although their investment costs become similar to the centralised large plants after 2025. Coal gasification is considered only in centralised large plants. Similar to SMR, these plants are considered mature, therefore their investment costs are kept constant over time. Medium and decentralised small plants are not taken into account as they are assumed to not be cost effective. Biomass gasification has the same pattern of SMR. Centralised large plants are kept constant over time, however medium plants are assumed to become cheaper than the large plants after 2020. Biomass gasification at decentralised small plants is the most expensive hydrogen production technology, however it is assumed that the cost decreases over time, becoming comparable to the centralised plants in 2050. Electrolysis is considered only in centralised medium plants and decentralised

small plants. In TIMA-UCL, it is assumed that the former has a capacity factor of 52300 kgH₂/day while the latter has a capacity factor of 1500 kgH₂/day. The mix of electricity source used in this type of plan depend on the scenario. The model select the mix of source that meet the emissions constraints. The electricity from the grid is distinguished in electricity from a centralised grid and from a decentralised grid. More details of the representation of the electricity sector and its input assumptions can be found in [Anandarajah et. al. \(2011\)](#).

TABLE 3.1: Capital investment costs of hydrogen infrastructure components in \$(2010)/(GJ/yr)

Description	2005	2015	2025	2050
Centralised large H2 from NGAS	16.50	16.50	16.50	16.50
Centralised large H2 from Hardcoal	39.60	39.60	39.60	39.60
Centralised large H2 from Browncoal	39.60	39.60	39.60	39.60
Centralised large H2 from BIO-GASIF	42.90	42.90	42.90	42.90
Centralised mid H2 from NGAS	34.74	34.74	28.12	23.16
Centralised mid H2 from C-ELC	71.50	37.40	23.10	23.10
Centralised mid H2 from BIO-GASIF	56.66	47.86	37.77	37.77
Decentralised small H2 from NGAS	85.00	59.40	18.89	15.11
Decentralised small H2 from BIO-GASIF	140.80	140.80	78.87	47.30
Decentralised small H2 from C-ELC	122.78	76.49	30.22	18.89
Decentralised small H2 from D-ELC	122.78	76.49	30.22	18.89
Centralised large H2 from NGAS +CCS			18.76	18.76
Centralised large H2 from coal +CCS			41.14	41.14
Centralised large H2 from BIO-GASIF+CCS			45.32	45.32
Trasportation -Long distance pipeline GH2	8.79	8.79	8.79	7.80
Trasportation -Long distance Truck LH2	17.26	16.51	15.76	12.78
Liquefaction- Large plant	28.33	19.83	11.33	11.33
Liquefaction- Medium and decentralised plants	28.33	23.61	18.89	18.89
Liquefaction- Liquefaction decentralised plant	28.33	23.61	18.89	18.89
Distribution- Pipeline GH2	18.18	17.76	17.34	17.34
Distribution- Truck LH2	5.18	4.95	4.73	4.73
Distribution- Refuelling station GH2 and LH2	37.40	32.73	28.05	20.90
Distribution - Refuelling station LH2 to GH2	50.60	44.55	38.50	29.70
Distribution- Decentralised refuelling station	71.50	64.08	56.65	38.50

Hydrogen can be transported using two different transportation options: long-distance pipeline in gaseous form or by trucks after the liquefaction process. The transportation by trucks over long distance is assumed to be more expensive than the transportation by long-distance pipeline. The average distance for hydrogen transportation is assumed to be 800 km. Hydrogen liquefaction plants are subjected to a scale effect, so that large plants are assumed to be cheaper than medium and decentralised liquefaction plants.

Two types of distribution can be distinguished. The first is the distribution by means of pipeline and trucks, like the transportation but over shorter distances. In contrast with the hydrogen transportation investment costs, the distribution by trucks of liquid hydrogen is assumed to be cheaper than the distribution of gaseous hydrogen through pipeline. The average distance for hydrogen distribution is assumed to be 100 km.

TABLE 3.2: Operational costs of hydrogen infrastructure components in $\$(2010)/(\text{GJ}/\text{yr})$

Description	2005	2015	2025	2050
Centralised large H2 from NGAS	0.83	0.83	0.83	0.83
Centralised large H2 from Hardcoal	1.98	1.98	1.98	1.98
Centralised large H2 from Browncoal	1.98	1.98	1.98	1.98
Centralised large H2 from BIO-GASIF	1.98	1.98	1.98	1.98
Centralised mid H2 from NGAS	1.39	1.39	1.12	0.93
Centralised mid H2 from C-ELC	3.58	1.87	1.16	1.16
Centralised mid H2 from BIO-GASIF	3.97	3.35	2.64	2.64
Decentralised small H2 from NGAS	3.40	2.38	0.76	0.60
Decentralised small H2 from BIO-GASIF	9.86	9.86	5.52	3.31
Decentralised small H2 from C-ELC	6.14	3.82	1.51	0.94
Decentralised small H2 from D-ELC	6.14	3.82	1.51	0.94
Centralised large H2 from NGAS +CCS			0.62	0.62
Centralised large H2 from coal +CCS			1.91	1.91
Centralised large H2 from BIO-GASIF+CCS			1.65	1.65
Trasportation -Long distance pipeline GH2	0.27	0.27	0.27	0.24
Trasportation -Long distance Truck LH2	1.73	1.73	1.73	1.73
Liquefaction- Large plant	1.98	1.39	0.79	0.79
Liquefaction- Medium and decentralised plants	1.98	1.65	1.32	1.32
Liquefaction- Liquefaction decentralised plant	1.98	1.65	1.32	1.32
Distribution- Pipeline GH2	0.46	0.45	0.44	0.44
Distribution- Truck LH2	0.52	0.52	0.52	0.52
Distribution- Refuelling station GH2 and LH2	1.87	1.64	1.40	1.05
Distribution - Refuelling station LH2 to GH2	2.53	2.23	1.93	1.49
Distribution- Decentralised refuelling station	3.58	3.20	2.83	1.93

The second type of distribution is that by means of refuelling stations. Different investment costs are assumed depending on the type of refuelling station. If liquid hydrogen is distributed and gaseous hydrogen is used in the end-users technologies, than a re-gasification process is assumed at the refuelling station. This results in an increased investment cost compared to the refuelling stations that don't require any further transformation. Decentralised small scale hydrogen production plants include refuelling stations that are assumed to be more expensive than the other cases. This is because they will likely be used to meet initial demands before a full-scale hydrogen infrastructure is built. In fact, high hydrogen delivery costs can be justified in more

remote and less populated areas where there are weak economies-of-scale ([Anandarajah et. al., 2013](#)).

The efficiency of each hydrogen infrastructure components as represented in TIAM-UCL are provided in table 3.3. As mentioned previously, the centralised plants can be equipped from 2025 with CCS, but with additional cost and with an efficiency penalty. In general, the efficiencies of all these technologies are assumed to improve over time.

TABLE 3.3: Energy efficiency of hydrogen infrastructure components (%)

Description	2005	2015	2025	2050
Centralised large H2 from NGAS	80.00	82.42	85.00	85.00
Centralised large H2 from Hardcoal	64.94	64.94	64.94	64.94
Centralised large H2 from Browncoal	64.94	64.94	64.94	64.94
Centralised large H2 from BIO-GASIF	50.00	50.00	50.00	50.00
Centralised mid H2 from NGAS	75.00	77.42	80.00	80.00
Centralised mid H2 from C-ELC	75.00	79.69	85.00	90.00
Centralised mid H2 from BIO-GASIF	50.00	50.00	50.00	50.00
Decentralised small H2 from NGAS	65.00	71.72	80.00	80.00
Decentralised small H2 from BIO-GASIF	50.00	50.00	50.00	50.00
Decentralised small H2 from C-ELC	75.00	79.69	85.00	90.00
Decentralised small H2 from D-ELC	75.00	79.69	85.00	90.00
Centralised large H2 from NGAS +CCS			81.00	81.00
Centralised large H2 from coal +CCS			63.00	63.00
Centralised large H2 from BIO-GASIF+CCS			60.61	60.61
Transportation -Long distance pipeline GH2	88.90	88.90	88.90	88.90
Transportation -Long distance Truck LH2	90.89	90.89	90.89	90.89
Liquefaction- Large plant	84.04	84.04	84.04	84.04
Liquefaction- Medium and decentralised plants	76.85	76.85	76.85	76.85
Liquefaction- Liquefaction decentralised plant	84.04	84.04	84.04	84.04
Distribution- Pipeline GH2	94.00	94.00	94.00	94.00
Distribution- Truck LH2	99.62	99.62	99.62	99.62
Distribution- Refuelling station GH2 and LH2	94.00	94.00	94.00	94.00
Distribution - Refuelling station LH2 to GH2	98.00	98.00	98.00	98.00
Distribution- Decentralised refuelling station	98.00	98.00	98.00	98.00

An emissions factor for a number of hydrogen infrastructure components is assumed in TIAM-UCL. It is the emission from a process as a function of each unit of activity. The activity is equal to the flow of the primary commodity which in this case is hydrogen. The emissions modelled are: CO_2 , CH_4 , and N_2O ; the emissions factors are expressed in kt/PJ and are shown in tables 3.6, 3.4 and 3.5.

TABLE 3.4: CO₂ emissions factors of hydrogen infrastructure components (kt(CO₂)/PJ)

Description	2005	2015	2025	2050
Centralised large H2 from NGAS	70.13	70.13	66.00	66.00
Centralised large H2 from Hardcoal	151.23	151.23	151.23	151.23
Centralised large H2 from Browncoal	155.69	155.69	155.69	155.69
Centralised large H2 from BIO-GASIF	7.00	7.00	7.00	7.00
Centralised mid H2 from NGAS	74.80	74.80	70.13	70.13
Centralised mid H2 from C-ELC	-	-	-	-
Centralised mid H2 from BIO-GASIF	7.00	7.00	7.00	7.00
Decentralised small H2 from NGAS	86.31	78.22	70.13	70.13
Decentralised small H2 from BIO-GASIF	7.00	7.00	7.00	7.00
Decentralised small H2 from C-ELC	1.33	1.25	1.18	1.11
Decentralised small H2 from D-ELC	-	-	-	-
Centralised large H2 from NGAS +CCS			6.39	6.39
Centralised large H2 from coal +CCS			16.68	16.68
Centralised large H2 from BIO-GASIF+CCS			7.95	7.95

TABLE 3.5: CH₄ emissions factors of hydrogen infrastructure components (kt(CH₄)/PJ)

Description	2005	2015	2025	2050
Centralised large H2 from NGAS	0.16	0.16	0.15	0.15
Centralised large H2 from Hardcoal	0.83	0.83	0.83	0.83
Centralised large H2 from Browncoal	0.83	0.83	0.83	0.83
Centralised large H2 from BIO-GASIF	1.00	1.00	1.00	1.00
Centralised mid H2 from NGAS	0.17	0.17	0.16	0.16
Centralised mid H2 from C-ELC	-	-	-	-
Centralised mid H2 from BIO-GASIF	1.00	1.00	1.00	1.00
Decentralised small H2 from NGAS	0.20	0.18	0.16	0.16
Decentralised small H2 from BIO-GASIF	1.00	1.00	1.00	1.00
Decentralised small H2 from C-ELC	-	-	-	-
Decentralised small H2 from D-ELC	-	-	-	-
Centralised large H2 from NGAS +CCS			0.15	0.15
Centralised large H2 from coal +CCS			0.83	0.83
Centralised large H2 from BIO-GASIF+CCS			1.00	1.00

3.2.3 Shipping representation in TIAM-UCL

Two categories of shipping are included in TIAM-UCL, one that considers the trade of non-energy commodities, and another that considers the trade of energy commodities. The trade of energy commodities is determined endogenously by TIAM-UCL based on the balance supply and demand among regions. The fuels consumed by ships for such a type of trade are estimated within the model. In contrast, the trade of non-energy commodities consists of two energy service demands that must be satisfied: international

TABLE 3.6: N2O emissions factors of hydrogen infrastructure components (kt(N2O)/PJ)

Description	2005	2015	2025	2050
Centralised large H2 from NGAS	0.78	0.78	0.73	0.73
Centralised large H2 from Hardcoal	2.78	2.78	2.78	2.78
Centralised large H2 from Browncoal	2.78	2.78	2.78	2.78
Centralised large H2 from BIO-GASIF	1.00	1.00	1.00	1.00
Centralised mid H2 from NGAS	0.83	0.83	0.78	0.78
Centralised mid H2 from C-ELC	-	-	-	-
Centralised mid H2 from BIO-GASIF	0.01	0.01	0.01	0.01
Decentralised small H2 from NGAS	0.95	0.86	0.78	0.78
Decentralised small H2 from BIO-GASIF	1.00	1.00	1.00	1.00
Decentralised small H2 from C-ELC	-	-	-	-
Decentralised small H2 from D-ELC	-	-	-	-
Centralised large H2 from NGAS +CCS			0.73	0.73
Centralised large H2 from coal +CCS			2.78	2.78
Centralised large H2 from BIO-GASIF+CCS			1.00	1.00

shipping named TWI, and domestic shipping named TWD. Usually international and domestic shipping energy service demands are based on the sum of the fuels that were consumed in that year in each region using IEA statistics. These energy service demands are projected forward using the regional growth in GDP.

Two generic ship technologies are available to satisfy these demands and their efficiency is assumed to increase by about 1% per year. Normally four types of fuel can satisfy the shipping energy service demands. They are: diesel, diesel from biomass, gasoline, heavy fuel oil and coal. TIAM-UCL chooses the mix of fuels based on its objective function. In years after the base year it is assumed that the maximum relative share of each of the four fuels increases. The maximum share of each fuel change so that any combination of fuels can be used.

3.2.4 Theoretical representational capacity of TIAM-UCL

TIAM-UCL is suitable to assess the hydrogen supply chain and its interactions with the rest of the global energy system. The resolution used is appropriate to represent a global deployment of hydrogen infrastructure technologies for shipping, although it is not able to capture and evaluate bunkering operations at port terminals. The different hydrogen pathways in the supply side are considered exhaustive and appropriate for the scope of this thesis. However, the shipping system specifications are poor. Hydrogen powered ships were not present before this thesis, and the entire shipping system is reduced to

a few categories of shipping trade with no further characterisation of ship types and on board technologies. The economic analysis is based on the objective function chosen. This is suitable to assess the cost effective choices that sectors might have in order to meet specific emissions reduction policies. The use of hydrogen in shipping was not included before this thesis but hydrogen was instead an option for other sectors such as other transport modes, residential and industrial.

3.3 The representation of the target system in GloTraM

GloTraM (Global Transport Model) is the maritime model that has been developed at UCL through the research project Low Carbon Shipping – A Systems Approach. Its use and development is also part of the more recent research project The Shipping in Changing Climates (SCC). According to [Smith et. al. \(2013b\)](#), GloTraM is a bottom-up time-domain simulation model that calculates the evolution over time of the global fleet in order to estimate the CO_2 emissions trajectories of the shipping industry. Figure 3.2 shows the conceptualisation of the model. A number of exogenous input data are selected at the beginning of the simulation and are considered external to the dynamics of the model. The model is capable of simulating how the fleet evolves both through stock turnover (newbuild and scrappage) and fleet management (lay-up, retrofit and operation). Outputs of the model are energy use, emissions and costs.

The CO_2 emissions trajectories are driven by two main factors: the transport demand (e.g. t.nm) over time, and the transport carbon intensity (e.g. $gCO_2/t.nm$) over time. The nature of the transport demand determines: which ships are allocated to which routes, the number of ships that are laid up, and the number of new builds ([Smith et. al., 2013b](#)). A transport demand scenario is selected at the beginning of the simulation, and is considered external to the system's dynamics. Transport demand and its supply are broken down into a number of component shipping markets e.g. dry, container, oil tanker etc. Each shipping market has specified commodity types and ship size categories. Table 3.7 provides the size classification by ship type used in this thesis, although it is possible to break down the fleet as desired. The allocation of ship types and sizes to specific trade flows and routes makes it possible to obtain national and regional statistics on CO_2 emissions.

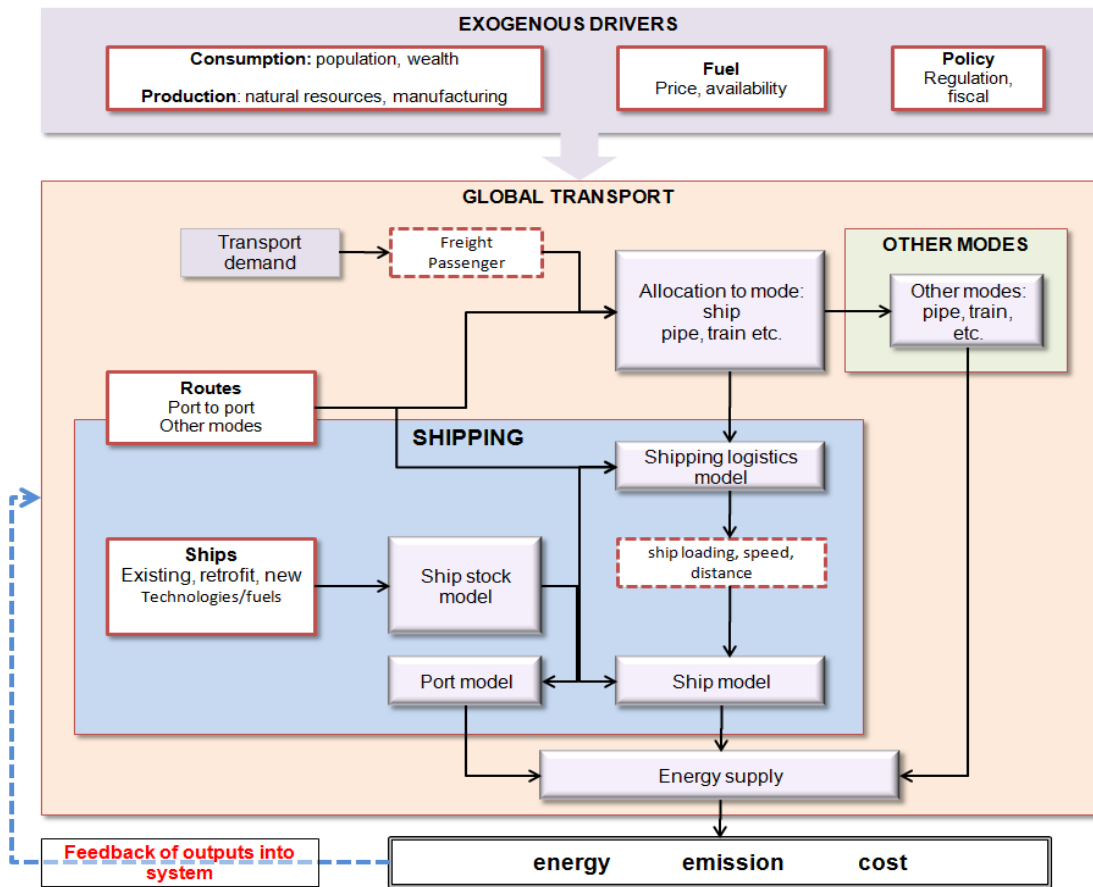


FIGURE 3.2: The global transport system as conceptualised in GloTraM

The CO_2 emissions trajectories are also driven by the transport carbon intensity. It is a function of the evolution of a fleet's composition and their technical and operational specifications. The choices that are made to determine technical and operational specifications of new build and existing ships are driven by both the profit maximisation of the ship owner and regulatory compliance. An important feature of the model is also its representation of the interaction between technical and operational specifications and the inclusion of technology additionality and compatibility (Smith et. al., 2013b).

GloTraM has already been used to evaluate future fuel mix in shipping as described in Argyros et. al. (2014). A more complete description of the method can be also found in Smith et. al. (2013b), and the derivation of the model's baseline input data can be found in Smith et. al. (2013a). GloTraM includes the representation of hydrogen powered ships, and the representation of hydrogen prices and availability at ports.

TABLE 3.7: Ship type by size category

Ship type	Tonnes/TEU/ m^3	
	\geq	$<$
container	0	1000
	1000	2000
	2000	3000
	3000	5000
	5000	8000
	8000	+
wet crude	0	10000
	10000	60000
	60000	80000
	80000	120000
	120000	200000
	200000	+
wet prod. chemical ad wet other	0	5000
	5000	10000
	10000	20000
	20000	60000
	60000	+
dry	0	5000
	5000	10000
	10000	35000
	35000	60000
	60000	100000
	100000	200000
	200000	+
gas carriers	0	50000
	50000	100000
	100000	200000
	200000	+

3.3.1 Hydrogen ships in GloTraM

GloTraM includes two types of technology, the first category includes all emissions abatement measurements that can be implemented on board (e.g. wind system, solar, superstructure streamlining etc.). The second category includes a number of main machinery options. Each of these options consists of the main engine, the auxiliary engines and fuel storage systems. The main engines and fuel types are matched with a compatibility matrix that defines which fuel can be used with which engines. Each combination engine and fuel can be compatible with a number of emissions abatement measurements. The types of engines and fuels can be selected at the beginning of the simulation.

Hydrogen as a fuel can be considered only in combination with fuel cell systems technology. Any of the ship type and size categories included in the model can theoretically

adopt hydrogen and fuel cells on board. Based on the objective function, each combination is assessed by the model. Along with the other possible combinations, hydrogen and fuel cells systems are characterised by a number of input parameters that describe the performance and costs associated with this main machinery option. They are:

1. Unit procurement cost (UPC) or upfront capital cost. This parameter assumes the investment costs associated with the hydrogen and fuel cell systems.
2. Through life cost (TLC) excluding fuel costs or in other words, the operational costs excluding the costs of the fuel. If a fuel cells system is selected such operational costs depend on the fuel cell stack changes and other maintenance requirements.
3. Specific fuel consumption at 75% MCR (sfc), which enshrines both the efficiency of fuel cell system technology and the energy density of hydrogen.
4. Dead weight tonnes loss (dwt_loss) to estimate the effect of the hydrogen fuel on the possible loss of cargo carrying capacity e.g. due to lower energy volumetric density of fuel storage compared to the traditional oil storage tanks.

The assumptions behind these input parameters are in the scope of this thesis and their estimations are provided in more detail in section [4.8](#).

3.3.2 Hydrogen prices in GloTraM

In addition to the performance and cost parameters associated with the main machinery technologies, another important input parameter is the fuel prices projection. The model GloTraM uses exogenous fuel prices projections that theoretically can be chosen by the user as desired. In general, fuel price projections are obtained from other studies or they are derived from oil and gas prices projections.

In general, hydrogen price projections have been obtained by implementing a technoeconomic analysis of a basic hydrogen infrastructure. This analysis is external to the model so the hydrogen infrastructure is not part of the dynamics of GloTraM. The infrastructure is composed of a hydrogen production plant at a centralised location from natural gas through steam methane reforming technology. A short pipeline of 100 km is assumed for the transportation of hydrogen to the delivery point. A liquefaction plant

is assumed to be off-shore. A more extensive description of the parameters used in this analysis can be found in [Smith et. al. \(2013a\)](#).

3.3.3 Theoretical representational capacity of GloTraM

Based on the description given in the previous sections, it can be concluded that GloTraM is suitable to assess the hydrogen uptake in shipping due to the great details that specify the shipping system. In addition hydrogen based technologies on board are described at an adequate level of detail that takes into account the main factors such as costs, efficiency and impact of the cargo capacity. This level of resolution ensures that the interactions between hydrogen ships and the rest of the shipping system are captured. The model is capable of assessing how competitive hydrogen powered ships might be in comparison with other competitor technologies in a number of shipping markets described in terms of ship types and size categorises. The level of resolution used implies that the implementation of hydrogen technologies on board is simplified as the model does not take into account many details associated with the design challenges. Despite the simplification used the model is considered appropriate to represent the main drivers that would lead to the adoption of hydrogen technologies on board ships.

Hydrogen price projection is obtained by analysing a very simple supply chain for shipping. Such analysis is external to the model and is not considered suitable to assess the hydrogen supply chain and its interactions with the rest of the global energy system. In general, fuel prices in GloTraM do not take into account the dynamics of the balance supply and demand for any type of fuel. The exclusion of such iterations and dynamics is a limitation of the model in representing the uptake of hydrogen in shipping.

3.4 The study of hydrogen in shipping with hybrid model

Using the discussion in the previous sections we can reach a number conclusions regarding the modelling of hydrogen use in shipping.

When an bottom-up energy system model is used to investigate hydrogen as an alternative marine fuel, we are able to account in some level of detail the competition for primary energy resources, the spatial factors, the effects of global economic and climate policy drivers. However this type of model generally lacks a proper representation of the shipping system, and is not able to capture the interaction between the technical

and operational specifications of ships that would occur in the event of switching to an alternative fuel such as hydrogen. TIAM-UCL is an example of such models. It has a detailed representation of hydrogen infrastructure system that includes a number of pathways describing the infrastructure requirements from the production stage to its final use.

When a bottom-up shipping simulation model is used to investigate hydrogen as an alternative marine fuel, we are able to analyse the interactions that occur within the shipping system. With this type of model we have the possibility to take into account factors such as the weight, volume, and cost of hydrogen fuel storage, the main machinery (e.g. fuel cells system), and the cost of maintenance of hydrogen-fuel cells machinery. These models ensure an accurate representation of the shipping system at different resolutions (e.g. different ship type and ship size), that is impossible to capture with energy system models. GloTraM is an example of such models, it can simulate different scenarios with different fuel availability and prices, together with other exogenous assumptions to include the signals from the global energy and economic system. Often the results are very sensitive to these type of assumptions and we are not able to take in account the fact that the fuel prices and their availability are affected by other energy service demands that are external to the shipping system yet internal to the dynamic of the global energy system.

As mentioned above there are a number of valuable findings from these types of models, however both appear to fail in considering all specifications required for the study of hydrogen uptake in shipping. They often provide divergent results, and both do not consider the supply and demand balance of hydrogen as an alternative marine fuel. The conclusions reached by using these types of models appear not sufficiently robust suggesting that a more rigorous approach is needed with a more complex representation of the hydrogen uptake in shipping.

In the field of energy and climate policy assessments, similar contexts have been recently addressed by analysts with an innovative method such as linking two different models. The remaining sections provide a literature review of studies that have applied this method, and identify the possible areas of improvement that lead to the research questions of this thesis.

3.4.1 Existing approaches of linking models

More often energy and climate policy assessment studies have proposed the integration between two models. The increasing computational power and the development of more standardised programming language are facilitating this process. A classification of the linking approaches is reported in section 4.2, while in this section the focus is on the reasons behind the need to link to different models.

A particular family of linking approaches is the soft-linking that is possible to divide into two category of studies: the first, that has linked top-down macroeconomic and energy bottom-up models, and the second that has linked energy-economic wide model and sectoral model.

The studies in the first category have justified their approach claiming that such a method is suitable to investigate the interactions between the energy system and the rest of the economy. Generally macroeconomic top-down models are suitable for modelling the entire economy, simulating at macro-level the economy system. They usually lack an accurate technological representation of the energy sector. In contrast, bottom-up energy models include the technology details that are required to capture the interactions within the energy system such as the substitution possibilities for energy commodities between sectors. They usually lack details of the economy and they treat sectoral differences without applying microeconomic foundations.

First examples of this type of studies are [Manne and Wene \(1992\)](#), [Wene \(1996\)](#), [Jacobsen \(1998\)](#), [Böhringer \(1998\)](#) and [Messner and Schrattenholzer \(2000\)](#). More recent studies include [Kumbaroğlu and Madlener \(2003\)](#), which developed SCREEN (Sustainability Criteria for Regional Energy policies) according to the theory developed by [Jacobsen \(1998\)](#). The need in this study was raised from the wish to overcome the gap between top-down and bottom-up models using the strengths of different modelling approaches to obtained a technologically detailed energy policy model. [Schaefer and Jacoby \(2006\)](#) developed CGE-MARKAL by linking a macroeconomic model CGE and a MARKAL type model of the transport sector. As stated in this study: *since top-down models include the macroeconomic description lacking in bottom-up models, and the latter include the technology detail lacking in the former, analysts have tried to gain the joint advantage of these two methods by combining them.* The macroeconomic model under various policy assumptions provides fuel prices, carbon taxes and transport demands that are passed to the MARKAL model of transport technology, which along

with other input generates that mix of technologies that minimises discounted cumulative costs. Other more recent examples can be found in [Bosetti et. al. \(2006\)](#), [Hourcade et. al. \(2006\)](#), [Bauer et. al. \(2008\)](#), [Böhringer and Rutherford \(2008\)](#), [Böhringer and Rutherford \(2009\)](#), [Moyo et. al. \(2012\)](#), and [Riekkola et. al. \(2013\)](#). Also in these studies, the strong interactions between the energy system and the rest of the economy are the reasons why a combination of top-down and bottom-up methods is emphasised.

Another stream of linking approaches are the studies that have developed a link between energy-economic wide model and sectoral model. These types of studies fall in the second category and generally they have justified their approach claiming that the linking method is suitable to capture different dynamics that generally take place at different levels of resolution.

A first example is [Strachan et. al. \(2009\)](#), who linked a spatial (GIS) modelling of hydrogen supply, demands and infrastructures, with an economy-wide energy systems model (MARKAL) to explore hydrogen scenarios under long term CO_2 emissions reduction constraints. The approach in this study is to use the strength of energy system models and limit the overall energy system interactions by focusing specifically on the spatial drivers of hydrogen deployment. The (GIS) tool is therefore used to characterise energy resources, infrastructures and demands. The results from different scenarios provided a spatial matching of supply and demand for optimal zero-carbon hydrogen deployment.

Another example is [Shukla et. al. \(2010\)](#), who developed an integrated modelling framework by soft-linking a land use model and the ANSWER MARKAL model. In this study the need for an integrated analysis comes from the fact that the energy system model ANSWER MARKAL is not suited for the analysis of land use, while a dedicated model can ensure that land requirements for different renewable energy sources are consistent with the overall storyline. The land use model analyses the land demand for the deployment of large-scale solar, biomass and biofuel plantations, and calculates the demand for land from agriculture, non-agricultural uses, and forests, which are passed to the energy system model.

More recently, [Deane et. al. \(2012\)](#) linked a dedicated power systems model (PLEXOS for Power Systems) and an energy model (Irish TIMES). By providing a transfer of information from the power systems model to the energy systems model, in this study the goal is to improve understanding of the energy systems model's results and to understand

what elements of the power system are important. As explained in Deane (2012), the two models are different in their focus and application. The power system model aims to represent the electrical power and does not consider the rest of the energy system. It takes into account more constraints and can process detailed temporal information and capture ancillary services. While the energy system model has the electrical power system endogenous driven by the combined behaviour of supply sectors and end-use sectors. It does not deal with any of the metrics described in the power model. Therefore the dynamics between the electrical power system and the rest of the energy system are captured in the energy system model which provides to the power systems model an electrical portfolio, fuel prices and demand. The power systems model enhances the energy systems model with greater and more realistic output derived from detailed assessment of the power system.

All this type of studies share the view that a combined model can provide better results using the strengths of both models, rather than trying to incorporate the models in one single model.

3.4.2 Area of improvements and research questions

The possible use of hydrogen in shipping has been studied with different approaches. A computational modelling approach is considered both suitable and a promising means of generating new knowledge and insights to investigate the possible uptake of hydrogen in shipping. Different models have been used so far, with various identified shortcomings. The scope to improve on these existing modelling approaches and address some of their shortcomings has been identified. Two specific types of models have been analysed: energy systems models and shipping system models. Although these approaches have highlighted a number of findings, the conclusions reached appear divergent and not necessarily sufficiently robust.

In particular, the theoretical representation capacity of two specific models has been assessed: TIAM-UCL and GloTraM. On the one hand, TIAM-UCL has the ability to represent the technological details of the hydrogen supply chains, and the energy system specifications in detail. On the other hand GloTraM has the ability to represent the technological details of the concepts design options for hydrogen and main machinery systems on board ships, the economic analysis of hydrogen-main machinery option, and the shipping system specifications in detail.

In similar context, analysts have tried to use the strength of two models by linking them. It is claimed that this would improve the results and in many cases would allow to capture interactions between different objects. The use of a linking approach between TIAM-UCL and GloTraM is seen as a possible new framework that can improve the modelling representation of hydrogen in shipping. By linking the two models, factors that are usually exogenous become endogenous to the framework (e.g fuel prices and demands). It is believed that this method can investigate the causal links between the energy and the shipping systems and provide new knowledge and insights regarding the potential of hydrogen to fuel international shipping.

In this thesis the link between TIAM-UCL and GloTraM has been developed through a code that has generated the integrated framework called TIAM-GloTraM. The linked model has the potential to overcome the shortcomings of existing models, therefore the first key research questions that this thesis will intend to answer is: *“is the modelling representation of hydrogen uptake in shipping improved in TIAM-GloTraM compared to TIAM-UCL and GloTraM?”*. TIAM-GloTraM has also the potential to provide new knowledge on the use of hydrogen in shipping, therefore, the second key research questions is: *“What type of results does TIAM-GloTraM provide regarding the potential of hydrogen to compete with LNG and current marine fuels to fuel international shipping? Under what circumstance would hydrogen be able to compete with LNG and current marine fuels in shipping and what would be the main economic and environmental implications?”*

Chapter 4

Detailed method development: TIAM-GloTraM

4.1 Developing a method for how to soft-link TIAM-UCL and GloTraM

This chapter provides a description of the method developed to soft-link the shipping model GloTraM and the global energy system model TIAM-UCL. The development of such method was required as a standard method for linking two different models does not exist. Based on the existing literature, however, it has been possible to highlight a number of common proceedings from other studies. Such proceedings have been analysed and taken into account when developing the method for how to soft-link GloTraM and TIAM-UCL. This particular method is based on four main steps. The first step is the identification of what to link, therefore establishing the degree of the linkage. The second step includes the development of all modifications and assumptions that are required to enable the link. The third step includes the actual process of transferring information from one model to another. Finally the fourth step includes the analysis of the consistency of the two models and the introduction of a process that ensure this consistency.

This chapter is organised as follow: section 4.2 provides a classification of the linking approaches used to date. Section 4.3 examines the proceedings and key steps of the studies that have analysed or experimented the soft-linking of two existing models. Section 4.4 provides an overview of the method. Sections 4.5 developed the first two steps of the method: the degree of the linkage and the process of enabling the links. Both are described in greater detail in section 4.6 (region definition), section 4.7 (fuel options) and section 4.8 (on board hydrogen technologies). Section 4.9, instead, provides the modifications to the initial condition. Section 4.10 develops the steps and assumptions used to transfer information from TIAM-UCL to GloTraM, while section 4.11 develops the steps and assumptions used to transfer information from GloTraM to TIAM-UCL. Finally section 4.12 explains the theoretical consistency of the two models and the iterative procedure implemented for ensuring this consistency.

4.2 Classification of the linking approaches

Linking different models is a relatively new idea, and several researchers have attempted to classify the linking approaches used to date. A commonly used classification is the one

proposed in [Böhringer and Rutherford \(2009\)](#), in which various modelling efforts that combine energy bottom-up and economic top-down models are divided into three categories. The first category is called *soft-linking* in which existing large-scale bottom-up and top-down models are coupled. In contrast, the second and third categories of linking approaches are both called *hard-linking*. While the former consists of the addition of a simplified representation of one model in another, the latter combines bottom-up and top-down within the same optimisation framework using the mixed complementarity problem solving routines as described in [Böhringer and Rutherford \(2009\)](#). The linking approach proposed in this study focuses on the soft-linking approach as hard linking would be too complex, if not impossible due to the different individual theoretical foundations of TIAM-UCL and GloTraM.

A more complete definition of soft-linking can be found in [Riekkola et al. \(2013\)](#): *when models are soft-linked, the macroeconomic model and the energy system model operate together in an iterative process until convergence in central parameters is achieved*. Another definition is in [Kumbaroğlu and Madlener \(2003\)](#): *the passing of price and quantity variables between the process oriented (bottom-up) and economic (top-down) sub-models and solving them iteratively*. [Wene \(1996\)](#) declared that the soft-linking approach is generally used when the bottom-up and top-down models describe the same object. However the author also declared that there are other forms of soft-linking where the models do not describe the same object, and that this latter case is used to investigate causal links between different objects. Studies that have used a soft-linking approach are classified in two categories in [Shukla \(2013\)](#). The first category includes studies that have linked top-down and bottom-up models and the second category includes studies that have linked sectoral and economy-wide models. According with [Shukla \(2013\)](#) the studies in the second category have used a sectoral model to help the modelling of sector specific issues, dynamics and policies in detail.

Based on the definition found in the literature the approach in this study is to soft-link the sectoral shipping model and the energy-system model. Such models describe two different objects, the shipping and the energy systems; the soft-linking approach enables the investigation of the causal links between the two systems.

4.3 Methods for how to soft-link models

In this section key studies regarding the soft-linking approach are analysed. The aim is to identify common proceedings, key steps and challenges that need to be taken into account when developing a method to soft-link TIAM-UCL and GloTraM. Some studies have focused on the linking process for pedagogic reasons, others have focused on practical experiments.

The soft-linking process is in principle described in a number of studies: [Bauer et. al. \(2008\)](#), [Böhringer and Rutherford \(2009\)](#), [Riekkola et. al. \(2013\)](#), [Wene \(1996\)](#). The descriptions of how to soft-link two models vary among studies, for example [Riekkola et. al. \(2013\)](#) and [Wene \(1996\)](#) have focused on the level of linkage by discussing which information should be exchanged. These information are called *connection points* in [Riekkola et. al. \(2013\)](#) or *common measuring points* in [Wene \(1996\)](#). A number of steps are described including: identifying similarities and differences between models, identifying overlaps and exogenous variables, and finally identifying what to link. [Wene \(1996\)](#) particularly emphasised the need to identify common, unambiguous measuring points for a controllable soft-link. According to the author, such points are the basis of the common language that should guide the following development of the soft-linking procedures. So, first the common areas should been identified, second the purpose of the soft-linking constrains the choice of which common measuring points should be exchanged.

Another study that focused on the steps to undertake when soft-linking two models is [Bauer et. al. \(2008\)](#). Such steps are described as: development of a reduced form of one system model, identification of the parameters taken from the optimal solution, introduction of an iterative procedure, and the identification of a stopping criterion. This study is important as it introduces the concept of an iterative procedure with stopping criteria. An iterative procedure is also introduced in [Böhringer and Rutherford \(2009\)](#), such procedure is used with the purpose of reaching the equilibrium prices and quantities between both models. In other words this should ensure that the two linked models are working in conjunction and providing consistent results.

The system theoretical consistency is a key challenge and many studies have debate it. [Wene \(1996\)](#), [Hourcade et. al. \(2006\)](#), [Bauer et. al. \(2008\)](#), [Böhringer and Rutherford \(2009\)](#), [Moyo et. al. \(2012\)](#), [Shukla \(2013\)](#), [Riekkola et. al. \(2013\)](#) have argued that such consistency can be reached. Others have argued that simultaneous equilibrium cannot

be guaranteed in the soft-linking approach, as explained in more detail in [Bauer et. al. \(2008\)](#).

A number of other key challenges are also presented in these studies; they can be summarised as: the need for a conversion process when exchanging variables that takes into account the differences in scope of the models (e.g. levels of disaggregation), the need to synchronise particular parameters in order to calibrate the reference scenario, the examination of the differences in the modelling platforms and software, and of the difference in the time horizon ([Riekkola et. al., 2013](#); [Moyo et. al., 2012](#)).

These studies have mainly focused on the description and interpretation of the linking process, however other studies have actually developed practical experiments. Four examples that are relevant to this study are briefly examined in the following paragraphs.

The first example is [Schaefer and Jacoby \(2006\)](#), which linked a global top down economic model and a MARKAL type model of the transportation sector. The two models are linked by means of another model that simulates the split among transport modes. Relative price of fuel and transportation demand are output of the economic model and input of the MARKAL model that simulate the uptake of technologies. The split model is also used to convert the transport demand from the economic model to the same level of aggregation of the MARKAL model. Total energy use in the transport sector should be consistent between the two models, and this is achieved with different calibration steps. The aggregate technology parameters in the economic model are adjusted to be consistent with the more detailed specification in MARKAL. The discount rate in MARKAL is adjusted to be consistent with the base-year fuel cost shares of the economic model. In this study it is possible to identify two important implications: the need for a conversion process due to the different aggregation levels of the models, and the need for a criterion for the model consistency based on the calibration of key parameters.

The second example is [Strachan et. al. \(2009\)](#) which linked a UK MARKAL energy systems model with a spatial model of hydrogen supply, demands and infrastructures. A geographical information system (GIS) tool was used to characterise the spatial drivers of hydrogen deployment such as the location of hydrogen production resources and demand areas. This characterisation provided a number of scenarios on demand disaggregation, supply disaggregation, and analysis on liquid, small-scale and large-scale pipeline hydrogen infrastructures that were integrated into the UK MARKAL energy systems model.

The integration was made by means of different hydrogen infrastructures input parameters such as capital and non-energy operating costs, technical performance (i.e., energy losses or required inputs), connectivity from resources to demand points, and minimum and maximum bounds on use. In this study it is not possible to find concepts such as model consistency or convergence of models, the key emphasis instead is on the integration into the energy model of spatial drivers of hydrogen deployment that can be captured at a different level of resolution and with a different representational structure. This integration required a sort of translating and conversion process.

The third example is [Rosenberg et. al. \(2010\)](#) which linked a Norwegian MARKAL energy system model with a hydrogen infrastructure model called H2INVEST. The latter has higher level of detail of hydrogen technologies and infrastructure, and includes technical, geographical and economic parameters. It optimises the evolution of a hydrogen supply infrastructure for a given development of hydrogen demand. In the description of the interaction between MARKAL and H2INVEST it is possible to identify a number of steps. First step is the definition in the MARKAL model of the initial conditions and required modifications to hydrogen technology data, and the definition of the distribution patterns of hydrogen demand in H2INVEST model. Second step is the identification of the parameters to exchange: transport costs and distances are transferred from H2INVEST to MARKAL, while the hydrogen demand for urban and rural areas is transferred from MARKAL to H2INVEST. Third step is the introduction of an iterative process that validates and calibrates the MARKAL assumptions on hydrogen distribution, and ensures the convergence towards a consistent solution.

Finally, a more recent study described in [Deane et. al. \(2012\)](#) linked an electricity power system model PLEXOS and an Irish TIMES energy system model. In this study it is possible to identify the need for sharing specific common inputs in both models such as the electricity profile shape and renewable generation profiles. Then a starting point with specific initial conditions was used to execute the TIMES model. The electricity generation portfolio is passed to the power system model, along with fuel prices and carbon prices. Due to the different time profile, annually in TIMES and half-hourly in the power system, a conversion process is used along with other assumptions based on historical data. There isn't any iterative process implemented, however once the power system model is executed, results from both models are compared and the reliability and flexibility of the power system is examined. This should ensure that the energy system

model has included the more detailed representation of the electrical power system, and therefore prove the consistency of the entire system.

4.4 Procedures for soft-linking TIAM-UCL and GloTraM

From the discussion in the previous section, we can deduce that there is not a standard methodology on how to soft-link two models, especially when sectoral models are used (e.g. transportation sector, spatial model of hydrogen supply, electricity power system). Due to the differences in such models the way we would link them with an wide energy-economic model would be technically different depending on the type of sectoral models involved. The experiences gained in these studies, however, allow us to depict a number of common key steps that can be categorised in the following key general procedures:

1. Deciding the degree of the linkage, identifying common areas, and deciding on which information to exchange
2. Identifying and deciding on common input assumptions, initial conditions and other required modifications
3. Translating and converting the exchanged variables in order to ensure the compatibility with the same level of sector/regional aggregation and disaggregation
4. Ensuring that the exchanged variables are calibrated within the system model
5. Introducing a proceeding such as an iterative procedure with a stopping criteria that ensures the convergence of the models towards the system consistency.

A brief overview of the method proposed for soft-linking the shipping model GloTraM and the global TIAM-UCL energy system model is provided below. The result of such method is the development of a new system model called TIAM-GloTraM. The following sections of this chapter describe all steps to develop TIAM-GloTraM in greater detail.

TIAM-UCL provides scenarios of the global equilibrium of the energy system, which also include future shadow prices of marine fuels (including hydrogen), carbon prices, and the trade of energy commodities. GloTraM provides scenarios of the evolution of shipping fleet composition and their technical and operational specifications, thus the future annual shares and consumptions of the marine fuels. TIAM-UCL is first used to provide marine fuel prices, carbon prices, and the trade of energy commodities to

GloTraM, which in turn feeds shipping energy service demands, and fuel mix shares back into TIAM-UCL.

A schematic representation of the two models and of the links that were implemented to transfer information between TIAM-UCL and GloTraM is shown in figure 4.1. This representation also shows that important exogenous parameters for each model are endogenised by the soft-linking. The run of TIAM-GloTraM consists of a number of iterations. In each iteration the parameters are exchanged between the models. A number of scripts written in Matlab were developed in order to automate this process.

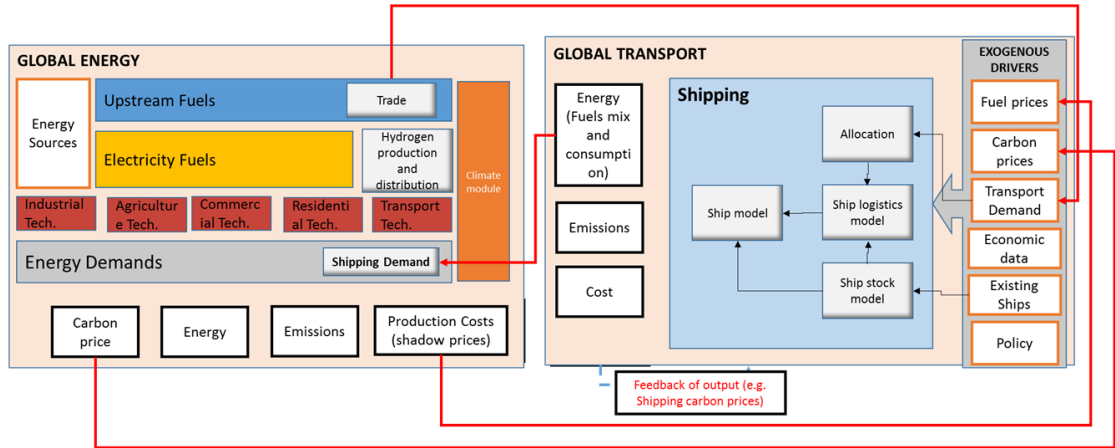


FIGURE 4.1: TIAM-GloTraM: Links between TIAM-UCL and GloTraM

Initial conditions and other modifications are set up to ensure that both models share common input parameters (see section 4.5). Eventually, both models operate together in an iterative process until convergence is achieved in a central parameter (the fuel prices). By doing so, an important element is ensured; the entire model system TIAM-GloTraM achieves consistency.

4.5 Degree of the linkage

According to Wene (1996), it is important to identify common, unambiguous measuring points for a controllable soft-linking. In order to identify the so called common measuring points, first the common areas are examined, so that it is possible to choose which information to exchange based on the purpose of the soft-linking. Once this is done, a common language can be implemented, which guides the development of the soft-linking procedures.

4.5.1 Common areas

In this section a description of the common areas is provided. Both models have a representation of the following elements:

1. Regions of the World
2. Shipping energy demand (fuel quantities and shares)
3. Marine fuels options (availability and prices)
4. Carbon price
5. Shipping fleet
6. Trade by ships of energy commodities between different regions

In TIAM-UCL the World is divided into 16 regions, while GloTraM has 11 regions. Details about which countries are included in each region can be found in [Anandarajah et. al. \(2011\)](#) and [Smith et. al. \(2013a\)](#).

Shipping energy demand in TIAM-UCL is divided into: energy required by ships for the trade of non-energy commodities and energy required by ships for the trade of energy commodities. The former is further divided into energy required for the trade between different regions (international), and energy required by ships for the trade within the same region (domestic). Both energy service demands are expressed in PJ per year and are projected according to:

$$demand(t) = demand(t - 1) * (driver)^\epsilon \quad (4.1)$$

with ϵ known as the decoupling factor and *driver* the growth in an exogenously specified factor such as GDP, population, GDP/capita etc. In the base year (2005) such demands are based on the sum of the fuels that were "consumed" (sold to ships) in that year within each of the 16 regions using IEA statistics. On the other hand energy consumed by ships for the trade of energy commodities between different regions is expressed as a percentage of the total PJ of energy transported per year for each trade origin destination. Such trades are calculated endogenously within the model.

In GloTraM the shipping energy demand corresponds to the amount of fuels consumed per each ship type and size category. This is an output of the model based on the

model framework. It is possible to obtain the fuel consumed of ships trading inbound to a region (international import), outbound from to a region (international export), and within a region (domestic) by ship type and size categories.

Marine fuel options and the relative prices is an important common area. In TIAM-UCL there are four marine fuel options: heavy fuel oil (TRAHFO), diesel (TRADSL), gasoline (TRAGSL), and coal (TRACOA), although it is possible to produce diesel from biomass. In the base year (2005) and the years 2010 and 2015 the relative shares of such fuels are forced to use the exact value given in the IEA statistics. In the years after 2015 it is assumed that the maximum relative share of each of the four fuels increases under specific constraints set by the user. The shadow prices of such fuels are generated by the model endogenously based on the objective function as explained in section 4.12.

In GLoTraM conventional marine fuels are represented by two categories for residual fuel of different sulphur contents (HFO and LSHFO), and one category for marine distillates (MDO/MGO). Alternative fuels options are LNG, methanol, hydrogen and biomass derived products equivalent or substitutes for all the options mentioned. Marine fuel prices are exogenous to the model and set by the user. In [Argyros et. al. \(2014\)](#), for example, fuel prices projections are obtained with different approaches. Oil-derived fuels (HFO, LSHFO, MDO, MGO, and Methanol) are assumed correlated to the oil price forecast and gas-derived fuels (LNG and hydrogen) are assumed correlated to gas price. Oil and gas price projections are taken from [DECC \(2012\)](#), and generally they are different based on the scenario selected. The assumptions and model used to obtain projections of marine fuel prices can be found in [Smith et. al. \(2013a\)](#).

In TIAM-UCL, carbon price is calculated endogenously by the model. Emissions of a number of greenhouse gases (GHG), merged in a single CO_2 -equivalent emission, are calculated, and used as input into the climate module. Based on the constraints in the global temperature rise, a number of emission mitigations can be accomplished such as for example: improved efficiency, CO_2 sequestration, demand reductions as reaction to increased carbon price. Therefore carbon price varies based on the emission reduction target selected, and on the ways the model has to mitigate such emissions. In contrast, in GLoTraM carbon price is exogenous to the model and it is selected at the beginning by the user based on the scenario selected. In [Argyros et. al. \(2014\)](#) carbon price is taken from [DECC \(2012\)](#) which provides three scenarios for this variable ([Smith et. al., 2013a](#)).

Shipping fleet is another common element. In TIAM-UCL two generic ship technologies are available to satisfy respectively the energy required for international trade, and domestic trade of non-energy commodities. The efficiency of these two generic ships is assumed to increase by about 1% per year, and there are no associated investment or operating costs (other than fuel costs). In GloTraM the global fleet can be divided into a number of ship type categories, each of them classified by a number of size categories. Initial conditions of the technical and operational specifications of each category are defined at beginning. The algorithm within the model defines the new specifications for the new building ships.

The last common area between the two models is the trade by ships of energy commodities between different regions. In TIAM-UCL the trades of energy commodities are generated to meet the energy services demands in each region. This is done based on its objective function. This also means that the impact of environmental policies on energy and permit trade is taken into account.

In GloTraM the trades of energy commodities are included in the transport demand. The transport demand is selected at the beginning based on the scenario selected, and it is an exogenous input variable. In particular, projections of transport demand are based on a number of datasets. The first dataset is from the TRANSTOOLS V-2 approach ([TENconnect, 2009](#)), which provides the trade for a country_to_country level and by commodity. Commodities are disaggregated to the NSTR level 2 (99 commodity groups). Among these commodity categories there are also energy commodities. Another dataset is from [Buhaug et. al. \(2009\)](#) which uses a globally aggregated value of transport demand ([Smith et. al., 2013a](#)). Such projections are based on the IPCC SRES scenarios for development of the future transport demand with particular focus on the A1B scenario ([IPCC, 2013a](#)). Greater details of transport demand scenarios in GloTraM can be found in [Smith et. al. \(2013a\)](#).

4.5.2 Exchanged variables

Once the common areas are defined, the choice of which information to exchange can be made, and it is based on the purpose of the soft-linking. In this thesis the purpose is on the representation of a possible future uptake of hydrogen in shipping. The interest is in learning about the interactions between two represented systems: the energy system that embodies the supply of marine fuels and the hydrogen supply infrastructure, and the

shipping system that embodies the hydrogen technologies on board. Having examined the common area, it is possible to decide on the variables to exchange.

Among the most important variables, there are the quantities of marine fuels consumed and their relative shares by regions. The simulation in GloTraM of the projections of future consumption of marine fuels is taken as the true representation, and therefore the quantities and shares are among the variables that need to be exchanged from GloTraM to TIAM-UCL. This is linked into the energy model as shipping energy demand.

Marine fuels availability and relative prices are other important variables that need to be exchanged. The simulation of fuels availability and price projections under different scenarios is better represented in TIAM-UCL, therefore they should be exchanged from TIAM-UCL to GloTraM. This implies that a decision needs to be made about which marine fuels to include among the options and how to match TIAM-UCL and GloTraM's fuel options. This discussion is provided in section 4.7.

In TIAM-UCL, carbon price is a possible mitigation option that would vary based on the specified carbon target. This variable has an impact on the voyage cost representation in GloTraM. Moreover the fuel choices made in the shipping industry may have implications on how this variable can vary. If the scope is learning about the interactions between the two represented systems, it is important to include this variable among the ones to be exchanged from TIAM-UCL to GloTraM.

Technology specifications of the shipping fleet could be transferred from GloTraM to TIAM-UCL, however this would result in an addition of complexity in the energy system that would not necessarily provide a more precise answer. The purpose indeed is not the integration of the two models and adding more details to either. Conversely, the purpose is on analysing the interactions between two different systems. This is why the specification of the shipping fleet is not transferred but rather it is simplified in TIAM-UCL. More details on how this is done are given in section 4.11.

A more complicated common area between the two models is the trade by ships of energy commodities between different regions. In TIAM-UCL such trades are part of the distribution of energy commodities, which can be seen as a component of the infrastructure of the supply. This component would have its own energy and emission performance, and it would be developed differently based on the specified scenario. At the same time such trade is part of the transport demand in shipping, which is an input assumption in GloTraM. While TIAM-UCL could inform the shipping system about

such trade, GloTraM could inform the energy system about the specifications of the fleet that would provide such trade.

Under wider CO_2 mitigation scenarios hydrogen can have the potential to reduce the emissions of a number of energy technologies in the energy system. This could have an impact on the mix of energy resources used, and thus on the future international trade which corresponds to the future transport demand of the shipping system. Therefore this trade should be included among the exchanged variables from TIAM-UCL to GloTraM with the purpose of investigating the effect of this feedback and ensuring a greater level of consistency between the two models.

The specifications of the future shipping fleet can influence the shipping transport costs that consequently can influence the trades within the global energy system. In this thesis these specifications are not transferred from GloTraM to TIAM-UCL because it is assumed that changes in such specifications would have a negligible effect on the trades of energy commodities. On one hand it is recognised that this assumption is a limitation of this version of the model and further research should put more attention regarding it. On the other hand, the effects on the energy system caused by changes of transport costs are not in the scope of this thesis therefore additional developments are left to further research efforts.

TIAM-UCL does not provide carbon or GHG emissions per each pathway in the upstream, rather emissions are calculated by process. An attempt to allocate upstream emissions to a single fuel commodity (hydrogen for shipping) is provided in section 6.3.3, however, such upstream emission are not exchanged between the models. Although it is recognised that they should be accounted to demonstrate the overall emissions impact of any potential future marine fuel, the upstream emissions are assumed to be excluded from the objective function of the shipping model. In other words, the shipowner profit maximisation approach assumes that the upstream emissions of any marine fuel are not included in the equation but only fuel price and operational emissions. As a consequence, upstream emission are not exchanged from TIAM-UCL to GloTraM.

Having defined the variables to be exchanged, a number of modifications need to be considered in both models before developing the soft-linking procedures. The variables chosen to be exchanged between TIAM-UCL and GloTraM are: marine fuels demand (quantities and shares), marine fuels options (availability and prices), carbon price, and trade of energy commodities. Modifications were required in both models, in order to

enable the links. Such modifications can be seen as developments applied to a number of assumptions and settings of the models. They regard:

1. the regions definition
2. the common portfolio of fuel options
3. the on board hydrogen technologies
4. the initial conditions on marine fuels demand

Each of these will be described in more detail in the next sections.

4.6 Regions definition

As mentioned in TIAM-UCL the World is divided into 16 regions, while GloTraM considers 11 regions. GloTraM regions were changed and matched with TIAM-UCL regions. Figure 4.2 shows the regions as defined in TIAM-GloTraM. The regions are defined as: Africa (AFR), Australia (AUS), Canada (CAN), Central and South America (CSA), China (CHI), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JPN), Mexico (MEX), Middle East (MEA), Other developing Asia (ODA), South Korea (SKO), United Kingdom (UK), United State of America (USA), Western Europe (WEU).

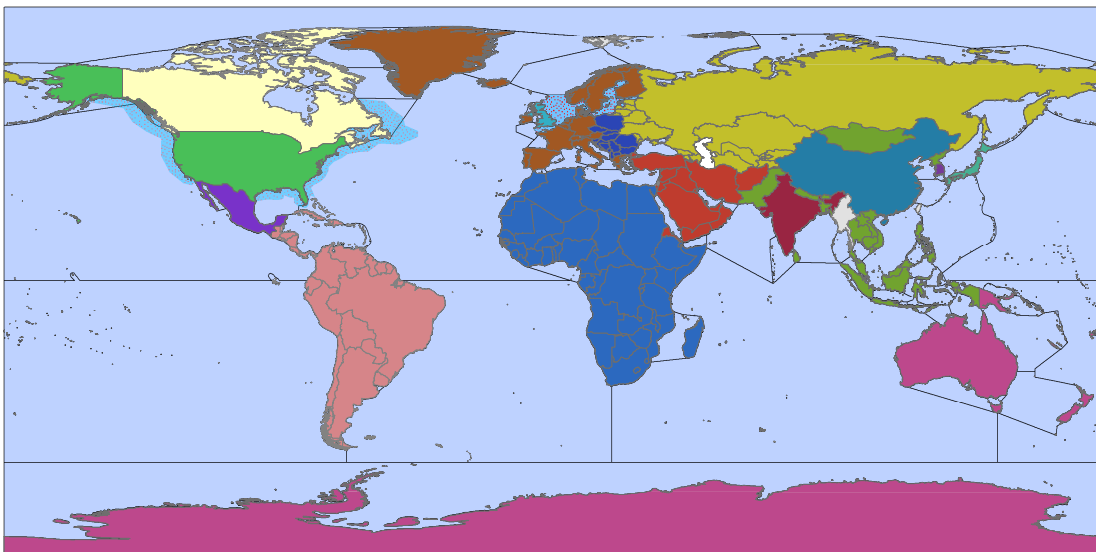


FIGURE 4.2: Regions as defined in TIAM-GloTraM

4.7 Common portfolio of fuel options

Assumptions on conventional and alternative fuels in shipping have to be consistent in both models in order to have a common portfolio of fuel options. Table 4.1 provides the list of fuel options in TIAM-UCL, and how they were matched with the fuel options in GloTraM in order to generate the common list used in this thesis. Assumptions on which fuel type to include were required, as well as a number of modifications to the models' structures to accommodate such a common list of fuels in both models.

TABLE 4.1: Fuel options in TIAM-UCL and GloTraM and common portfolio in TIAM-GloTraM

TIAM-UCL	GloTraM	TIAM-GloTraM
TRAHFO	HFO	Heavy fuel oil (HFO)
TRADSL	MDO/MGO	Marine distillates (MDO)
TRAGSL	-	-
TRACOA	-	-
TRADLS-Bio	Biomass derived products	-
-	LSHFO	-
-	LNG	LNG
-	Methanol	-
-	Hydrogen	Hydrogen

As mentioned in the previous sections, conventional marine fuels in TIAM-UCL are heavy fuel oil (TRAHFO), diesel (TRADSL), gasoline (TRAGSL), coal (TRACOA), while in GloTraM they are residual fuels of different sulphur contents (HFO and LSHFO), and marine distillates (MDO/MGO). TRAHFO was matched with HFO, and TRADSL was matched with marine distillates fuels MDO/MGO.

Alternatives to the conventional fuels in TIAM-UCL are TRAGLS and TRACOA and diesel produced with biomass. In contrast, alternative fuels in GloTraM are represented by biomass derived products equivalents or substitutes of the other options, as well as LNG, methanol and hydrogen. TRAGLS and TRACOA were excluded as well as LSHFO, biofuels, and methanol, and only LNG and hydrogen were included as alternative fuels in this thesis.

Coal and gasoline were excluded from this thesis as they are not considered future fuel options in shipping, although coal has been used in the past. Low sulphur heavy fuel oil (LSHFO) refers to a category of fuel obtained from the refinery and it generally requires extra equipment and processing to extract the additional sulphur [EPA \(2008a\)](#). Not all refineries include such additional requirements and there is an ongoing discussion on the

availability of such types of fuel to meet future energy demand from shipping. Although it is recognised that LSHFO could play a role in the imminent future fuel mix in shipping, it was decided to exclude this option as the purpose of this thesis is to focus on a long term solution. It was assumed that LSHFO would have a minor role in the long term because it has a high carbon content that might not be in line with a decarbonisation strategy. Instead other alternative fuels with low carbon content are considered more likely to take up in shipping in long term. This assumption adds uncertainty to the results and more investigations are required in support of this hypothesis. In further research efforts it is suggested to consider LSHFO as a future marine fuel option.

In this thesis the decision to exclude a biofuels option was taken, as it was assumed that biofuels in shipping will have relatively little uptake in the future. [IEA \(2011\)](#), for example, reported that 11% of the total biofuels use would be adopted in shipping in the 2050 BLUE Map scenario corresponding to about 3 EJ. The total contribution of biofuels in 2050 might be not so significant considering that 3 EJ represents a relative small share of the current energy required in shipping and that the latter is projected to increase significantly in the future ([Smith et. al., 2015](#)). In general biofuels for shipping face two main obstacles. The first obstacle is that biomass production suffers from the competition with the agriculture sector, and the second is that the current and future production of biofuels is likely to be used in other transportation sectors. In aviation, for instance, advanced biofuels are seen as the only low- CO_2 option for substituting kerosene. Biofuels can also be blended with conventional fossil fuels, and many vehicles in inland transportation systems are compatible with the blends currently available ([EU, 2013](#)). Another reason in support of the decision to exclude biofuels in this study is that they are modelled in a different manner than the other options in both models. As consequence, their inclusion would have required extensive modifications in both models that are considered out of the scope of this study. It is recognised, however, that they should be included for an accurate representation of the system and this is a limitation of this version of the model.

Methanol could be a valid alternative, however its deployment in the shipping industry would depend on the way it would be produced, and its demand as a conventional chemical. If it would be produced from biomass it would follow the same considerations of biofuels. TIAM-UCL models methanol production; however its representation is quite poor, therefore in this thesis it was decided to exclude methanol among the options.

LNG is considered the main competitor of hydrogen as an alternative fuel in the long term, therefore it is included in the portfolio of fuel options for this thesis. LNG is certainly the most pronounced alternative in the shipping industry to date. Uncertainties regarding LNG are related to possible competing users of natural gas, and to the future global market for gas, which is difficult to predict. TIAM-UCL is able to model LNG dynamics on the supply side and GLoTraM has it among the options. LNG was introduced as a transport fuel in shipping and its trade between different regions was enabled in the energy model TIAM-UCL.

Hydrogen is in the scope of the thesis, therefore it is included in the common portfolio. Two important assumptions were made. First assumption is that only liquid hydrogen storage system will be used on board ships. Second assumption is that liquid hydrogen will be available at bunkering terminals. The representation of hydrogen infrastructure in TIAM-UCL was modified according to this assumption. The justifications behind these assumptions will be examined in more detail in the following sections.

In conclusion, four type of fuels were chosen for the combined system: HFO, MDO, LNG, and hydrogen. These options are considered a sufficient starting point for this research, however, other fuels such as biofuels, methanol and ammonia could play a role in the future for shipping. It is recognised that for an accurate and complete representation it is necessary to include all fuel competitors (especially other low-carbon options) that might be used in shipping to take in account the competitiveness of hydrogen in comparison with all other options.

4.7.1 Hydrogen storage in maritime applications

An important assumptions used in this thesis is that assumption only liquid hydrogen storage system will be used on board ships, however there are many types of hydrogen storage systems. There are at least three hydrogen storage system categories: high-pressure gas cylinders, liquid hydrogen storage, and metal hydrides. Each of these categories can contains a number of storage systems which may differ by type of material used. In general, on board ships where space requirements can be more important than weight, it becomes of high importance the volumetric density of hydrogen storage system as it influence the volume requirements on board. The volumetric and gravimetric hydrogen density of hydrogen storage systems can vary significantly. Generally metal

hydrides storage systems offer the highest volumetric density followed by liquid and gaseous storage. A brief description of maritime applications for each of these types is provided below, while a complete discussion of hydrogen storage systems can be found in [IEA \(2006\)](#), [Züttel et. al. \(2010\)](#) and [Jens Oluf Jensen and Bjerrum \(2010\)](#).

High-pressure gas cylinders hydrogen storage system is the most developed system and is being used on board ships such as the FCS Alsterwasser inland passenger ship, which has been sailing since August 2008 ([Zemships, 2008](#)). The relatively low energy requirements for this particular ship made it possible to accommodate ten gas cylinders with a low impact on space on board. The very low volumetric density of about $27 \frac{kg}{m^3}$, however, could be a limit for the application on board larger ships. If we assume that the same amount of energy would be stored on ships, then gas cylinders hydrogen storage system would occupy about ten times more volume than the HFO tanks. In addition, the gravimetric energy density is also relatively low, less than 5% mass for a pressurised gas storage steel tank. High-pressure gas cylinders hydrogen storage system is certainly the type of storage that is today commercially available and more developed compared to the other systems. Its application on board ships, however, is seen as a key challenge when the volume occupied is taken into account ([Gerd, 2009](#)).

Liquid hydrogen storage systems can have a volumetric density of about $75 \frac{kg}{m^3}$ and gravimetric density of about 10%. Liquid hydrogen can be stored in cryogenic tanks at 21.2K at ambient pressure and in open systems. Hydrogen stored in hydrocarbons such as ammonia are considered in this thesis as a different alternative fuel and not as a form of hydrogen storage, however according with [Züttel et. al. \(2010\)](#) ammonia has the potential for the highest gravimetric hydrogen energy density (17.6% mass) although the volumetric energy density appears to be lower (about $15 \frac{kgH_2}{m^3ammonia}$) than liquid hydrogen. The volumetric density of liquid hydrogen at the boiling point (21 K) is $70.8 \frac{kg}{m^3}$. This is approximately double than high-pressure gas cylinders. According with [Züttel et. al. \(2010\)](#), one of the challenges for liquid hydrogen storage is the thermal insulation of the cryogenic storage vessel in order to reduce the boil-off of hydrogen (typically $0.4\% \frac{1}{day}$ for tanks with a storage volume of $50 m^3$, 0.2% for $100 m^3$). The continuous boil-off of hydrogen limits the possible applications for liquid hydrogen storage systems, however, applications in which hydrogen is consumed within a rather short period of time, e.g. shipping space, could be possible. In this thesis the boil-off of hydrogen is, therefore, assumed to be negligible. It is recognized, however, that more investigations

are needed on this aspect. [Rohde and Nikolajsen \(2013\)](#) created a concept for a zero-emission ferry powered by liquid hydrogen. The hydrogen was stored in C-type tanks on deck, capable of holding 140 m^3 . The gravimetric energy density was assumed to be around 10-15%, which is generally higher than that of high-pressure gas cylinders and metal hydrides.

Metal hydrides could be used to store hydrogen on board ships. They have been successfully used in submarines ([Hammerschmidt, 2016](#)). Although they have a high volumetric density ($150 \frac{\text{kg}}{\text{m}^3}$ is found in Mg_2FeH_6 and $\text{Al}(\text{BH}_4)_3$), all the metallic hydrides that work around ambient temperature and atmospheric pressure have a volumetric density of about $50 \frac{\text{kg}}{\text{m}^3}$, and a gravimetric hydrogen density limited to less than 2% mass ([Züttel et. al., 2010](#)). This means that if we assume that the same amount of energy would be stored on board ships, then such a hydrogen storage system would weigh about 7 times more than the current HFO tanks. Although space requirements can be more important than weight on board ships, the very low gravimetric density could limit its application for large ships (as in general large ships store relatively larger amount of fuel on board). In addition the metal hydrides storage system is the less developed and it seems there are not commercial applications yet.

The focus of this thesis is on the potential of hydrogen as a fuel in shipping, deciding on which is the best type of hydrogen storage system on board ships requires more research efforts which includes a detailed examination of efficiency, leakages and costs for each of the possible storage system as well as other types of considerations such as safety, location, and extra technological equipment that any hydrogen storage system would require on board. However, one of the most important characteristics for maritime applications appears to be the energy density of the storage system in terms of volume and weight occupied.

As example, table 4.2 provides some estimate of volumetric and gravimetric energy density in various materials and systems.

The interest, in this thesis, is focused on a hypothetical hydrogen storage system that might be used on board ships in the future, and of which it is possible to assume representative volumetric and gravimetric energy densities. Liquid hydrogen appears to have an optimal trade-off of volumetric and gravimetric energy density that could suit for an application on ships, therefore it is assumed that only liquid hydrogen would be used in shipping. It is assumed that such a hypothetical hydrogen storage system

TABLE 4.2: Gravimetric and volumetric hydrogen density in various materials and systems. The density is estimated for systems and in parenthesis is the theoretical limit of the material given. Source:(Züttel et. al., 2010)

Storage type	grav. density (%) (<i>kg_{fuel}/kg_{system}</i>)	vol. density (<i>kg_{fuel}/m³_{system}</i>)
pressure cylinder (500 bar, 25°C)	4	27
liquid hydrogen (1 bar, −253°C)	3 (100%)	40(71)
metal hydrides (1 bar, 25°C)	1.2 (1.85%)	50(110)
complex hydrides (1 bar, 150°C)	4 (13.5%)	50(120)
metals (1 bar, 25°C) Zn (H ₂ O)	3 (3.8%)	90
ammonia (1 bar, −33°C)	(17.6%)	(15)
hydrocarbons (1 bar, 25°C)	14 (14%)	10
water (1 bar, 25°C)	11	11

has a volumetric density of about 75 $\frac{kg}{m^3}$ and gravimetric density of about 10%. It is recognised that further effort should be concentrated on this topic as the volumetric and gravimetric energy density for each of the hydrogen storage types described above can vary significantly within each type of category. The study of which might be the best hydrogen storage option for shipping is left to further research.

4.7.2 Hydrogen infrastructure for shipping

The representation of hydrogen infrastructure in TIAM-UCL is analysed in section 3.2.1. The production and transportation components of the hydrogen infrastructure can also be representative in the case of the shipping industry. Hydrogen from centralised large and medium scale plants in both forms (gaseous and liquid) can be available for the distribution at refuelling port terminals.

The distribution components depend on the assumptions of the type of hydrogen storage system that would be adopted on ships. In this thesis it is assumed that only liquid hydrogen is used on ships, therefore liquid hydrogen from centralised and decentralised plants was linked to the hydrogen-powered ships while gaseous hydrogen was not linked to the shipping sector as a liquefaction process on board ships is considered unlikely to happen. A bunkering component was added into the representation which includes the storage of hydrogen at ports. Input assumptions for this component were not found in the literature, therefore, they were derived from the input assumptions found in TIAM-UCL used for LNG. The capital investment cost for hydrogen bunkering component was assumed to be 70 \$(2005)/(GJ/yr), while the operational costs 2.40 \$(2005)/(GJ/yr). The efficiency was assumed to be 40% (including leakages and losses).

As a consequence, the representation of hydrogen infrastructure was modified as shown in figure 4.3. Moreover, because it is assumed that hydrogen would be produced with regional resources, hydrogen trade between different regions was not enabled. The latter assumption is another limitation of this version of the model as hydrogen trade should be included for an accurate representation of the system. In this thesis it is assumed that only locally produced hydrogen can be found sustainable, so that hydrogen is close to the energy demands of users, while the energy sources to produce hydrogen can be traded worldwide with the exception of electricity for electrolysis .

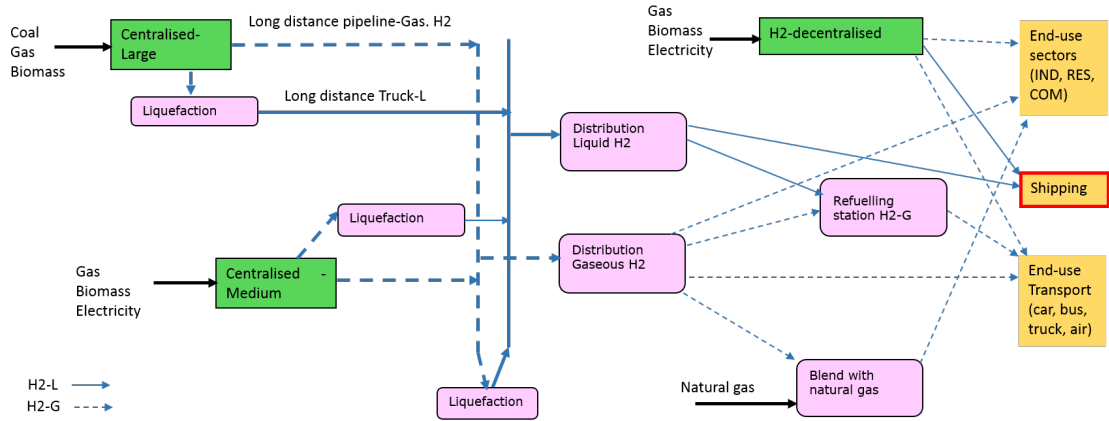


FIGURE 4.3: Hydrogen infrastructure in TIAM-UCL for this thesis

4.8 On board hydrogen technologies

The shipping model GloTraM includes a number of important assumptions regarding the main machinery options on board ships. The main machinery options are all combinations of the main engines and types of fuel that are evaluated within the shipping model. Their key assumptions are intended to be representative of all shipping fleet or sometimes of a specific ship type and size categories. Often the estimated parameters come from a generalisation as not always differentials among ship types are taken into account. The combinations of main engines and types of fuel considered in this thesis are described in table 4.3, which provides the type of fuel associated with each main engine .

Besides the conventional options with HFO and MDO fuels in combination with internal combustion engines (ICE) in shipping, LNG and hydrogen were also considered

TABLE 4.3: Main engine and fuel type combinations

Description	Fuel			
	HFO	MDO	LNG	H2
2 stroke diesel	v	v		
4 stroke diesel		v		
diesel electric	v	v		
4 stroke spark ignition			v	v
fuel cells			v	v

with ICE; while fuel cell systems were considered in combination with LNG and hydrogen. Hydrogen could also be used in gas turbine or as hybrid solution with other fuel, however, these options have not been included in this thesis. Different technological configurations can be associated with each of these combinations, however it was preferred to keep a general description of the main machinery options, avoiding complexity and small differences among the options that are not considered relevant to the scope of the research questions.

Each of these combinations is evaluated within the shipping model during the process that defines newbuild ships and retrofits. It is important to have a good estimate of the performance of each combination as the specific performance's parameters affect the model's choice of the main machinery option.

The energy and economical performances of each combination are provided by the parameters analysed in section 3.3, however these parameters depend on several assumptions; for example costs and space requirements of hydrogen storage system on board depends on the assumption of the type of storage system. The process of defining such key assumptions involves considerable uncertainty as it is sometimes difficult to have reliable data; for example it is difficult to predict what the capital cost of hydrogen storage systems for ships would be in the future. Nevertheless the interest is on the effects that these assumptions have in driving the global fleet evolution and therefore the possible uptake of hydrogen. Hence, although these assumptions can be very sensitive and somehow fragile, it is expected that the estimated values are going to be representative in order to examine the effects that they would have on the fleet evolution. Eventually an analysis of the results would be helpful to understand the relative influences of such parameters as examined in chapter 6).

The following parameters were estimated for on board hydrogen technologies: the

specific fuel consumption (sfc), the dead weight tonnes loss (dwt_loss), the unit procurement cost (UPC), and the through life cost (TLC). The methods and assumptions used to estimate such parameters are examined in more detail in the next subsections. For the sake of completeness LNG assumptions are also provided.

4.8.1 Analysis of the specific fuel consumption

The specific fuel consumption (sfc) is defined by the formula 4.2. It depends on the efficiency of the main engine system $[\eta]$, and the energy density of the fuel used in kWh/kg $[\delta]$, therefore sfc enshrines both the efficiency of the engine and the energy content of the fuel.

$$sfc = \frac{1}{\eta * \delta} \quad (4.2)$$

The efficiency of the main engine system is a key variable. Current marine engines are already considered very efficient, reaching up to more than 50%. The efficiencies used in this thesis for conventional marine engines were taken from [Smith et. al. \(2013b\)](#) and are presented in table 4.4. Conversely, the efficiency of fuel cell systems was estimated. Such efficiency can vary significantly with the type of fuel cells and the load factor [Alkaner and Zhou \(2006\)](#). Furthermore, fuel cells efficiency can be improved by thermal integration, allowing energy-recovery systems for use in conjunction/integration with fuel cell systems. This makes it difficult to estimate a representative efficiency of fuel cell systems on ship. According with [Han et.al. \(2012\)](#) and [Ludvigsen and Ovrup \(2012\)](#), however, fuel cells might be more efficient than the other conventional marine engines. In this thesis the electrical efficiency of fuel cell systems was assumed to be constant and equal to 55% as found in [Ludvigsen and Ovrup \(2012\)](#).

When fuel cells are used on board an electric motor also has to be taken into account to convert the electricity in mechanical work for the propeller. The efficiency of the electric motor is assumed to be 95% taken from [ABB \(2013\)](#). The efficiency of fuel cells in combination with the electric motor was therefore 52%. Furthermore, when fuel cells are used with other hydrocarbon such as LNG, a reformer is needed. So in this case the efficiency of the reformer has to be taken into account. Generally fuel cells with a reformer have much lower efficiency at partial load due to heat losses and other

inefficiencies in the reformer. We assumed the efficiency of the reformer on board ships to be about 70% based on [Dokter and Lamm \(1999\)](#).

Assumptions and results of the analysis of sfc using formula 4.2 are presented in the table 4.4. Energy density of hydrogen and LNG are assumed respectively to be 33.33 and 13.89 kWh/kg. Sfc for hydrogen with fuel cells is estimated to be about 57 g/kWh.

To store hydrogen in a liquid state, an active cooling is required. The amount of cooling would depend on the heat transfer to the hydrogen, which would depend on the effectiveness of the tank insulation which can vary. There is not a single figure, according with [Jens Oluf Jensen and Bjerrum \(2010\)](#), the energy demand for liquid hydrogen storage is on the order of 40-45 % of LHV, and it should be possible to reach 25% 21% of LHV in very large liquefaction plants. Moreover, there will inevitably be some boil-off as the gaseous hydrogen is removed from the tank through a valve to prevent a high-pressure build-up and subsequent structural damage to the tank. In a well-designed system, the boil-off would be used to power the ship engines, so minimising losses. In general, a boil-off rate depends on the tank insulation and the effectiveness of the active cooling system. These parameters are not included in the calculation of sfc and further analysis would be needed in order to identify the impact on sfc. It is assumed that a liquid hydrogen storage system would be implemented on board so that the energy demand and losses are minimised and therefore negligible. This is a limitation of the approach used in this thesis and a discussion on the possible implication on the final results is provided in section 7.2.2.2.

TABLE 4.4: Specific fuel consumptions of the main machinery options

Name	main engine system	η	Fuel type	δ (kWh/kg)	sfc (g/kWh)
HFO2S	2 stroke diesel	52%	HFO	11.25	171
HFOdEle	diesel electric	47%	HFO	11.25	189
MDO2S	2 stroke diesel	52%	MDO	11.84	162
MDO4S	4 stroke diesel	47%	MDO	11.84	180
MDOdEle	diesel electric	47%	MDO	11.84	180
LNG4SI	4 stroke spark ign.	48%	LNG	13.89	150
LNGRFC	Reformer+FC+Ele mot	37%	LNG	13.89	197
H2HFC	FC+Ele mot	52%	H2	33.33	57

4.8.2 Analysis of the loss of cargo capacity

The `dwt_loss` is a parameter to estimate the effect of the alternative fuel storage systems on loss of cargo carrying capacity due to their typically lower energy density. This analysis does not take into account the technical issues relative to the conceptual design and engineering of a hydrogen-powered ship, this analysis instead focuses on the extra space requirement that might be needed in comparison with a conventional fuel oil tank.

In the case of hydrogen in combination with fuel cells the power density of future marine fuel cells systems should also be included, as ships require a high power installed on board and a fuel cells system's volume and weight increases incrementally with the power installed (Krčum et. al., 2004). Data on large fuel cells power density were not found in the literature, although a possible design solution would be to allocate different module of fuel cells in different location on board ship in order to limit the space requirement. How manufacturers would cope this is highly uncertain. In this thesis, it is assumed that hydrogen storage system density is expected to have the biggest impact on the loss of cargo capacity because of the very low volumetric density of hydrogen storage system, therefore, only the fuel storage system affects the loss of cargo capacity. Although, more research should be dedicated to explore the applicability and space requirement of fuel cells in the maritime context, a robustness analysis discussed in section 6.5 will explore the sensitivity of the results in comparison with variation of the hydrogen volumetric energy density. This variation can also be seen as the inclusion of marine fuel cells space requirements.

To evaluate the loss of cargo carrying capacity, first the volume occupied by the hydrogen storage system is calculated (V_{H2}), second the volume occupied by a HFO storage tank is calculated (V_{ref}) as a reference of comparison against which the extra volume is estimated. The `dwt_loss` is then calculated converting the extra volume expressed in m^3/kWh in *tonnes/kWh*, assuming that each m^3 on board ships is equal to 0.8 tonnes of cargo capacity (see formula 4.3), and dividing all per the energy stored on board in KWh (E_{st}).

$$dwt_loss = \frac{(V_{H2} - V_{ref}) * 0.8}{E_{st}} \quad (4.3)$$

The volume occupied by a fuel storage system can be expressed as a function of the amount of fuel required on board and the volumetric density of the fuel storage system.

So, formula 4.3 can be written as:

$$dwt_loss = \frac{(S_{H2}/\gamma_{H2}) * 0.8 - (S_{ref}/\gamma_{ref}) * 0.8}{E_{st}} \quad (4.4)$$

The kilograms of fuel stored on board is S_x , while γ_{H2} is the volumetric density of the liquid hydrogen storage system, assumed to be equal to 40 kg/m^3 based on Kunze and Kircher (2012). In contrast, γ_{ref} is the volumetric density of a HFO tank, and it is assumed to be equal to 930 kg/m^3 based on Monique and Vermeire (2012).

The assumptions on the amount of hydrogen that would be stored on board are very uncertain, because it would depend on the type of ship, the size and the specific design, but also on the demand for energy produced on board, which in turn depends on the desired range (hours that a ship would sail with a full tank), the power installed and the voyage conditions during a full tank voyage. The kilograms of fuel stored on board (S_x) can be estimated with the formula 4.5.

$$S_x = E^{\text{out}} * sfc_{mm} \quad (4.5)$$

Where:

E^{out} is the demand for energy used on board.

sfc_{mm} is the specific fuel consumption of the main machinery option.

The demand for energy used on board can be estimated with the formula 4.6.

$$E^{\text{out}} = \sum_{i=1}^n (R * T_i) * (P * L_i) \quad (4.6)$$

Where:

R is the range of the ships in hours

T_i is the time in % of R in which the ship sails in each mode i .

L_i is the engine load in % of the P (power installed) in which the engine is working in each mode i .

The voyage conditions during a full tank voyage can be assumed, precisely they are: the time spent in a specific engine mode and the engine load. They were assumed equal

to the one found in the TEAMS model of Winebrake et. al. (2007) and are presented in table 4.5. Also, they are assumed to be constant, so they do not change according to ship type and size and type of fuel on board.

TABLE 4.5: Assumed engine mode and the engine load condition during a voyage that would consume the full tank

	Idle	Manoeuvring	Precautionary	Slow Cruise	Full Cruise
Mode [T] (%)	1.25%	1.75%	5.00%	7.00%	85.00%
Load factor [L]	2.00%	8.00%	12.00%	50.00%	95.00%

The energy stored on board in KWh for hydrogen can be expressed as:

$$E_{st} = \frac{E^{H2}}{\eta_{FC}} \quad (4.7)$$

E^{H2} is the energy produced on board with the hydrogen and fuel cells system combination and η_{FC} is the assumed efficiency of fuel cells. It is, therefore, possible to write equation 4.4 as:

$$dwt_{loss} = \left[\frac{E^{H2} * sf_{CH2FC} * 0.8}{\gamma_{H2}} - \frac{E^{ref} * sf_{cref} * 0.8}{\gamma_{ref}} \right] * \frac{\eta_{FC}}{E^{H2}} \quad (4.8)$$

$$\begin{aligned} dwt_{loss} = & \frac{(\sum_{i=1}^n R_{H2} * T_i * P_{H2} * L_i) * sf_{CH2FC} * 0.8}{\gamma_{H2}} \\ & - \frac{(\sum_{i=1}^n R_{ref} * T_i * P_{ref} * L_i) * sf_{cref} * 0.8}{\gamma_{ref}} \\ & * \frac{\eta_{FC}}{\sum_{i=1}^n R_{H2} * T_i * P_{H2} * L_i} \end{aligned} \quad (4.9)$$

$$dwt_{loss} = \left[\frac{R_{H2} P_{H2} * 0.8}{\eta_{FC} * \beta_{H2} * \gamma_{H2}} - \frac{R_{ref} * P_{ref} * sf_{cref} * 0.8}{\gamma_{ref}} \right] * \frac{\eta_{FC}}{R_{H2} * P_{H2}} \quad (4.10)$$

$$dwt_{loss} = \left[\frac{0.8}{\beta_{H2} * \gamma_{H2}} - \frac{R_{ref} * P_{ref} * sf_{cref} * \eta_{FC} * 0.8}{R_{H2} * P_{H2} * \gamma_{ref}} \right] \quad (4.11)$$

It is possible to write R_{H2} and P_{H2} as a proportion of R_{ref} and P_{ref} using the factors $f1 = R_{H2}/R_{ref}$ and $f2 = P_{H2}/P_{ref}$. Also, the efficiency of fuel cells can be expressed as $\eta_{ref} + f3$. So, equation 4.11 becomes:

$$dwt_loss = \left[\frac{0.8}{\beta_{H2} * \gamma_{H2}} - \frac{sf_{ref} * (\eta_{ref} + f3) * 0.8}{f1 * f2 * \gamma_{ref}} \right] \quad (4.12)$$

By varying the factors $f1$, $f2$, and $f3$ the loss of cargo capacity can be evaluated as shown in figure 4.4. If $f1=1$ and $f2=1$ this means that we assume the range and power installed on board a hydrogen-powered ship will not change in comparison to a reference ship with HFO. If $f3$ varies then it means that the efficiency improves and a new surface is generated in the figure. On the other hand if $f1$ and $f2$ are minor than one, it means that the range and power of the hydrogen-powered ship is in percentage lower than the reference ship with HFO. For example if $f1=0.8$, it means that the range of the hydrogen-powered ship is 80% of the range of the reference ship. The variation of the factors generates surfaces in figure 4.4, that shows how these range, power and efficiency affect the loss of cargo capacity. If the range and the power decrease significantly there would be no loss of cargo capacity. When the surface is under the zero level, it means that there would be more space available for cargo for the hydrogen-power ship than in the reference ship with HFO. also shows that if range and power on board ships is reduced then the loss of cargo capacity due to the lower density of hydrogen storage systems decreases and eventually results in having no impact on extra space requirements. In this thesis it is assumed that range and power of a hydrogen power ship will remain the same as the reference ship with HFO on board. Using equation 4.11 the dwt_loss was estimated to be 0.52 tonnes/kWh. Also, the effect of LNG tank specifications was calculated with the same method, therefore assuming the volumetric density of the tank equal to 420 kg/m³ the dwt_loss for LNG is estimated at 0.06 tonnes/kWh as reported in table 4.6.

TABLE 4.6: Assumptions and estimates of dwt_loss for LNG and Hydrogen storage systems on board

Type	δ (kWh/kg)	Vol. δ (Kg(f)/m ³)	dwt_loss (te/MWh)
LNG tank	13.89	420	0.06
Liquid H2 tank	33.33	40	0.52

4.8.3 Analysis of the upfront capital cost

The upfront capital cost (or unit procurement cost) of the main machinery is assumed to be constituted of two components: the capital cost of the main propulsion system (UPC_{mp}) and the capital cost of the fuel storage system (UPC_{fst}), as shown in

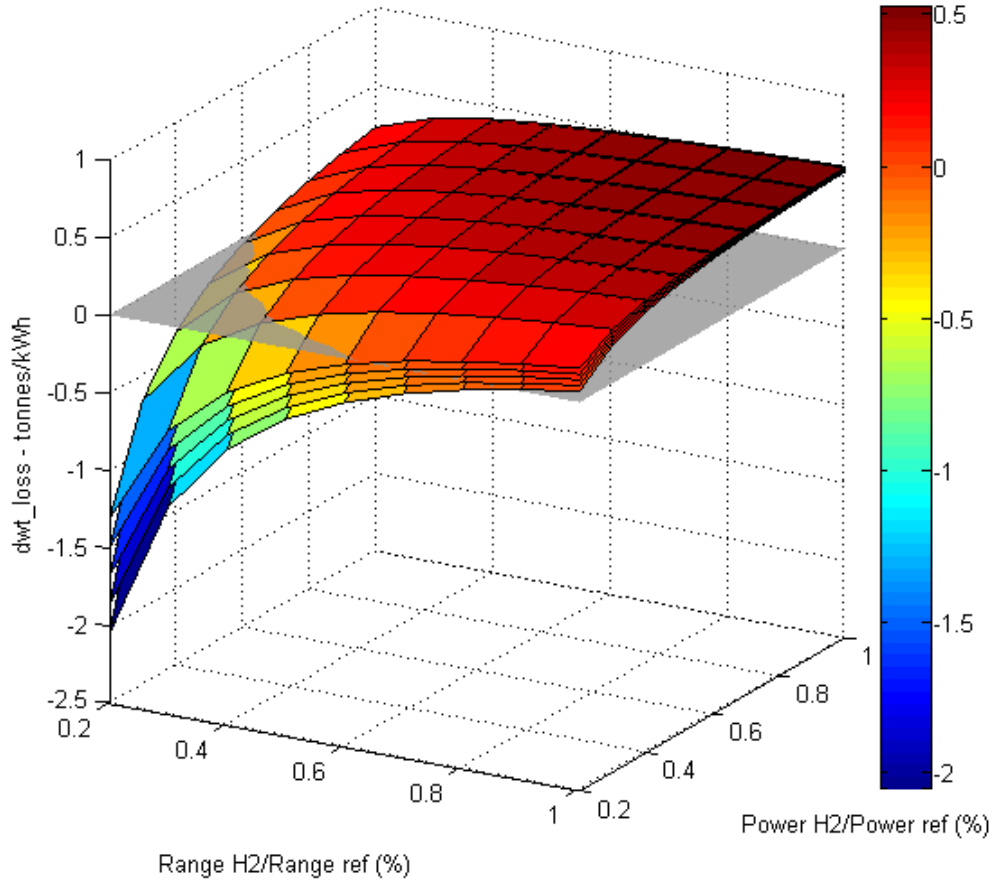


FIGURE 4.4: Loss of cargo carrying capacity (tonnes/kWh) due to the effect of a liquid hydrogen storage system on board in relation to range, power and efficiency changes

formula 4.13. The capital cost of the main propulsion systems is generally found in \$ per kW of power installed, while capital cost of the fuel storage systems is generally found in \$ per kg of fuel stored. The unit procurement costs of the conventional main machinery options were taken from [Smith et.al. \(2013b\)](#); they include both the cost of the engine and the cost of the fuel storage system. Conversely, a different approach was undertaken for the options with hydrogen and LNG.

$$UPC_{tot} = UPC_{mp} + UPC_{fst} \quad (4.13)$$

Generally, capital costs of the main machinery technologies depend on the costs of the components and their size, yet the capital cost of new technologies such as fuel cells and hydrogen storage systems are affected also by other factors such as the predicted annual production volume, the learning curve ratio, and the R&D activities. In this

thesis data was collected from a number of sources and best-guess of projected costs for marine fuel cells and for liquid hydrogen storage systems on ships were estimated. Although it is recognised that such costs will vary over time, only the projected costs are used as the shipping model is assessing future technology costs.

Many studies have looked at the estimates of capital cost of fuel cells in other applications, and less focus has been placed on the estimates for fuel cell systems in maritime applications. One of the most studied applications is the automotive application. A recent study published by IEA on the technology roadmap for hydrogen and fuel cells (IEA, 2015) provided current initial investment costs of a number of fuel cells types for automotive application; they vary from 200 to 6000 \$/kW. Another study was carried out by a consortium of several companies and organisations, (Anon, 2009), envisaging a projected cost for fuel cells in cars of 42 \$/kW in 2050. The energy system TIAM-UCL includes assumptions on fuel cell systems costs in different applications such as bus, car, commercial, light, medium and heavy trucks based on a number of sources and reported in Dodds and McDowall (2012). McDowall (2012) carried out a study on the technology learning curve for fuel cell systems, identifying a current capital cost in cars of 883 \$/kW and a *floor cost* of 27 \$/kW; in comparison the US DOE 2015 target is \$30/kW. James et al. (2012) carried out a study on the cost estimates of stationary fuel cell systems in relation to the power system and the production rate. This study recognised that capital cost decreases with increasing system power and with increasing production rate. The cost of SOFC systems with 100 kW power and a high production rate was estimated at 402 \$/kW. Data of costs were collected from a number of other studies such as Dodds et al. (2015); Schoots et al. (2010); Zaetta and Madden (2011)

Little data on marine fuel cell system costs was found in literature. So far in maritime application, the attention is mainly focused on the use of fuel cell systems as auxiliary engines as for propulsion purposes the high power demand, requires a fuel cell system of about 5 MW, which is not an existing technology at the moment. On one hand the required higher power size on board ships could reduce the cost in terms of \$/kW. On the other hand in shipping, fuel cells may not have the same reduction potential as fuel cells for land-based transportation vehicles, since they may not be produced on the same volume scale (Taljegard et al., 2014). Sødal (2003) referred to different estimates for predicted marine fuel cells capital costs, ranging from 100 to 1500 \$/kW. More recently, Cohen et al. (2011) proposed an SOFC module on board ships and used an acquisition

cost of 884 \$/kW, and [Ludvigsen and Ovrum \(2012\)](#) referred to a target investment cost of 1500 \$/kW, while [Han et. al. \(2012\)](#) refereed to a cost of 750 \$/kW with a high production volume. Data on costs was also collected from a number of other studies including [Gerd \(2009\)](#); [EPA \(2008b\)](#).

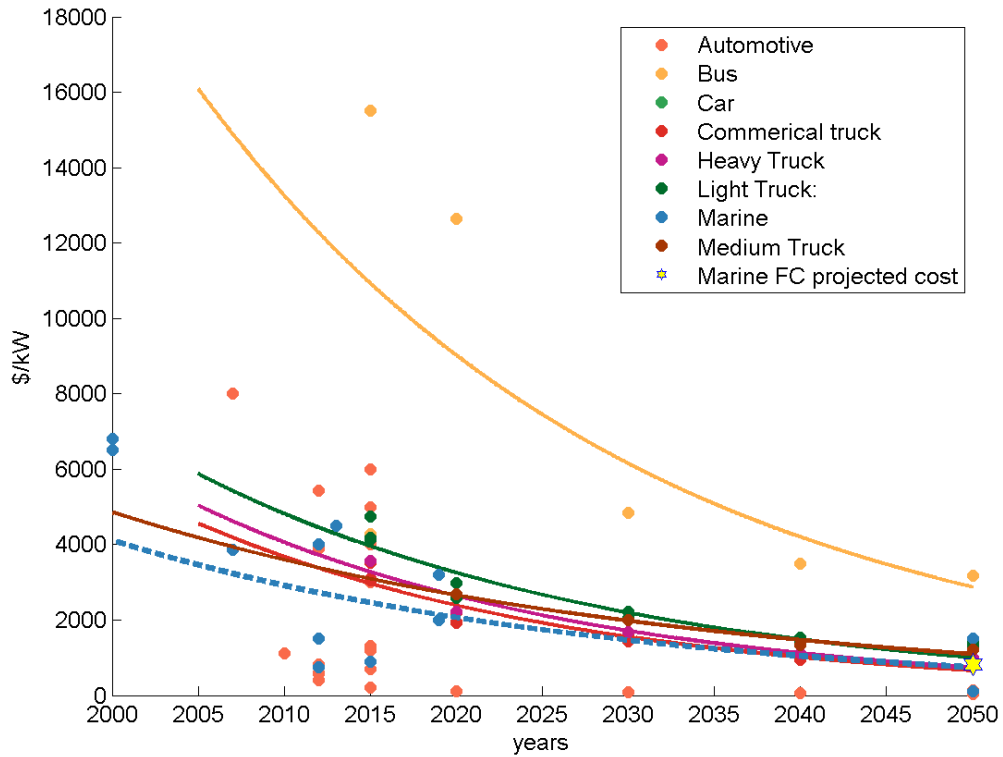


FIGURE 4.5: Projected fuel cell costs

Capital costs found in literature are shown for each specific application in figure 4.5. It is difficult to estimate a projected fuel cell system capital cost for marine applications as not much data is available, however this thesis identifies a best-guess projected cost for marine fuel cell systems of 830 \$/kW. This is lower than the cost suggested in [Ludvigsen and Ovrum \(2012\)](#), however it is close to the value used in [Cohen et. al. \(2011\)](#) and higher than the one in [Han et. al. \(2012\)](#). The figure 4.5 also shows the reduction cost functions used to obtain the projected costs for marine fuel cells.

Fuel cells systems would require an electric motor to convert the electricity produced in mechanical work for the propeller. Therefore, the unit cost of an electric motor has to be taken into account. It may vary with size, however a constant value is used equal to 116 \$/kW according with [ABB \(2013\)](#). When LNG is used with fuel cells, a fuel reformer is required to extract hydrogen, which increases the UPC of the main machinery option.

According with [FCH \(2015\)](#) the cost of the reformer required on board is approximately of 20-30% of total fuel cells system. As consequence about 350 \$/kW were added to the unit cost of fuel cells.

The second component of UPC_{tot} is the capital cost of the fuel storage system. The capital cost of the liquid hydrogen storage system needs to be converted from \$/kg to \$/kW of power installed, in order to sum the two terms in formula [4.13](#). The formula [4.14](#) is used to estimate the UPC_{fst} in \$/kW, assuming a certain amount of fuel stored on board S_x for each ship type with an assumed power installed P_x on board.

$$UPC_{fst} = \frac{(S_x * ucs_i)}{P_x} \quad (4.14)$$

Where:

UPC_{fst} is the unit capital cost for hydrogen storage technology of power size P_x in \$/kW

S is the kilograms of fuel required on board for a ship type x .

ucs is the unit capital cost of hydrogen storage technology in \$/kg

The unit capital cost of hydrogen storage technologies in terms of \$/kg(H₂) (ucs_{h_2}) depends on many factors; first it depends on the type of storage technology chosen. As discussed previously, hydrogen storage system options are generally classified: compressed gaseous hydrogen, liquid hydrogen and solid-state hydrogen storage. Many types of hydrogen storage technologies exist under each of these options, however a generic liquid hydrogen storage system option was assumed in this thesis. [James et. al.](#) claimed that for such a type of storage system the unit cost generally decreases as hydrogen storage capacity increases. A recent study from [IEA \(2015\)](#) estimated the cost of liquid storage systems ranging from 27 to 333 \$/kg with a capacity of 30 Mton. It remains difficult however to estimate the unit cost as not much research has been devoted to estimate the cost of hydrogen storage technologies of large dimension on board ships. Although some cost variations can result from using larger capacity, a constant value equal to 71 \$/kg was assumed as best-guess unit cost of a liquid hydrogen storage technology on board based on data found in [Dodds and McDowall \(2012\)](#). The estimated ucs for hydrogen includes the standard required safety systems. There might be a need of

extra safety equipment, however in this simplification extra costs associated with these were ignored.

Although there are different options for the storage of LNG on board ships, it was assumed a unit cost of 3000 \$/m³ as found in Andersen et.al. (2011). Taking into account the energy density of LNG, it corresponds to 7.14 \$/kg.

The kilograms of fuel stored on board (S_x) can be calculated with the formula 4.5 described above. The formula 4.5 can be incorporated in 4.14 obtaining formula 4.15.

$$UPC_{fst} = \frac{(E^{\text{out}} * sfc_{mm}) * ucs_i}{P} \quad (4.15)$$

$$UPC_{fst} = \frac{(\sum_{i=1}^n R * T_i * P * L_i) * sfc_{mm} * ucs_i}{P} \quad (4.16)$$

E^{out} depends on the range and the power and the operational conditions during a voyage that would consume a full tank. The range for the base year ships fleet by type and size category were obtained using fuel capacity data from Clarckon database 2011, as well as for sfc and power installed. During the simulation of the evolution of the global fleet the ratios $\frac{E^{\text{out}}}{P}$ was assumed to remain constant to the base year ships fleet. These ratios were calculated for each ship type and size category aggregation of the baseline fleet in 2010, and the average of the sizes was used as representative for the ship type category. Then they are used in formula 4.15 to calculate the total UPC of the fuel storage system. Using sfc_{H_2FC} the UPC_{st} for the liquid hydrogen storage system were estimated by ship type and size categories as shown in figure 4.6. The estimated cost of the hydrogen storage system UPC_{H_2} was finally added to the cost of fuel cell system UPC_{FC} as described in formula 4.13 to obtain the total UPC.

4.8.4 Analysis of the through life cost

In addition to the upfront capital cost the through life cost (TLC) also needs to be estimated for all main machinery options. It is expressed as \$/kW per year. The simplification taken in this thesis is that the cost differences among the main machinery options are negligible apart from the replacement of the fuel cells stack. Only the main machinery options that includes fuel cells are affected by the TLC.

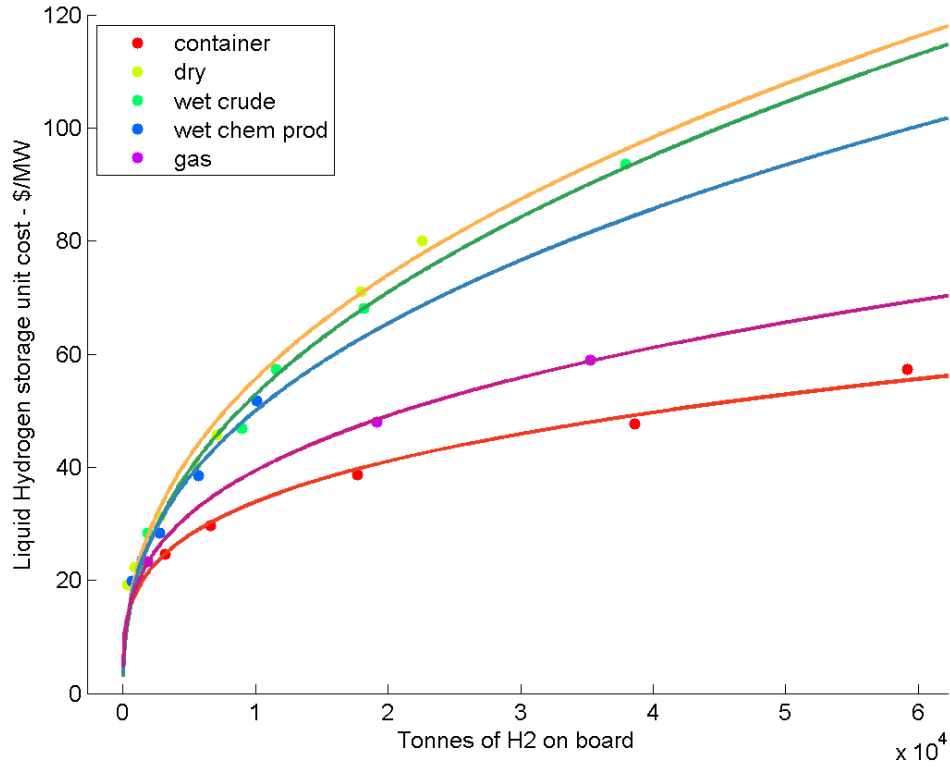


FIGURE 4.6: Liquid Hydrogen storage costs by ship type and size

The current lifetime of fuel cells stack vary in a range from 10,000 to 90,000 hours, therefore during the life of a typical vessel (generally 30 years) the fuel cell stack needs to be replaced. It was assumed a representative lifetime of 47,500 hours and the cost of the fuel cells stack equal to 60% of the whole fuel cells system as the average found in [James et. al. \(2010\)](#). Using the equivalent annual cost (EAC) of all fuel cells replacements required during the ship's lifetime, it was possible to calculate the TLC per year. Such EAC was calculated with the formula 4.17 taken from [Copeland et. al. \(2005\)](#). The resulting value of TLC was estimated at 87 \$/kW.

$$EAC_{fcs} = \frac{NPV}{A_{t,r}} \quad (4.17)$$

Where:

NPV is the net present value calculated as $\sum_{t=0}^{30} \frac{FC}{(1+i)^t}$ with discount rate $i = 5\%$ and time of the cash flow t .

A is the annuity factor calculated as $\frac{1-(1+r)^{-t}}{r}$

t is the ship lifetime (30 years)

r is the interest assumed equal to 10%

4.9 Modifications to the initial conditions

In the TIAM-UCL model the energy demands for international and domestic shipping are based on the data of fuel sales by country using IEA datasets, as explained in section 3.2.3. These energy demands are projected using the regional growth in GDP. The model chooses the mix of fuels, however upper and lower bounds constrain the share that each fuel is allowed to reach in each time step. Such bounds are input assumptions and are set to avoid unrealistic uptake.

Instead, in this thesis fuel quantities and shares are taken from the output of GloTraM, so TIAM-UCL does not choose the mix of fuels, and demands are not exogenous. At the first run of TIAM-UCL, however, fuel quantities and shares have to be calibrated to certain initial conditions. This is an important input assumption as it may have an effect on the final results. Such initial conditions are derived from data reported in [Smith et.al. \(2015\)](#) and assumptions derived from [Argyros et.al. \(2014\)](#) and provided in section 5.2.

4.10 Transferring information from TIAM-UCL to GloTraM

As analysed in section 4.2 when two models are soft-linked two important processes take place when transferring information from one model to the other. They are: the translating and converting process that ensures the compatibility between the variables, and the calibration process that ensures the models work under consistent input variables. In this section both processes are developed in order to transfer information from TIAM-UCL to GloTraM.

The information that is transferred from TIAM-UCL to GloTraM is: the trade of energy commodities also called transport demand of energy commodities in GloTraM, the marine fuel prices, and the carbon prices. The methods developed are presented in the following subsections.

4.10.1 Transport demand of energy commodities

TIAM-UCL simulates the trade of energy commodities between different regions, while GloTraM uses exogenous transport demand aggregated by group of commodity between different countries. The trade between different regions from TIAM-UCL needs to be converted into trade between different countries in GloTraM. Therefore only trade of energy commodities between different countries that belong to different regions is modified in GloTraM, while trade of energy commodities between different countries that belong to the same region is not modified in GloTraM. Table 4.7 provides the list of energy commodities that are defined in TIAM-UCL and the associated group commodity as defined in GloTraM.

TABLE 4.7: Energy commodities as defined in TIAM-UCL and the associated group commodity as defined in GloTraM

TIAM-UCL		GloTraM	
Commodity description	Name	Energy density <i>MJ/tonnes</i>	Group commodity description
Bio crops	BIOCR	17000	Wood and cork
Bio diesel	BIODST	39000	Fuel derivatives
Bio jet kerosene	BIOJTK	39000	Fuel derivatives
Bio kerosene	BIOKER	39000	Fuel derivatives
Bio naphta	BIONAP	39000	Fuel derivatives
Solid biomass	BIOSLD	15000	Wood and cork
Hard coal	COAHCO	24000	Coal
LNG	GASLNG	55000	Gaseous hydrocarbons
Crude oil	OILCRD	42000	Crude petroleum
Distillates	OILDST	42600	Fuel derivatives
Gasoline	OILGSL	40500	Fuel derivatives
Heavy fuel oil	OILHFO	40500	Fuel derivatives
Naphta	OILNAP	44000	Fuel derivatives
Natural gas liquids	OILNGL	42000	Fuel derivatives

There might be a case in which the energy commodity as defined in TIAM-UCL does not cover all commodities defined in each group in GloTraM, resulting in a possible underestimation of such trade. For example bio-crops is associated with the group commodity wood, however in the group commodity wood there may be other commodities that are not defined in TIAM-UCL. It is assumed that the commodities as defined in TIAM-UCL are representative of all commodity groups as defined in GloTraM, although it is recognised that this approximation can be a limitation of this approach.

In order to convert the trade by region into trade by country, the transport demand dataset present in the shipping model was used. The dataset was used to obtain the *countries shares* that are assumed to be the same in TIAM-UCL trade. For example, for a specific commodity trade in a specific year between region A and region B, the countries' shares of region A are calculated as ratios of the total trade from region A over the trade from the specific countries that belong to region A. Similarly it is done for the receiving region B. So that, when TIAM-UCL calculates the trade between region A and B, such countries' shares are used to convert the regional level trade to country level trade. Figure 4.7 shows an illustrative example of such a process. This process is done for each time step, for each energy commodity, for each trade. Since regional trade is expressed in PJ in TIAM-UCL, they are converted into tonnes, using the energy densities reported in table 4.7. Each commodity group trade is associated to a specific ship type as in the transport demand dataset in GloTraM.

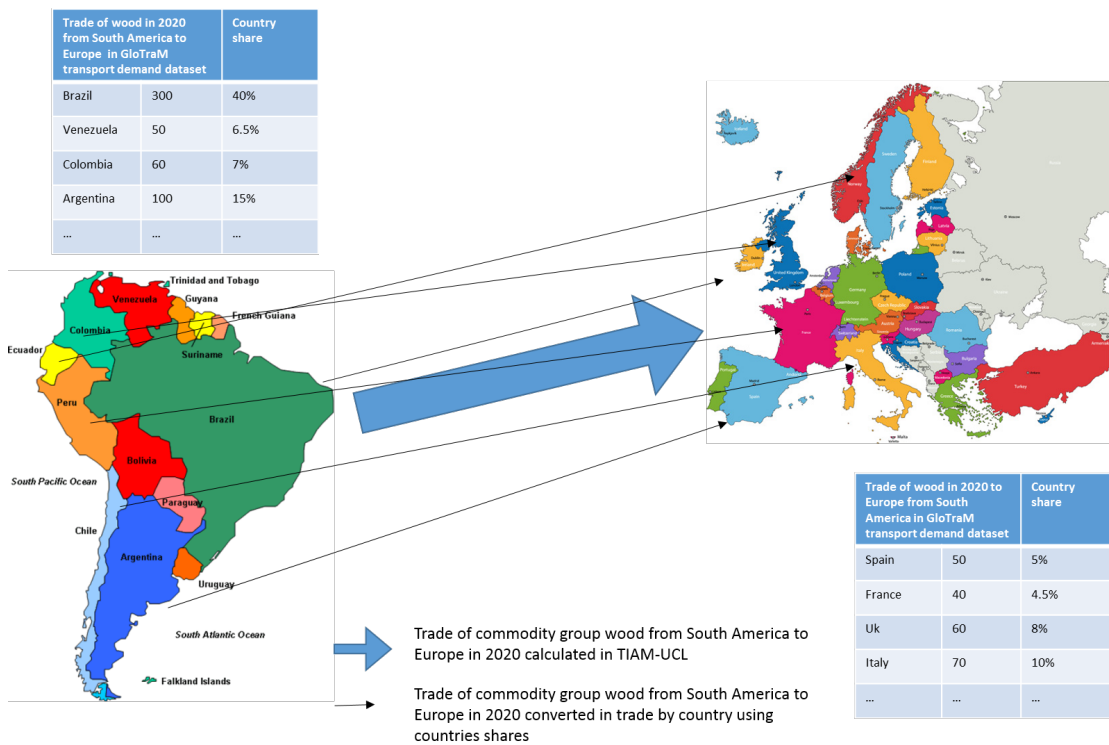


FIGURE 4.7: Illustrative example of converting regional trade from TIAM-UCL to trade by country level in GloTraM

If a regional trade calculated in TIAM-UCL does not exist in the transport demand dataset in GloTraM, then a representative country is used to transfer such trade from regional level to country level. In this case the entire regional trade is associated with the trade of two specific countries in origin and destination regions.

It is important to note that TIAM-UCL also takes into account the fuel consumed for such trade of energy commodities. This needs to be considered when transferring quantities from GloTraM to TIAM-UCL in order to avoid the double counting of such consumptions. This is explained in section 4.11.

4.10.2 Production derived cost as a proxy for fuel price

In TIAM-UCL the price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity's price. This thesis uses the elastic demand version of the model, which allows energy service demands to react to changes in commodity prices. So, for example, the hydrogen price affects its demand in shipping, which is affected by its price. In addition, the CO_2 shadow prices estimated in any scenario can influence the commodity prices. A cost mark-up will be reflected in the commodity price if the steps to produce such a commodity require energy that is carbon intensive. So, for example, a mark-up will increase the commodity prices of oil in a carbon-constrained scenario as the extraction, processing, and transport of such commodities requires energy which is carbon intensive.

The TIAM-UCL model generates endogenously a shadow price for each commodity by matching supply and demand. The shadow price is defined as the price paid for an increment of additional production, and it incorporates the costs of production, the choice of substitutes, the constraints that are imposed (e.g. ramp-up rates on new sources of production), and any long-term energy-service demand elasticities. 'Price' and 'shadow price' are not necessarily the same as the latter does not include some elements that are in the real world as extraction taxes. Due to these taxes the commodity price of oil is significantly lower than in the real world (the global-average government tax take of a barrel of oil is around 67%) (McGlade and Ekins, 2014).

In order to use such shadow prices as a proxy of real prices different assumptions are made. Particularly, diverse assumptions are considered for conventional oil derived fuels (HFO and MDO), and for alternative marine fuels (LNG and hydrogen).

As noted, shadow prices of oil derived fuels in TIAM-UCL generally tend to be lower than the expected real prices. If we use such shadow prices in GloTraM this can have an impact on results as the model is calibrated for marine real fuel prices. It is assumed, therefore, that for such fuels the shadow price plus a mark-up corresponds to a proxy of the real world price. Based on this assumption a fixed cost-mark up was added to

the estimated shadow prices. The fixed cost mark-up is calculated as the percentage difference between the TIAM-UCL shadow price and the real world fuel prices in 2010 taken from [Smith et. al. \(2013a\)](#). This means that the relative increase in shadow prices is indexed back to the real price in 2010. A similar approach has also been used in [Solano and Drummond \(2014\)](#).

Nowadays, for example, gas price is driven from factors such as type of contract and oil price. These factors are not modelled in TIAM-UCL, so the estimation of the shadow prices for LNG and hydrogen in TIAM-UCL implies an assumption that a global price would be formed in the future. Hydrogen and LNG global markets do not yet exist, so their prices are based on fuel production costs, and supply-demand fundamentals. In this thesis, it is assumed that shadow prices of hydrogen and LNG calculated in TIAM-UCL are representative of future real prices.

TIAM-UCL does not provide a shadow price if there is no demand for a commodity. For instance, if hydrogen or LNG are not demanded in shipping during the period 2010 to 2015 then their prices are not available. In this case it is assumed that the average global price for that period is higher than the first observed global price, in this example the price in 2015. This assumption is based on the consideration that a global price before the actual demand takes place is affected by the investment required for the development of a global supply infrastructure. It is difficult to estimate how much higher the global prices in this specific period would be compared to the first observed prices estimated in TIAM-UCL. In this thesis a factor of 10% has been used to take into account a penalty that would represent the fact that early adopters will have to pay a high price, eventually the price will decrease as the global supply infrastructure for hydrogen and LNG develops.

It is important to note that TIAM-UCL estimates regional shadow prices, while GloTraM uses as input exogenous global fuel prices. Therefore, each global fuel price is calculated as a weighted average of the regional shadow prices. Generating a single global price on the basis of the diverse regional prices is a large simplification for commodities such as LNG and hydrogen which would have different pricing mechanisms around the world, especially in the near future. So, in reality there would be locations where hydrogen or LNG could have a competitive price and other locations where hydrogen or LNG prices would be extremely expensive. However, as the focus is on a long term view it can be expected that the global price for LNG and hydrogen will develop.

4.10.3 Carbon price

Carbon price can be transferred from TIAM-UCL to GloTraM. Generally, TIAM-UCL simulates the *global carbon prices* in order to meet the emissions reduction target of the selected scenario. GloTraM, instead, requires an exogenous *shipping carbon price*, or alternately it can be estimated internally through a feedback of the output back to the shipping system. The latter case is used in the simulations where the shipping industry is restricted on the total amount of GHG that can be emitted until 2050 to a certain CO_2 budget. This case simulates the implementation of a Market Based Measure (MBM), which adjust the cost-benefit available in the model to enable take-up and in-sector emissions mitigation.

As consequence two different cases can be considered. In the first case, it is assumed that the shipping carbon price is equal to the global carbon price as estimated in TIAM-UCL. The assumption in this case is that the global carbon price that derives from a global action of all sectors to de-carbonise, is representative of a shipping carbon price although the latter is acting independently from the rest of the energy system. In the second case, this assumptions is rejected and instead it is assumed that the shipping carbon price is equal to the one estimated internally in GloTraM. The assumption in this case is that a shipping carbon price will be set according to the introduction of a MBM measurement that uses the part of the carbon taxes to fund environmental and low carbon programmes and investments.

The first case is considered in the simulations analysed in chapter 5, while the second case is considered and explained in more detail in chapter 6.

4.11 Transferring fuel consumptions from GloTraM to TIAM-UCL

This section presents the process of transferring information from GloTraM to TIAM-UCL. The projections of future consumption of marine fuels are taken from GloTraM and then they are transferred in terms of quantities and shares by region in TIAM-UCL.

Future consumption of marine fuels can be expressed in GloTraM as fuels consumed by ships trading inbound to a region (international import), outbound of a region (international export), and within a region (domestic). The disaggregated consumptions are

calculated based on estimated ship movements in terms of number of discrete voyages that are required to satisfy the allocated transport supply. Operational data is consistent for inbound, outbound and domestic voyages by ship type and size categories, however differences are considered for laden and ballast voyages. In particular, it is assumed that the voyage is always laden if it is a container ship, otherwise, every loaded voyage is followed by a ballast voyage. Other assumptions regarding the fleet operational characterisation can be found in more detail in [Smith et. al. \(2013a\)](#) and [Smith et. al. \(2013b\)](#).

On the other hand, TIAM-UCL requires the energy consumed by ships that trade between different regions (international trade), and energy consumed by the ships that trade within the same region (domestic trade). Both energy service demands are expressed in PJ per year and exclude the energy consumed by the ships that trade energy commodities as they are calculated endogenously within the model.

In summary, GloTraM estimates the fuel consumptions and TIAM-UCL requires marine fuel demands by region. In order to transfer this information from GloTraM to TIAM-UCL a conversion process is needed. As a first step, two simplifications were applied. First no distinction was assumed between international and domestic energy service demand in TIAM-UCL, rather a generic energy service demand was considered that includes both international and domestic. Second no distinction was assumed between inbound, outbound and domestic voyages, rather the global fuel consumptions were taken into account. This means that the total consumption of marine fuels at global level needs to be decomposed into marine fuel demands by region.

Such marine fuel demands are associated to the region where the refuelling takes place and not where the fuel is actually produced as it is the energy model to establish the region where it is most cost effective to produce the fuel and to transport to the refuelling location. The second step of the conversion process is, therefore, the decomposition of the global fuel consumption in regional marine fuel demands that corresponds to assume where ships refuel at regional level.

In the real world, route and schedule decisions affect the options for refuelling characterised by their geographical locations, port costs, and bunker price [Vilhelmsen et. al. \(2014\)](#). According with [Oh and Karimi \(2010\)](#), ship operators make their refuelling decisions after monitoring the market prices and trends, and searching for the best possible prices on their trade routes. Typically prior to the arrival at a port the fuel supplier

and the ship operator reach an agreement on the bunkering price and refuelling timelines, then the refuelling process proceeds. Since the defined regions are relatively big it is possible to ignore such dynamics and assume that ships refuel in specific ports constrained by the configuration of the maritime trade network. The configuration of maritime trade routes is a function of obligatory points of passage, which are strategic locations of physical constraints (coasts, winds, marine currents, depth, reefs, ice) and of political borders [Rodrigue et. al. \(2013\)](#). It is possible to assume that this configuration is going to be relatively unchanged over time, and that any changes to this configuration would have a minor effect on the refuelling options. In addition, the location of refuelling ports terminals is influenced by logistics and transport cost factors. According with [EPA \(2008a\)](#) often such terminals are strategically located close to supply sources (petroleum refineries) and consumers of transported goods (major population centres), and along high-density shipping routes. This is why a few ports seem to dominate fuels sales because of their strategic location [Vilhelmsen et. al. \(2014\)](#). Large bunkering ports such as Singapore, Rotterdam and Gibraltar, Panama, and Los Angeles, San Francisco, New York, Philadelphia, Houston, and New Orleans dominate the market and affect the sales of their country. IEA provides statistics of the marine fuels sales. The most important fuels used as bunkers in IEA's datasets are *fuel oil* and *gas diesel*. The former dominates the markets; figure 4.8 shows an intensity world map of fuel oil sales in 2010 for international shipping by country. This map confirms that the majority of fuel sold to shipping is focused on few locations.

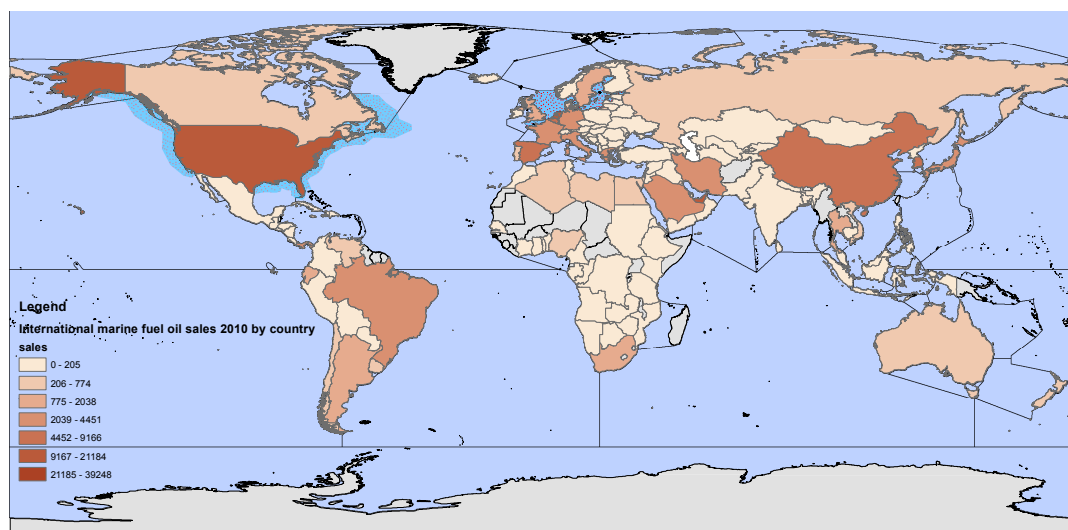


FIGURE 4.8: Fuel oil (HFO) sales to fuel ships 2010 in million tonnes

Historical marine fuels sales by country can be aggregated by region as defined in TIAM-GloTraM, so regional shares can also be calculated. Such shares were calculated per each fuel and were used to disaggregate the global fuel consumptions estimated by the shipping model into regional fuel demands. For the base year 2010, the actual shares in that year were used to disaggregate the global fuel consumptions in 2010 in regional fuel demands. These demands were used to calibrate the energy model at base year.

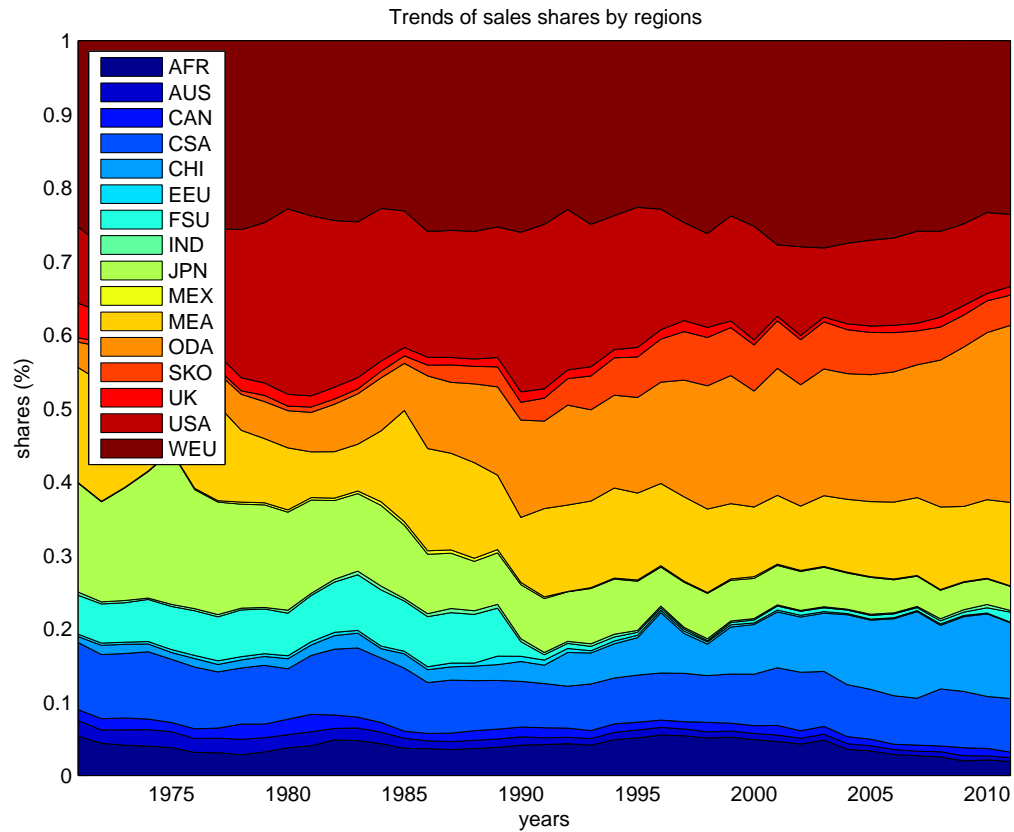


FIGURE 4.9: Historical shares of marine fuel oil sales aggregated by TIAM-GloTraM region - Africa (AFR), Australia (AUS), Canada (CAN), Central and South America (CSA), China (CHI), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JPN), Mexico (MEX), Middle East (MEA), Other developing Asia (ODA), South Korea (SKO), United Kingdom (UK), United State of America (USA), Western Europe (WEU). Source: IEA World Energy Statistic

The projected global fuel consumptions were disaggregated in regional fuel demands by using fixed regional shares obtained with the analysis of historical trends. Figure 4.9 provides the trend of fuel oil sale shares (domestic and international) by region. The shares of some regions such as Western Europe, Australia, Canada, Central and South America, UK, and Middle East seem to be almost constant over time. Other regions

show a more unstable trend. USA and Japan have decreased their shares especially during the last decades, conversely South Korea since 1985 has increased its share and it seems to be stable over the last decade. China and Other developing Asia have clearly increased their shares, while Former Soviet Union dramatically dropped its shares in 1990 and only in recent years has a significant share. Other regions such as Mexico, India, and Eastern Europe seem to have a very small share.

Figure 4.10, instead, shows the historical trend of gas diesel sales shares (domestic and international) by region. The shares of some regions have unstable trends, for example China increases significantly, while Former Soviet Union and Western Europe decrease. The rest of the regions seem to have almost a constant share. Even though dramatic changes are observed, since 1990 such changes are generally small for many of the regions.

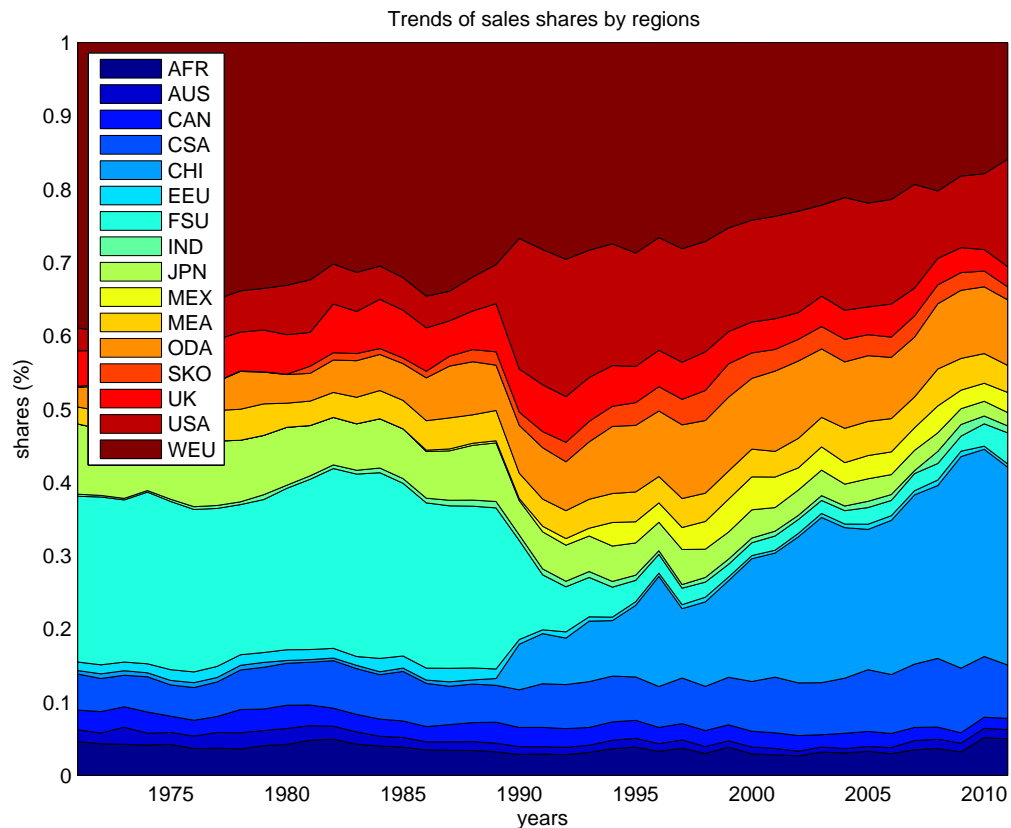


FIGURE 4.10: Historical shares of marine gas diesel sales aggregated by TIAM-GloTraM region - Africa (AFR), Australia (AUS), Canada (CAN), Central and South America (CSA), China (CHI), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JPN), Mexico (MEX), Middle East (MEA), Other developing Asia (ODA), South Korea (SKO), United Kingdom (UK), United State of America (USA), Western Europe (WEU). Source: IEA World Energy Statistic

Another way to present the variance of the regional shares is by using the box plots. For each region, it is possible to represent the variance of the share with a rectangle that ends to the upper and lower quartiles. Figure 4.11 shows the box per region for fuel oil and for gas diesel considering IEA historical data from 1991 to 2011. It also includes the mean, the median and the outliers per region. In general it can be observed that median and mean are very similar. The biggest variances for fuel oil are observed in Western Europe, USA, Other developing Asia (that includes Singapore), and China. Overall the shares in (%) can be considered relatively constant.

Based on the means presented in figure 4.11, fixed shares were considered in order to disaggregate the projected global fuel consumptions into projected regional fuel demands. In particular, the means of historical regional shares of fuel oil and gas diesel were used for HFO and MDO demands respectively. There is no historical data for LNG and hydrogen in shipping, therefore it is assumed that such alternative fuels would be available and sold at the main refuelling port terminals as for the current conventional marine fuels. This means that the regional shares would be similar to the one for HFO and MDO. As consequence the mean of the regional shares of both fuel oil and gas diesel fuels were used to obtain the fixed shares for LNG and hydrogen.

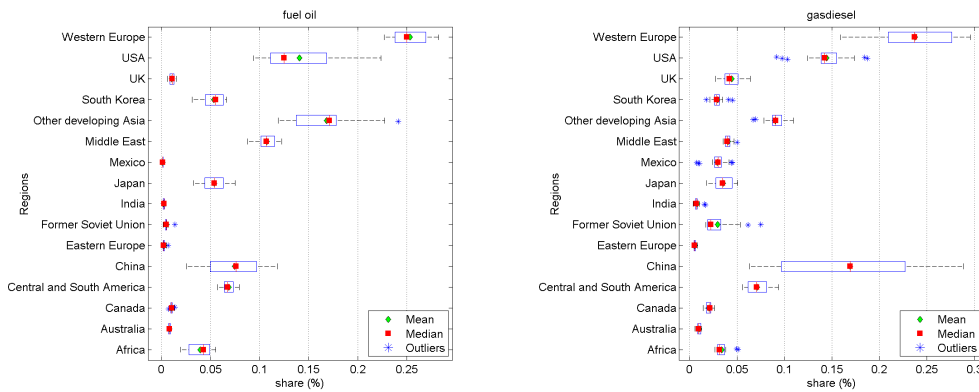


FIGURE 4.11: Variance of the regional shares for fuel oil on the right, and for gas diesel on the left. Data from 1991 to 2011. Source IEA World Energy Statistics. Overall the shares in (%) can be considered relatively constant, although variances are observed in particular regions.

In conclusion it is assumed that ships would always refuel in specific regions and such shares will not change significantly in the future. Nevertheless, it is assumed that possible future variance of such shares would not affect the results dramatically and therefore they are neglected. Once the fixed shares were estimated, it was possible

to decompose the total marine fuel consumption into regional marine fuel demands and finally, quantities and shares from GloTraM were transferred as shipping energy demands in TIAM-UCL.

4.12 Consistency

The last part of the soft-linking process undertaken to link TIAM-UCL and GloTraM is the introduction of a proceeding that ensures the convergence of the models towards the system consistency. This is done using an iterative procedure with a stopping criteria. Such theoretical consistency concerns of the understanding of how the two models interact with each other, and the implications of reaching the system consistency. In order to analyse such theoretical consistency, the objective functions of both models are discussed first, then the iterative process and its implications are examined.

4.12.1 The objective functions

TIAM-UCL belongs to the family of TIMES models. According with [Loulou and Labriet \(2008\)](#), TIMES model computes a partial equilibrium on energy markets. This means that the supply-demand equilibrium has the property of maximising the total surplus, defined as the sum of suppliers' and consumers' surpluses.

The supply-demand equilibrium is at the intersection of the supply function and the demand function, in which an equilibrium quantity Q_E and an equilibrium price P_E are obtained as shown in figure 4.12.

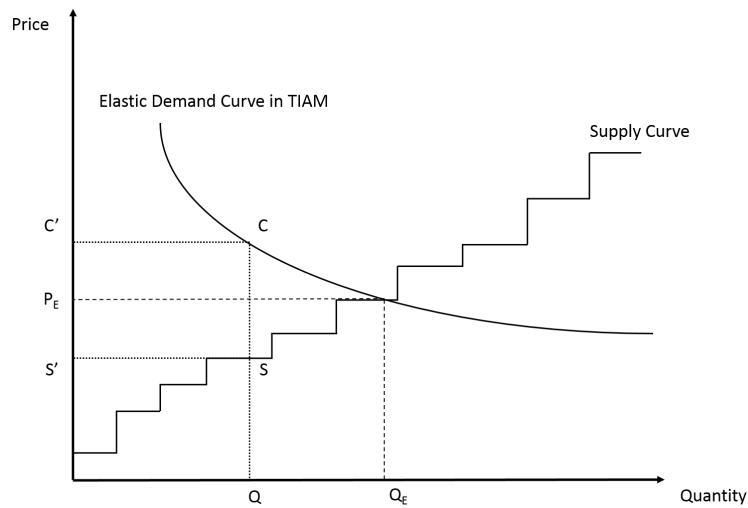


FIGURE 4.12: Supply-demand equilibrium in TIAM-UCL

The supply curve characterises the set of suppliers of a commodity, where the suppliers of a commodity are technologies that procure a given commodity, for example hydrogen. Such a supply curve is endogenously derived by the model itself, providing the marginal production cost of the commodity as a function of the quantity supplied. Usually in TIMES models the supply curves are represented by non-linear functions as a stepped sequence of linear functions. For example a supply of some resource may be represented as a sequence of linear segments, each with rising unit cost. Such horizontal steps indicate that the commodity is produced by a certain set of technologies. Each time the quantity produced increases, a change in the production mix occurs, due to the fact that one or more resources in the mix is exhausted, and the system starts using a different (more expensive) set of technologies. This generates one step of the staircase supply function (Loulou and Labriet, 2008).

On the other hand the demand curve characterises the consumers of a commodity, that are technologies or demands that consume a given commodity, for example the shipping energy demand. Generally such demand curves are exogenously defined by the user, and they are assumed to have a constant own price elasticity function defined by the following equation:

$$\frac{D}{D_0} = \left(\frac{P}{P_0} \right)^e \quad (4.18)$$

where D_0 and P_0 is a reference pair of demand and price values obtained from solving a reference scenario, and e is the own price elasticity of that energy service demand chosen by the user.

The supply-demand equilibrium is reached when the total surplus is maximised. The suppliers' surplus is the net revenue attached to a given commodity, corresponding to the area between the horizontal segment SS' and the supply curve. Similarly, the consumers' surplus is the opportunity gain of all consumers who purchase the commodity at a price lower than the price they would have been willing to pay, corresponding to the area between the segment CC' and the demand curve. The total surplus of an economy is the sum of the suppliers' and the consumers' surpluses, therefore for a given quantity Q , the total surplus is the area comprised between the two inverse curves and located at the left of Q . The total surplus is maximised when Q is equal to the equilibrium quantity Q_E (Loulou and Labriet (2008)).

As mentioned GloTraM provides scenarios of the evolution of shipping fleet's composition and their technical and operational specifications. Such evolution is simulated assuming that the trade-off of design speed, energy efficiency and sunk costs are aligned with a single agent, the ship owner [Smith \(2012\)](#). Therefore every investment is evaluated by maximising the annual profit of the ship owner expressed as:

$$\pi_{pa} = R_{pa} - C_{s-pa} - C_{v-pa} \quad (4.19)$$

Where C_{s-pa} is the annual sunk (or fixed costs), C_{v-pa} is the annual variable costs, and R_{pa} is expected annual revenue generated from a series of cargo movements. It is said that *a rational ship owner will select a design and operation specification that maximises profit* ([Smith, 2012](#)). The annual revenue R_{pa} is a function of the price paid for units of transport supply and the quantity of transport supply per year. The latter is in turn a function of the design and operation specifications such as the *dwt*, the days spend at sea, the loaded efficiency and the speed. The sunk costs C_{s-pa} are composed of both capital costs and annualised fixed operating costs, where capital costs are divided into investments in energy efficiency and hull and investments for the engine, for example fuel cells with hydrogen. Fixed operating costs are exclusive of voyage costs. The voyage costs C_{v-pa} are the variable costs associated with a voyage. These are a function of fuel prices, fuel carbon content, carbon price, efficiency of the main machinery, and other technical and operational specifications ([Smith, 2012](#)). This implies that GloTraM calculates the consumption of the marine fuels by simulating the way the shipping industry is likely to respond to a number of inputs such as future fuel prices, carbon prices, and transport demand. In other words the consumption of marine fuels is a function of fuel prices, carbon price, transport demand, technology and a number of other technical and operational specifications of the shipping system.

4.12.2 The iterative procedure

The consumption of a marine fuel corresponds in TIAM-UCL to the technologies that consume a given commodity, which characterises the *demand curve*. When transferring marine fuel consumptions from GloTraM and TIAM-UCL, it corresponds to the *demand curve* represented as a vertical line as illustrated in [4.13](#) for each time step. The theoretical consistency of TIAM-GloTraM is ensured by the iterative process. Figure [4.13](#) also

illustrates the steps involved in this process. First TIAM-UCL is solved determining the supply curve and the equilibrium Q_0 and P_0 based on initial condition D_0 . This also parametrises GloTraM input data, which computes the fuel consumption, thus the demand curve D_1 . In the next iteration TIAM-UCL evaluates the energy market based on the new demand curve, finding a new equilibrium in Q_1 and P_1 . This parametrises again GloTraM input data, which generates the new demand curve D_2 . The iterative process converges when the equilibrium prices of two consecutive iterations (for example P_3 and P_2) are relatively small so that the changes in the fuel quantities (fuel demands) are negligible.

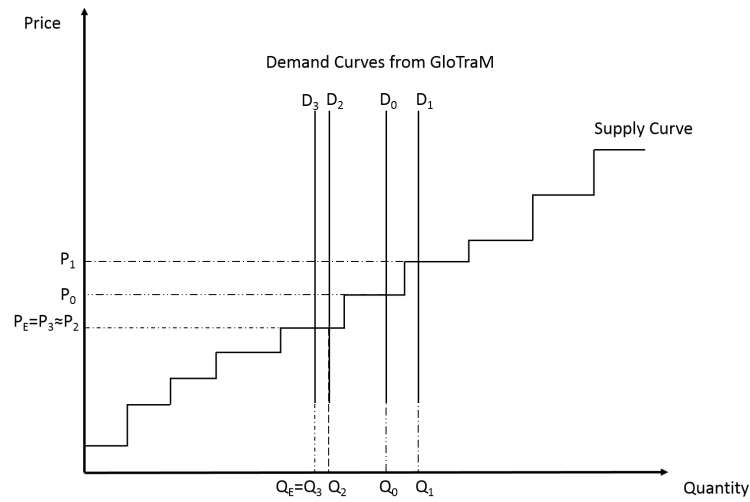


FIGURE 4.13: Iterative process between TIAM-UCL and GloTraM

The iterative process consists in a continuous exchanging of information between TIAM-UCL and GloTraM until convergence in central variables is achieved. The central variables are the fuel prices, while the convergence is ensured by a stopping criteria. The iterative process stops when fuel price projections at iteration n change by less than 5% than the fuel price projections at iteration $n + 1$ for all fuel types in all years of the analysed period.

It is important to note that the consistency of TIAM-GloTraM is ensured not only by the iterative process but also by the entire soft-linking method developed which takes into account all main steps developed in this chapter.

4.12.3 Assumptions embedded in the soft-linking framework

The developed soft-linking framework embeds assumptions about the real world phenomena. The target system is the uptake of hydrogen in shipping taking into account

the supply of hydrogen in shipping and its use on board ships. The real world phenomena, therefore, is the interaction between the energy system that provides energy in the form of fuels to ships and the shipping system itself. If we assume that the dynamics of supply and demand of hydrogen in shipping in the real world are similar to the ones in the model *TIAM-GloTraM*, then it becomes important to highlight what are the assumptions that the developed linking procedure embeds about the interaction between the energy and the shipping systems.

A first assumption regards the two different assumed behaviours of the systems. The shipping system and the energy system act under different philosophical aims, which means that there are two different objective functions with two different scope. In other words, on one hand the energy system informs the shipping system of the fuels prices based on the least-cost abatement function, and on the other hand, the shipping system inform the energy system of fuels shares due to the investment that shipowners would adopt based on profit opportunity.

Another assumption regards the behaviour of the shipping system under a global decarbonisation scenario. In the case in which shipping carbon price is set equal to the global carbon price estimated in *TIAM-UCL*, essentially it means to include the shipping system within the optimal decarbonisation of the whole energy system. Because of this, the framework allows the shipping system to buy offsets for CO_2 emissions from the rest of the economy. So, in this case although the shipping system acts differently to the other sectors, it receives from the rest of the energy system the global carbon price that would be required if there will be a global effort to mitigate emissions. Alternately, setting the shipping carbon price equal to the one calculated in *GloTraM* means that the shipping system will act independently to meet its own CO_2 budget, while it is allowed to buy offset for CO_2 emissions from the rest of the economy at a fixed proportion. Also in this case the shipping system acts differently to the other sectors, however it sends back to the rest of the energy system the fuel shares that would meet the internal shipping emission target and the energy system will estimate fuel prices and global carbon price as if there will be a global effort to mitigate emissions. A possible alternative regarding the behaviour of the shipping system under a global energy decarbonisation scenario is that instead to have the assumptions that the rest of the energy system would act together, also the other sectors would act independently (based on different objective function) fighting each other to maintain a certain carbon budget that it would be proportional

to their relative contribution. This is not captured by the developed framework and it can be considered as a further area of research.

Chapter 5

Results of the soft-linking framework

5.1 Introduction to the results

This chapter addresses the first research question: how the soft-linking framework can improve the modelling representation of the uptake of hydrogen in shipping. To answer this question the results of key variables obtained with TIAM-GloTraM are compared with the ones obtained with independent runs of TIAM-UCL and GloTraM. The aim is to demonstrate that the soft-linking framework improves the modelling representation of hydrogen's take-up in shipping by providing a more consistent set of results that enables the explanation of dynamics between the energy and the shipping systems that cannot be observed with independent simulations. If so, TIAM-GloTraM represents an improvement of the substance of modelling hydrogen in shipping in terms of its representational capacity of the target system, and it can be used to explore possible emergences in the energy-shipping system.

A total of six simulations were examined. Table [5.1](#) describes the six simulations. There are two reference scenarios: 4°C and 2°C. The first is a scenario that simulates the target system, ensuring that the average global temperature rise is below 4 °C, while the second is a scenario with a deep decarbonisation that ensures an average global temperature rise is below 2°C. First, TIAM-UCL and GloTraM were independently used to simulate the two reference scenarios, then TIAM-GloTraM was used.

There are a large number of outputs from each simulation, however the focus is only

TABLE 5.1: Simulations

Simulation name	Description
IT4D	Independent TIAM-UCL 4°C
IG4D	Independent GloTraM 4°C
TG4D	TIAM-GloTraM 4°C
IT2D	Independent TIAM-UCL 2°C
IG2D	Independent GloTraM 2°C
TG2D	TIAM-GloTraM 2°C

on the key variables that are transferred between the two models; these are: the shipping transport demand of energy commodities, fuel and carbon price, the fuel consumptions and fuel shares mix. Such variables are not always outputs of the model used in each simulation, for example the trade of energy commodities is an output in IT4D and IT2D, while it is an input in IG4D and IG2D. Table 5.2 summarises such differences among the simulations.

TABLE 5.2: Variables examined

Variable	Model		
	TIAM-UCL	GloTraM	TIAM-GloTRaM
Trade of energy commodities	Output	Input	Output
Fuel and carbon prices	Output	Input	Output
Fuel shares mix	Output	Output	Output
Fuel consumption	Input	Output	Output

A simple comparison between these variables is unable to completely demonstrate that the results from TIAM-GloTraM are an improvement of the ones from the independent runs, because such variables are not all outputs of the model used. Every time a variable is an input then assumptions are required; for instance, fuel prices are output from TIAM-GloTraM and input in GloTraM. This means that when fuel mix are compared, it is difficult to demonstrate that one result is an improvement of the other results as the fuel prices input assumptions in GloTraM could have influenced the results and they cannot be associated with the representational capacity of the model. In other words, because of the different boundaries of the models, they cannot be used under the same exact assumptions, which prevents a fair comparison of the results themselves.

Even though the comparison of the results cannot demonstrate that TIAM-GloTraM can provide improved results, such a comparison is still very useful. The interpretation of the results for the variables in table 5.2 reveals a different level of insights depending on the model used. If TIAM-GloTraM is able to provide a more consistent and detailed

interpretation of its results, it demonstrates that the model is an improvement of the representation of the target system. The relationship between the modelling representation and interpretation is the focus. If my interpretation of the results can be more complete, detailed, and consistent then I should have a improved modelling representation of the system.

This chapter is organised as follows: section 5.2 and section 5.3 provide a general description of the key assumptions used for the two reference scenarios, including the assumptions required when the variables examined are inputs of the model used. Section 5.4 provides the results from the independent runs of TIAM-UCL for the 4°C and 2°C reference scenarios (IT4D and IT2D). Similarly, section 5.5 provides the results from independent runs of GloTraM (IG4D and IG2D). Then section 5.6 provides the results from TIAM-GloTraM. Finally the comparison of the results and discussion are provided in section 5.7.

5.2 Key assumptions in TIAM-UCL

This section provides the key assumptions of the reference scenarios in the energy model. In particular they regard: the constraint on carbon-equivalent (CO_{2e}) emissions, the availability of bioenergy and carbon capture sequestration technologies (CCS), and the projection of the shipping energy demand. As mentioned there are some differences in the assumptions used depending on the simulation. Such differences will also be detailed in this section.

The scenarios 4°C and 2°C refer to the average global temperature rise. In practice, a global constraint on CO_{2e} emissions is applied on the energy model. TIAM-UCL is constrained to keep the atmospheric concentrations of CO_{2e} below a certain value of ppm in all years up to 2100. The 4°C scenario constrains the model to 720 ppm, while the 2°C scenarios to 425 ppm. This results in an equal chance of keeping the average global temperature rise respectively below 4°C and 2°C (McGlade and Ekins, 2014). The model is free to determine the least-cost global abatement as it is assumed that there will be a global effort to mitigate emissions. However, regional emission caps are also imposed on the model in order to provide more realistic scenarios. For instance, in the 2°C scenario the maximum pledges made as part of the Copenhagen Accord are used to constrain the model in 2020 (McGlade and Ekins, 2014).

In addition to the emissions constraints, a number of other factors are important in the energy model that are relevant for describing the reference scenario. They are: the availability of bioenergy and CCS technologies. For these assumptions there were no differences between the reference scenarios 4°C and 2°C.

Although in this thesis biofuels are not considered in shipping, in a low carbon scenario they might compete with hydrogen in other sectors. In addition, since hydrogen can be derived from biomass like biofuels, it becomes important to evaluate the global availability of bioenergy. Such a parameter is highly uncertain, however in both reference scenarios it was assumed that the global availability of biomass grows steadily over time from 47 EJ/year in 2005 to 118 EJ/year in 2050. This is in accordance with the assumption used in [McGlade and Ekins \(2014\)](#).

The availability of CCS technologies is another important factor. In both the reference scenarios it was assumed that in 2020 in each region CCS can be applied to a maximum of 15% of total electricity generation. After 2020 all CCS technologies can grow at a maximum rate of between 10 and 15% per year. Instead, from 2030 CCS is free to be applied to the majority of processes and technologies without restriction [McGlade and Ekins \(2014\)](#). In particular for hydrogen production plants, CCS technologies can be applied after 2020 in SMR, coal gasification and biomass gasification centralised large plants, but it is not considered in centralised medium and decentralised plants.

When TIAM-UCL is used independently, assumptions regarding the shipping energy demand over the period studied are required. This demand is exogenous to the model, although TIAM-UCL is free to choose the fuel shares mix that meets such a energy demand. It is expressed in PJ per year for each region and it is distinguished in international and domestic shipping energy demands (TWI and TWD) as shown in figure 5.1. In this thesis, those shipping energy demands are derived from data reported in [Smith et. al. \(2015\)](#) and [Argyros et. al. \(2014\)](#).

In TIAM-GloTraM the shipping energy demand corresponds to the total fuel consumption (international and domestic) estimated in the shipping model. It is endogenous to the model, although initial conditions of the regional demands and fuel shares mix are required. Such initial conditions include the fuel share projections which are used to initialise the first run of TIAM-UCL. The fuel share projections are then overwritten by the results obtained from GloTraM, so effectively they do not have a real impact on the final results. The initial condition are estimated using the same data sources for the

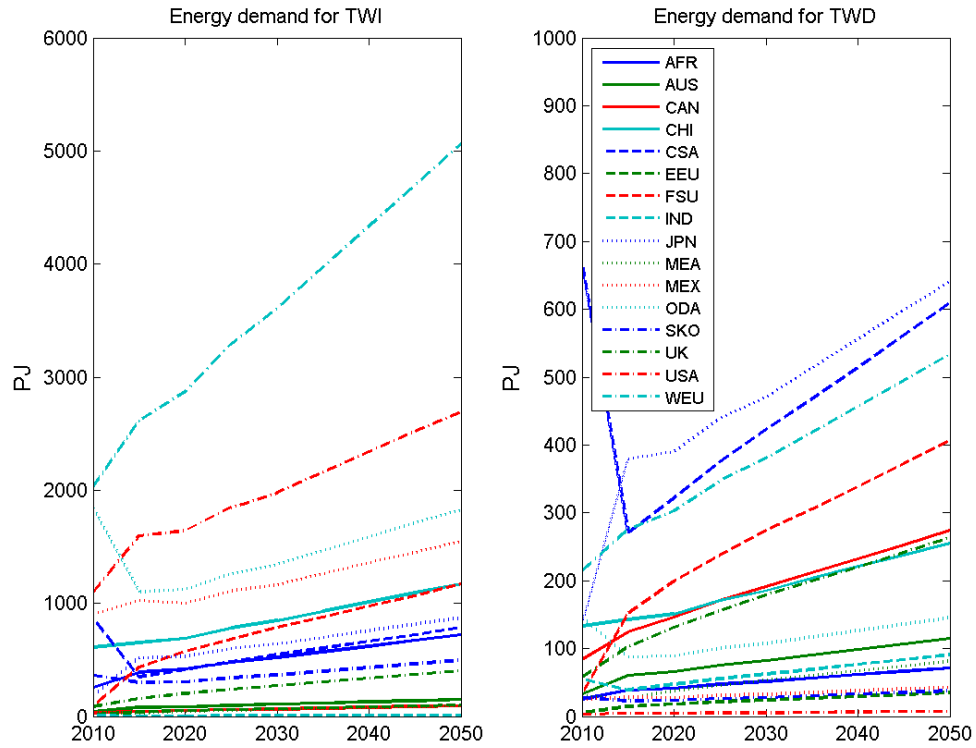


FIGURE 5.1: Exogenous regional shipping energy demand. On the left international shipping energy demands by region. On the right domestic shipping energy demands by region. Africa (AFR), Australia (AUS), Canada (CAN), Central and South America (CSA), China (CHI), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JPN), Mexico (MEX), Middle East (MEA), Other developing Asia (ODA), South Korea (SKO), United Kingdom (UK), United State of America (USA), Western Europe (WEU)

independent runs of TIAM-UCL.

5.3 Key assumptions in GloTraM

This section provides the key assumptions of the reference scenarios in the shipping model. In particular they outline: the shipping regulations, the shipping transport demand, the economic factors, and the main engines and fuel characteristics. As in the energy model TIAM-UCL, there are some differences in the assumptions used in GloTraM depending on the simulation. Such differences will also be provided in this section.

The shipping model takes into account the MARPOL regulation. It includes the limit of sulphur and nitrogen content of marine fuel as defined in the regulation. The

only difference between the two reference scenarios is in regard to the implementation date of a limit of 0.5% to the sulphur content of marine fuel. In the 2°C scenario the date at which the global 0.5% sulphur cap is anticipated in 2020 as shown in figure 5.2, while for the 4°C scenario starts in 2025.

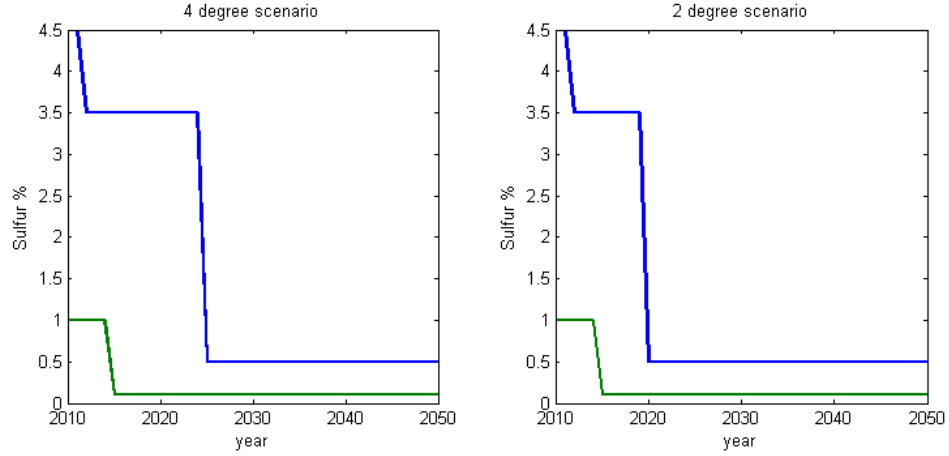


FIGURE 5.2: Sulphur regulations in the reference scenarios

In addition to the regulations another important factor that defines the reference scenarios in GloTraM is the shipping transport demand. There is a difference in this variable depending on whether GloTraM is used independently or TIAM-GloTraM is used.

In the independent runs of GloTraM the transport demand is completely exogenous and is based on the assumptions used in [Smith et. al. \(2013a\)](#). This demand describes aggregations of 100 commodities traded between all of the world's countries in terms of their annualised mass flows and annualised values. It represents the trade that would be required under a low carbon scenario. In particular, this shipping transport demand is associated with the assumptions used for the A1B scenario in IPPC SRES. The characteristics of such a scenario consists of very rapid economic growth, a global population and the rapid introduction of new and more efficient technologies. In addition, the A1B scenario is distinguished by its technological emphasis on a balance across all sources, in the sense that the system does not rely too heavily on one particular energy source ([IPCC, 2013b](#)).

The global trade of energy commodities is part of the shipping transport demand and it can be divided into trade between different regions and trade in the same region. Figure 5.3 provides the total trades for each commodity group. It also provides the total by energy commodity. Overall we can observe an increased total trade of coal

and wood, while the total trade of crude petroleum, gaseous hydrocarbons and fuel derivatives increases gradually until 2040, and starts to decrease afterwards. In each commodity group the trade between different regions represents the majority of the total trade, except for fuel derivatives and gaseous hydrocarbons, where the trade in the same regions represents a more significant part.

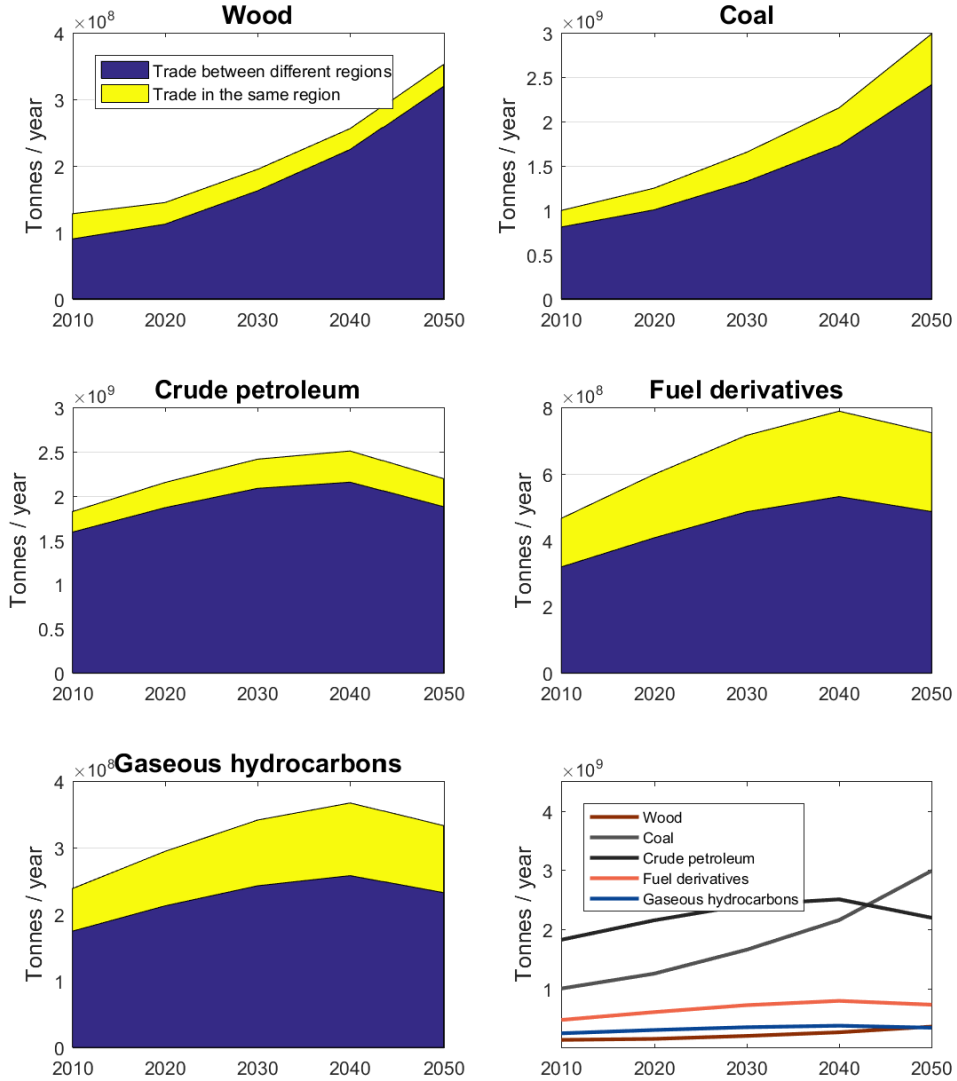


FIGURE 5.3: Exogenous total trade of energy commodities assumed in GloTraM

In the independent runs of GloTraM the shipping transport demand is equal in both 4°C and 2°C reference scenarios, as it was assumed there were no significant changes in the transport demand due to a different global emissions target.

The transport demand in the soft-linking framework is the same as the one provided above except for the transport demand of energy commodities between different regions. The shipping transport demand of non-energy commodities and energy commodities in the same region remains exogenous and is based on the assumptions used in [Smith et. al. \(2013a\)](#). In contrast, the shipping transport demand of energy commodities between different regions is endogenous to the model and it changes based on the reference scenarios. As can be expected in a scenario with a more decarbonised energy system, the trade of energy commodities can be different from a scenario with lower focus on emissions abatement mechanisms. It is recognised that only this part of the trade of energy commodities is endogenous as the trade of energy commodities by ships in the same regions are not modelled in the energy model and so they are exogenous to TIAM-GloTraM.

Fuel price assumptions are different by simulation. In the independent runs of GloTraM, fuels and carbon prices are taken from the independent runs of TIAM-UCL respectively for the 4°C and 2°C reference scenario. In contrast, in the soft-linking framework the fuels and carbon prices are endogenous variables. With particular regard to the for carbon price, two different approaches can be considered. The first approach assumes that the shipping's carbon price is equal to the global carbon price as estimated in TIAM-UCL. The second approach assumes that the shipping's carbon price is equal to the one calculated internally in GloTraM in order to meet a certain CO_2 budget. In the simulations considered in this chapter the first approach was used, while the second approach was used in the simulations analysed in chapter 6.

Besides the fuels and carbon prices, a number of exogenous economic data is used to determine the ship owner's costs and revenue. The first is the barrier factor (TC), which represents the effect of market barriers in setting the time charter prices. In both reference scenarios a value of 0.5 is assumed (if TC is equal to 1 it means there is a perfect market and zero barriers). The second is another barrier factor (VC), which represents barriers in the voyage charter market. It is set at the default of 1 which means that there are no barriers in the voyage charter market. Another two factors are finally included: the interest rate used to discount future profits (disc), and the time horizon (NPVyear) over which the profitability of an intervention (change in design speed, fuel or adoption of low carbon technology) is assessed. In both reference scenarios disc is equal to 10% and NPVyear is equal to 5 years.

The assumptions regarding the main engine and fuel characteristics are used to evaluate important factors for each fuel/machinery option. The assumptions for the main engine are: unit capital cost, efficiency, life time and unit cost associated with required component replacement. The assumptions for the fuels are: energy density, gravimetric and volumetric energy density of the storage system, and unit cost of the storage system. The characteristics of the main engines considered in this thesis are provided in table 5.3, while the characteristics of fuels are provided in table 5.4. These are input assumptions, and they are equal in both reference scenarios.

TABLE 5.3: Main engine options

main engine system	η	\$/kW	life(hr)	\$/kW (repl)
2 stroke diesel	52%	400	-	-
4 stroke diesel	47%	400	-	-
diesel electric	47%	500	-	-
4 stroke spark ign.	48%	400	-	-
Fuel cells	55%	830	47500	498
-Electric motor	95%	116	-	-
-Reformer	70%	350	-	-

TABLE 5.4: Fuel options

fuel	kWh/kg	kg/m ³	Kg(f)/Kg(s)	\$/kg
HFO	11.25	930	1	-
MDO	11.84	880	1	-
LNG	13.89	420	0.8	7.14
Liquid H2	33.33	38	0.09	71

5.4 TIAM-UCL independent simulations

This section provides the results of the examined variables obtained with the independent runs of TIAM-UCL. The trade of energy commodities, the fuel mix in shipping and fuel and carbon prices are presented and examined for IT4D and IT2D scenarios.

5.4.1 Scenario 4 Celsius degree with TIAM-UCL

The shipping transport demand of energy commodities between different regions is endogenous in TIAM-UCL. A global constraint on CO_{2e} emissions affects the way each region meets its energy needs. Each region would require different amounts and types of energy commodities, which would affect the total trade of each energy commodity group

in terms of the amount required and trends over the period studied. It is important to note that the shipping transport demand does not represent the total consumption of the energy commodities, therefore it would be incorrect to only use these variables to explain how each region meets the emissions target.

Figure 5.4 displays the global trade in tonnes over the period from 2010 to 2050 of five energy commodities groups for the scenario IT4D as defined in section 4.7. How the patterns of this trade change between regions is not in the scope of this thesis, nevertheless the interest is only on the total trade. Overall the results from the IT4D scenario show an increased total trade of wood, coal and fuel derivatives and a decline in the total trade of crude petroleum and gaseous hydrocarbons. In particular, the trade of commodity group wood rose slightly until 2035 and showed an upward trend in the remaining years. The trade of coal remained almost constant until 2040, after that it tended to increase. There were considerable fluctuations in crude petroleum trade until 2040, then such trade dropped dramatically. Fuel derivatives which include oil-derived fuels and biofuels trade rose significantly in this scenario while gaseous hydrocarbons trade, which corresponds to natural gas, remained constant over the period. The restriction to keep the temperature rise below 4 °C in 2100 did not require significant increases in trading cleaner energy sources. The projected energy demand would require an increased trade of coal and fuel derivatives. Only in the latest period, the trade of crude decline and wood started to slightly increase, which can be associated with the use of more available biomass. Natural gas, which can be seen as a cleaner energy source, did not increase significantly highlighting the fact that in this scenario traditional energy sources remained the most traded.

In the independent runs of TIAM-UCL, the model selects the cost-effective fuel option that is in line with the global emission target. Figure 5.5 shows the results of the fuel shares mix in shipping of the IT4D scenario. At the top right of the figure, fuel consumption is expressed in *EJ* per year with the corresponding *CO*₂ emissions on the top left expressed in *tonnes* per year. At the bottom the same results are displayed as percentage of the total. In this scenario TIAM-UCL selected HFO as the most cost effective fuel in shipping. The use of MDO in shipping fell dramatically during the first years as its use is more cost effective in other sectors of the energy system. LNG started to take up from 2035 reaching its share of about 30% in 2050. Hydrogen take up in shipping was not observed. In this scenario the shipping sector increased significantly

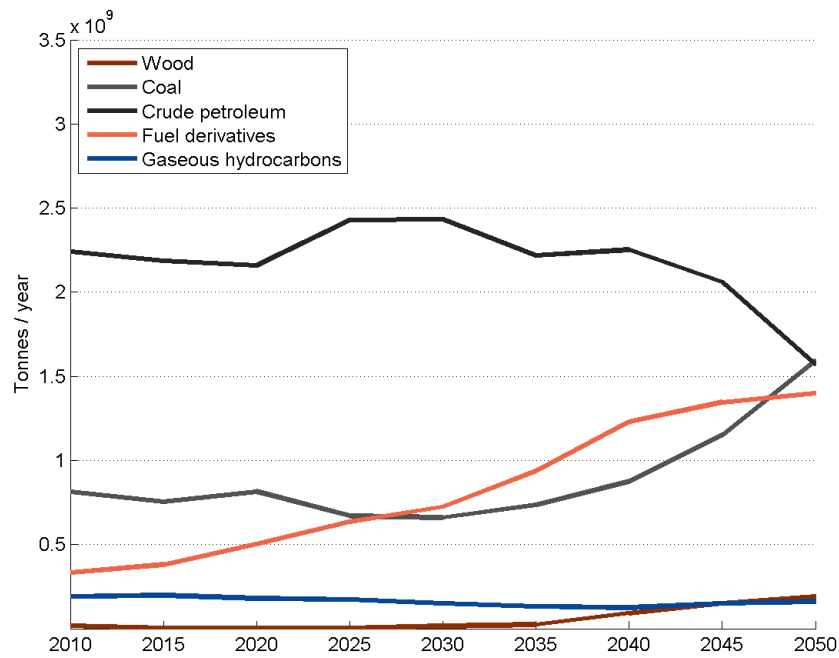


FIGURE 5.4: TIAM-UCL trade of energy commodities between different regions IT4D scenario

its emissions. The global shipping CO_2 emissions reached a value of almost 1400 million tonnes in 2050, of which about the 80% is associated with HFO consumption.

TIAM-UCL endogenously produces a shadow price for all fuels used in shipping; they were converted in global fuel price as explained in section 4.10.2. Figure 5.6 displays the global fuel prices in \$ per tonnes and \$ per GJ weighted with the regional fuel consumptions of IT4D scenario. Their trends were almost the same, increasing steadily over time. HFO and LNG prices were almost the same, while MDO and hydrogen resulted to be more expensive than the others.

In this simulation, hydrogen price depends on the equilibrium between its demand and supply. The global demand of hydrogen in IT4D scenario is relatively small and the amount of hydrogen demanded in shipping was so small that cannot be appreciate in figure 5.5. The hydrogen supply is affected by the demands of hydrogen in other sectors of the energy system. In IT4D scenario, hydrogen was produced from coal gasification, therefore important investments were not required for the production of a more sustainable hydrogen.

Finally, carbon price was clearly negligible in this scenario. Figure 5.9 shows its trend. In order to keep the temperature rise below $4^\circ C$ a global carbon prices was not necessary

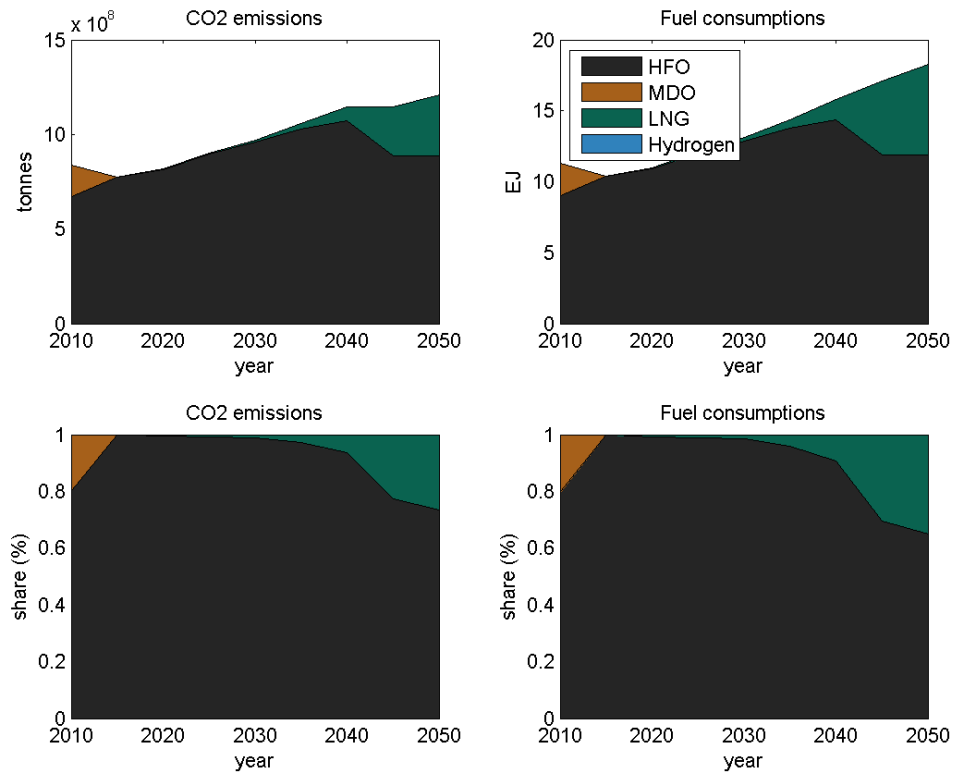


FIGURE 5.5: TIAM-UCL emissions and fuel consumptions IT4D scenario. On the left, emissions in tonnes at the top and share (mass) % at the bottom. On the right, fuel consumptions in EJ at the top and share (mass) % at the bottom

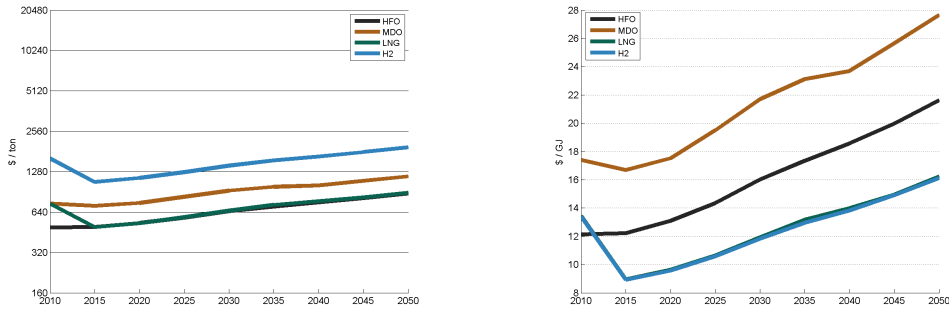


FIGURE 5.6: TIAM-UCL fuels prices IT4D scenario in \$/tonnes (left) and \$ /GJ (right)

meaning that the emissions target would be achieved only with the introduction of more convenient and efficient technologies.

5.4.2 Scenario 2 Celsius degree with TIAM-UCL

In the IT2D scenario a lower global constraint on CO_{2e} emissions was applied. The total trade of energy commodities between different regions was affected by the more stringent

constraint. Figure 5.7 displays the global trade in tonnes over the period 2010-2050 of the five energy commodity groups for the scenario IT2D. Overall such results show an increased total trade of wood and gaseous hydrocarbons and a significant decline of the total trade of coal and crude petroleum respectively after 2015 and 2040. Fuel derivatives trade increased gradually until 2025 and then a tendency to remain almost constant was observed afterwards.

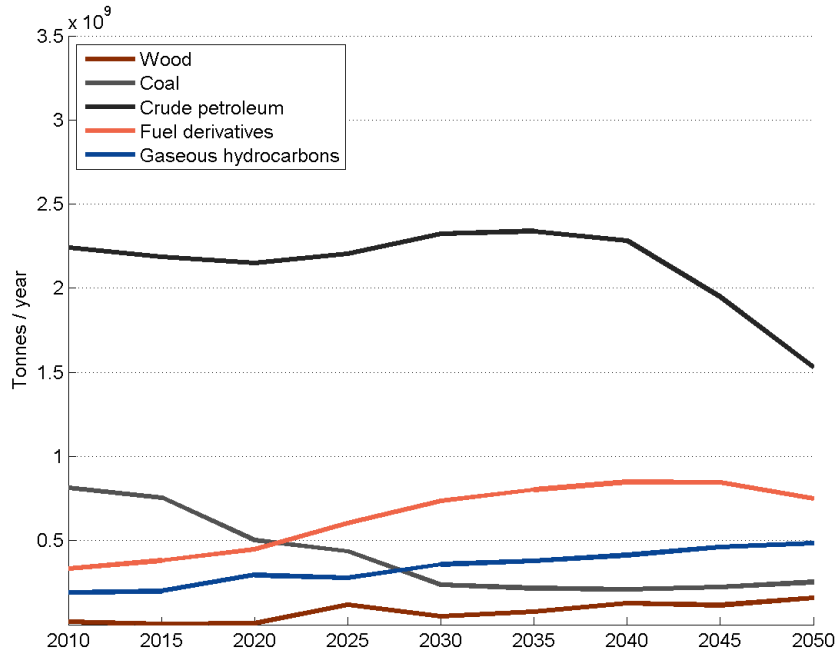


FIGURE 5.7: TIAM-UCL trade of energy commodities between different regions IT2D scenario

The trade of commodity group wood rose gradually and it can be associated to an increased demand of solid biomass to be traded. Fuel derivatives are composed of oil derived fuel and biomass derived fuels, its relative increasing trend in this scenario can be associated to an increased demand of biofuels that offsets a declined demand of oil derived fuels. Coal trade decreased considerable over the period studied, which can be correlated with the stronger decarbonisation path. Crude petroleum trade fluctuated slightly until 2040, then such trade drop dramatically. Gaseous hydrocarbons trade rose significantly meaning that in a deep de-carbonised energy system there would be a high trade of natural gas.

Results of the fuel shares mix in shipping for IT2D scenario are shown in figure 5.8. In this scenario LNG started to take up from 2020, quickly increasing to cover almost

the entire fleet by 2030. MDO in shipping was not a cost effective solution as it might be too expensive and in demand from other sectors. HFO remained the only solution until 2020, after which its use fell dramatically. Hydrogen take up in shipping was negligible. The global CO_2 emissions reached a value of around 1000 million tonnes in 2050, of which about the 95% is associated with LNG consumption.

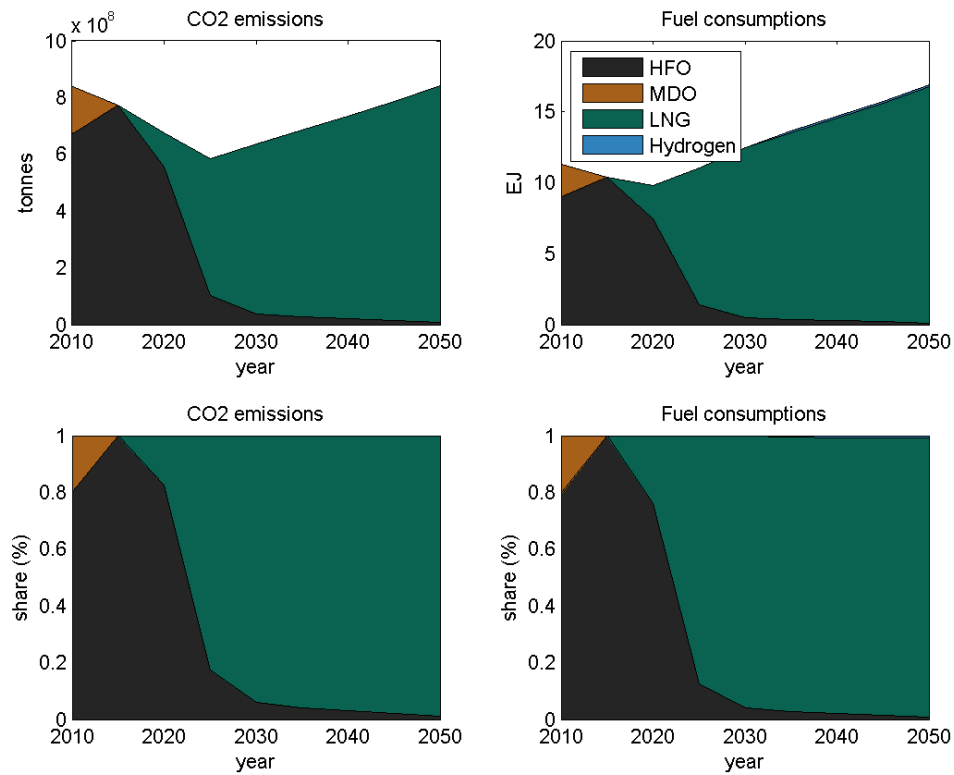


FIGURE 5.8: TIAM-UCL emissions and marine fuel consumptions IT2D scenario

The tighter restrictions on the global emissions caused the introduction of a carbon price as mechanism to meet the emissions target. Figure 5.9 shows the trend of such carbon prices in IT2D. The increasing trend over the period 2015 to 2050 is a reason why LNG started to be more cost effective due to the lower carbon content of such fuel.

Figure 5.10 displays the global fuel prices weighted with the regional fuel consumptions for IT2D scenario. HFO prices fell steadily until 2030 associated with a drop in its demand, although it tended to stabilise and eventually increase afterwards. The trend of hydrogen prices was very similar to the trend of LNG prices until 2035 but considerably more expensive. Afterwards hydrogen price increased as it was in demand from other sectors. Hydrogen price depends on its demand and supply. In contrast with IT4D, the demand of hydrogen from other sectors was higher in this scenario. Hydrogen was

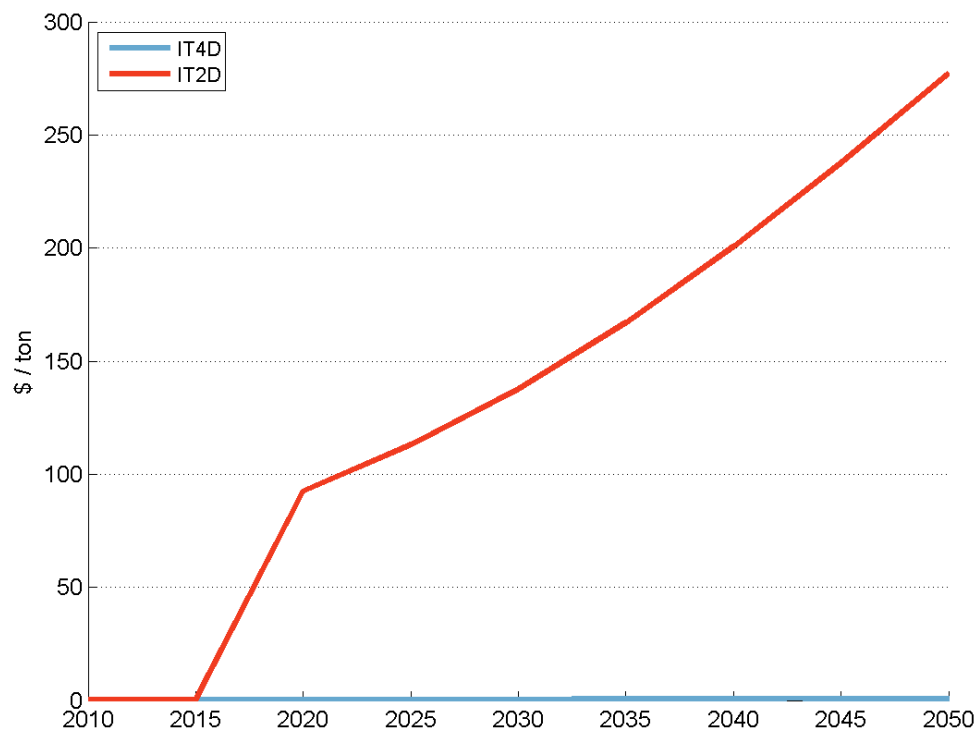


FIGURE 5.9: Carbon prices IT4D and IT2D scenarios in TIAM-UCL

produced from SMR and after 2025 with biomass gasification with CCS. This change in the production made its prices more expensive, although hydrogen demand in shipping was still negligible.

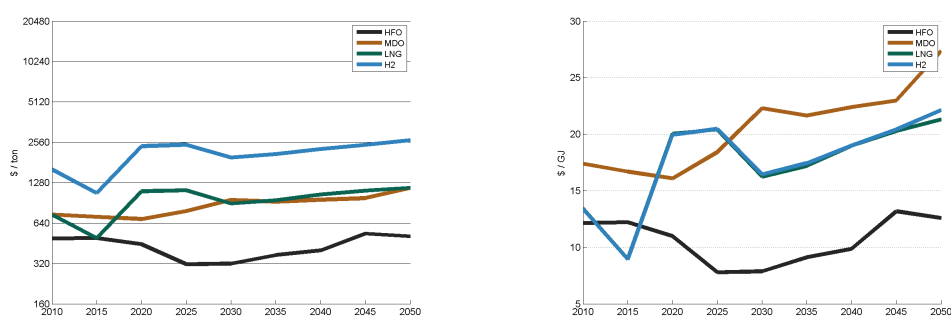


FIGURE 5.10: TIAM-UCL fuels prices IT4D scenario in \$/tonnes (left) and \$ /GJ (right)

5.5 GloTraM independent simulations

This section provides the results of the examined variables obtained with the independent runs of GloTraM. As for the independent runs of TIAM-UCL, the scenarios examined are IG4D and IG2D. Only the fuel mix in shipping is presented as the trade of energy commodities and fuel and carbon prices are exogenous variables for these simulations.

5.5.1 Scenario 4 Celsius degree with GloTraM

In this simulation, the transport demand is exogenous to the model and is equal to the one defined in section 5.3. Also fuel and carbon prices are exogenous input data in GloTraM. The fuel price projections obtained from the independent simulation IT4D scenario were used in this scenario named IG4D. Results obtained with GloTraM can be very sensitive to these exogenous input assumptions which are very difficult to predict. Other fuel and carbon price projections could have been used, however each of them would be based on different assumptions being not endogenous to the model. Because the results depend also on these input data a comparison between the fuel mix obtained with GloTraM and the one obtained with TIAM-GloTraM cannot be exhaustive for demonstrating that TIAM-GloTraM provides an improved fuels mix projection. The focus is, therefore, on the different types of insight and not on the results itself.

Results of the fuel mix in shipping for IG4D scenario are shown in figure 5.11. In this simulation a rapid uptake of LNG was observed, and the total ship fleet analysed resulted to be completely powered by LNG from 2040. LNG prices in this scenario are assumed to be extremely competitive as it is very similar to HFO prices (figure 5.6). The small price difference made LNG use very convenient from the shipowner's profit perspective. Abatement technology options on board ships were not found to be convenient, and a switch to LNG resulted to be the most profitable option that would comply with the MARPOL regulations. The use of HFO and MDO decreased significantly over the period studied with a similar trend, while there was not an uptake of hydrogen in this scenario. The global CO_2 emissions reached a value of around 1000 million tonnes in 2050, which is associated entirely to LNG consumption.

The switch to LNG in this scenario can be associated with its convenient price in comparison with conventional marine fuels. Such a LNG price made the option of switching to LNG more profitable than the use of HFO with scrubber and MDO.

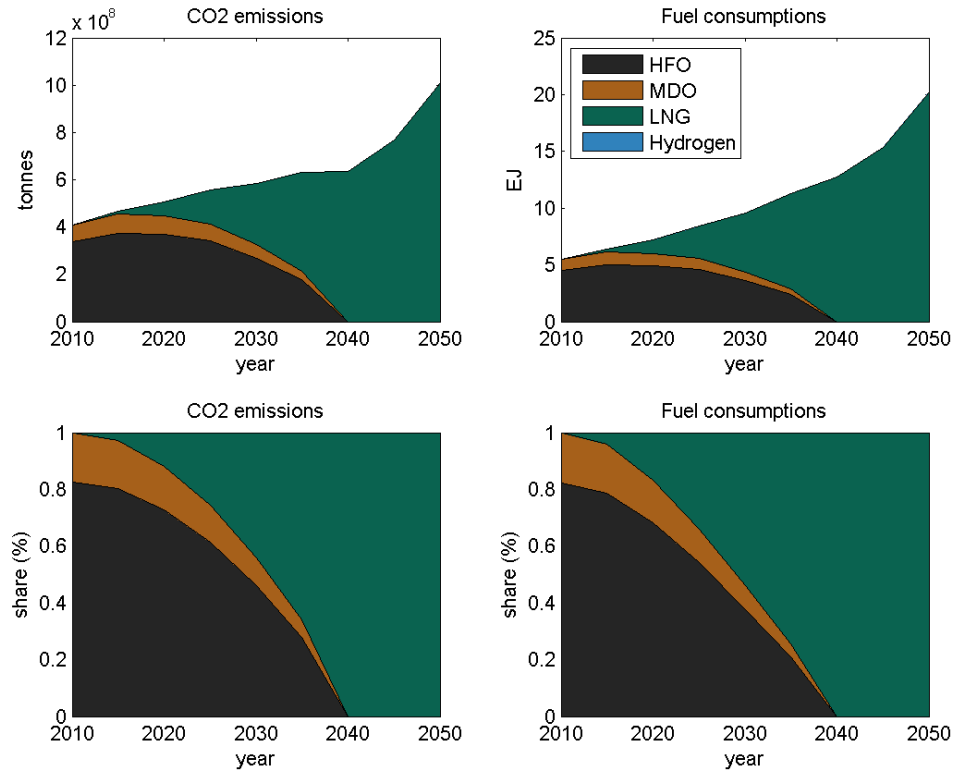


FIGURE 5.11: GloTraM emissions and fuel consumptions IG4D scenario

5.5.2 Scenario 2 Celsius degree with GloTraM

The scenario IG2D is obtained with an independent simulation of GloTraM. In this case, fuel and carbon prices are assumed to be equal to the one obtained with the independent simulation IT2D. As for IG4D, the transport demand is assumed exogenous to the model and is equal to the one defined in section 5.3. The fleet's operational specifications, the main engines and fuel characteristics and technology options were kept the same as IG4D, so the only differences were on MARPOL regulations (introduction of a global sulphur in 2020) and fuel and carbon prices assumptions.

Results of the fuel mix in shipping for IG2D scenario are shown in figure 5.12. In this simulation hydrogen was taken up from 2020 and it showed a tendency to remain stable at around 10% of the total fuel consumption with a slightly decrease after 2035. The assumed hydrogen prices combined with an increased carbon prices and stringent sulphur regulation made this option profitable for some ship type since 2025. After 2035, hydrogen price increased, while LNG price remained stable. Although, carbon price continued to increase in this period, the increased gap between hydrogen and LNG

prices made LNG more convenient from the shipowner's revenue perspective. LNG started to be used from 2025 and its share increased over the period. However, LNG uptake was lower than the one in IG4D scenario (60% in comparison of the 95%) due to the smaller gap between LNG and HFO prices. HFO and MDO shares decreased but they maintained together approximately 40% of the total consumption in 2050, meaning that such fuels with abatement technology on board were still profitable for some specific ship types and size categories.

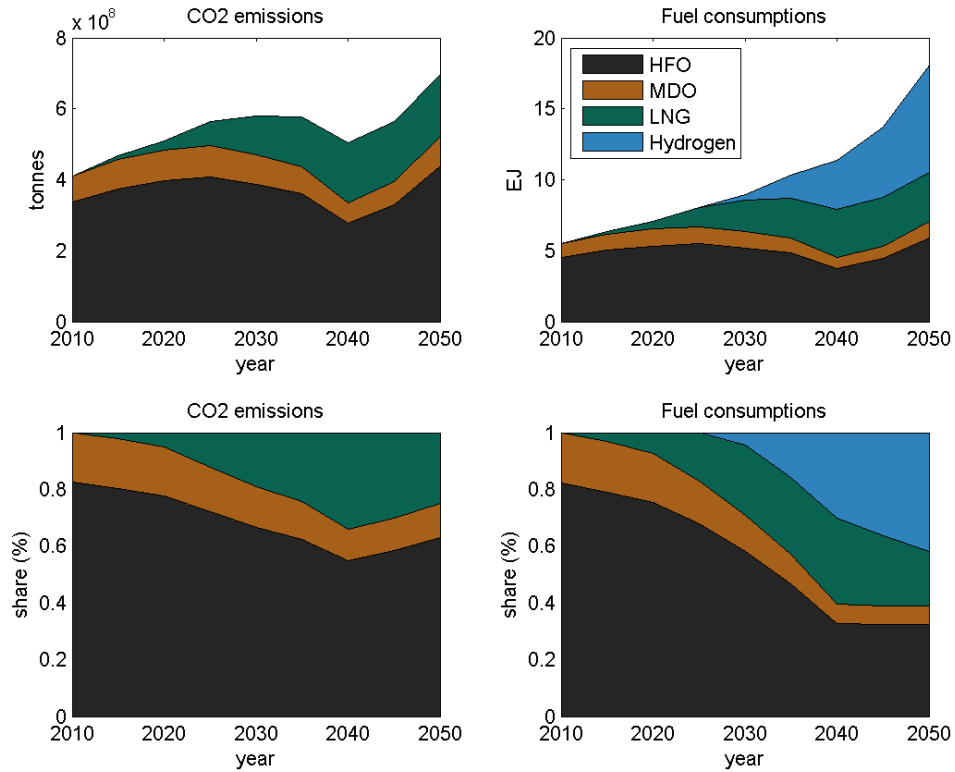


FIGURE 5.12: GloTraM emissions and fuel consumptions IG2D scenario

The global shipping CO_2 emissions reached a value of approximately 900 million tonnes in 2050 associated with HFO and MDO consumption for the 40% and for the remaining 60% associated with LNG. There are no contributions from hydrogen in CO_2 emissions since it does not have any associated operational emissions (see figure 5.12).

In this case the introduction of a carbon price and a more stringent shipping regulations from 2020 had an important role in making LNG and hydrogen an investment opportunity as HFO and MDO prices were assumed to remain low and almost constant.

There was an uptake of hydrogen in this scenario, however it is important to note that the hydrogen price is derived from the simulations of TIAM-UCL (IT2D). This

price does not take into account such uptake of hydrogen in shipping. Being exogenous to the model, hydrogen price is based only on the assumption and results derived from the simulation IT2D.

5.6 TIAM-GloTraM simulations

This section provides the results of the examined variables obtained with the simulations using TIAM-GloTraM. The reference scenarios are: TG4D and TG2D. TIAM-GloTraM uses the iterative process consisting of a continuous exchanging of information between TIAM-UCL and GloTraM until convergence. Therefore, along with the final results at last iteration, also the results from the iterative runs are presented and examined in this section. All variables examined in this chapter are output of TIAM-GloTraM, therefore results and associated interpretations are provided for: the trade of energy commodities, fuel and carbon prices, and fuel shares mix.

5.6.1 Scenario 4 Celsius degree with TIAM-GloTraM

In the simulation TG4D the modelling framework TIAM-GloTraM is constrained to keep the average global temperature rise below 4°C. The iterative process including in this simulation stopped at the 10th iteration, reaching the convergence as defined in [section 4.12](#).

The transport demand is the first variable examined. In particular the trade of energy commodities between different regions is shown in [figure 5.13](#) which displays the results of the iterative runs from each commodity group and the results at final iteration for all commodity groups in TG4D scenario. In each iteration TIAM-UCL provides a new transport demand of energy commodities based on the only variation of fuel consumptions and fuel shares mix in shipping. There were relatively small differences for all commodity groups by each iterative run suggesting that the influence of a different fuel mix in shipping on the trade of such commodity groups are relatively small.

The differences among the iterative runs can be easily observed for gaseous hydrocarbons. Such a trade increases and after 2030 varies among the iterative runs. In particular, in some iterations the ratio at which the trade increases is higher than in others. This can be explained by the fact that LNG in that period can have an oscillatory uptake in shipping among the iterative runs as analysed in more details later in

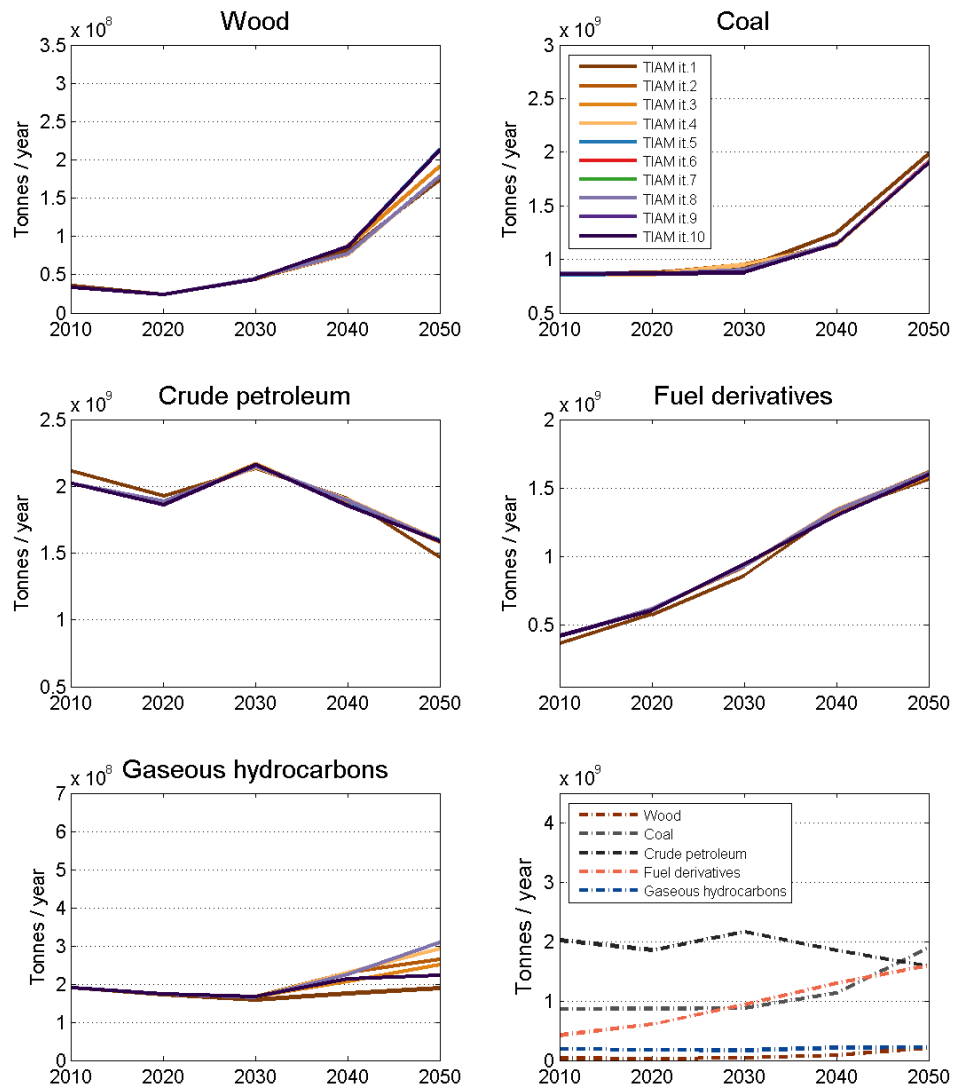


FIGURE 5.13: Convergence of energy commodities trade TG4D scenario

this section. When the share of LNG is high, more natural gas is traded among regions, and vice versa. The trade of all the other commodities: coal fuel derivatives, crude petroleum and wood, had minimal changes among the iterative runs, suggesting that these commodity were not affected by the changes of fuel mix in shipping.

Overall, the transport demand in TG4D scenario at last iteration is characterised by an increased trade of fuel derivatives, a fluctuation of the trade of crude petroleum and a gradual increase of coal, gaseous hydrocarbons and wood trade. In particular, the trade of commodity group wood increased significantly from 2040, while the trade of gaseous

hydrocarbons increased from 2030. The trade of coal remained almost constant until 2040, after which it tended to increase substantially, while the trade of crude petroleum declined after 2030. The trade of fuel derivatives rose significantly in this scenario reaching a higher value of the trade of coal during 2045 to 2050. Similar to IT4D simulation, the constraint to keep the temperature rise below 4 °C did not required a significant switch to cleaner energy sources. In fact, the trade of coal and fuel derivatives including oil derived fuels were the ones with the most significant increase.

Carbon price was negligible in this scenario similarly to IT4D simulation. Figure 5.18 shows its trend at final iteration. In contrast with the GloTraM's independent runs, fuel prices and fuel mix in shipping are both output variables of the soft-linking framework. Figure 5.14 shows the fuels shares mix by iterations, while figure 5.15 shows the fuel prices by iterations. At beginning of the simulation, initial conditions of fuel shares were assumed in TIAM-UCL. As can be observed in figure 5.14, the initial conditions of hydrogen share increase from 2020 reaching more than 20% in 2050. As mentioned earlier in this chapter, such initial fuel share projections do not have a real impact on the final results as they are only used to initialise the first run of TIAM-UCL. The differences at base year 2010 are explained by the fact that at first iteration GLoTraM overwrites the fuel share initial conditions based on the price generated after the first run of TIAM-UCL. Therefore, in the first iteration hydrogen price is associated with the initial condition of an increasing uptake of hydrogen. Despite that, the shipping model did not see economically convenient the switch to hydrogen and its share appears basically negligible along the whole period. Also, the following iterations generated a negligible hydrogen share which is correlated with the hydrogen price shown in figure 5.15. There were no appreciable variations among the iterations except for the first iteration. At those prices and without the introduction of a carbon price, hydrogen was found to be inconvenient for the shipowner's revenue perspective. The fact that there is an increasing hydrogen price after 2035 can be associated to the hydrogen demand from other sectors of the energy system.

The dynamic of how the converge is reached can be clearly examined by looking at HFO and LNG variables. Initial conditions of the HFO share starts from more than 60 % in 2010 and steadily decreases reaching about 40% in 2050. In contrast LNG share increases constantly covering about 20% of the total in 2050 (figure 5.14). The initial conditions are responsible for the associated fuel prices in first iteration, shown in figure

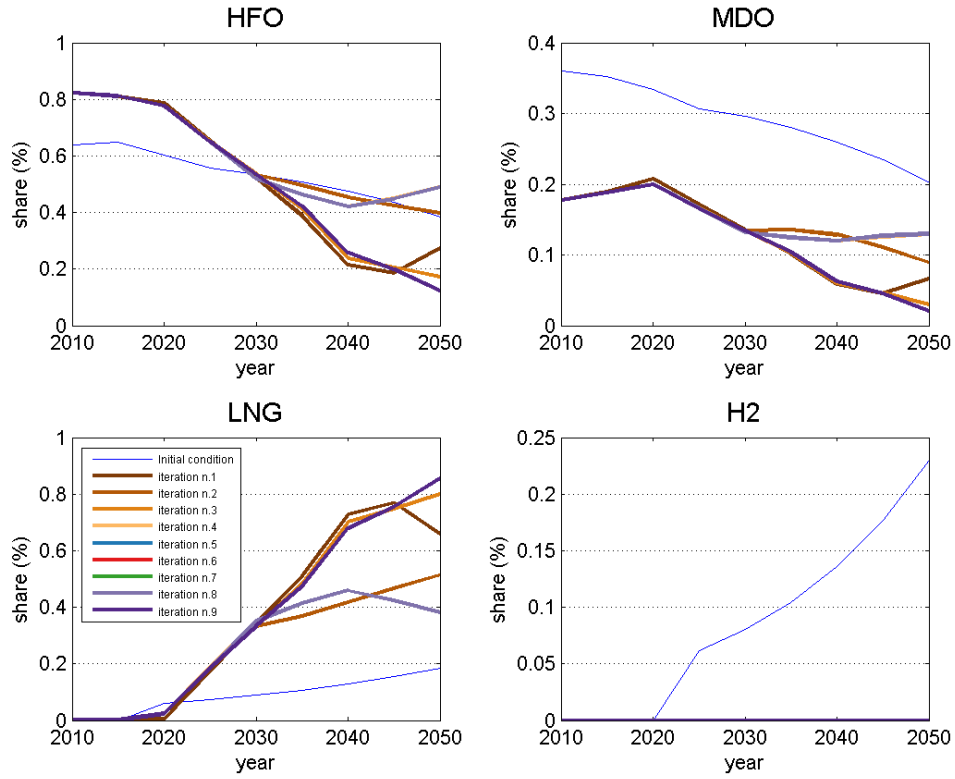


FIGURE 5.14: Convergence of fuel shares in shipping TG4D scenario

5.15. Consequently, HFO and LNG fuel prices in first iteration are responsible for the associated fuel shares in the first iteration, and so on.

It is possible to distinguish two different types of trend. In the first type, HFO share decreased similarly to the initial conditions reaching 40% in 2050, and LNG share, instead, increased reaching about the 40%. In the second type of trend, HFO share decreased significantly to about the 20% in 2050, and LNG share increased to about 80%. As a response of the first type of shares, HFO price increased dramatically ranging between 700 and 900 \$/tonnes (17 and 22 \$/GJ) in 2050 and LNG increased moderately reaching almost 1000 \$/tonnes in 2050 (18 \$/GJ). Instead, as a response to the second type of shares, HFO price increased ranging between 500 and 600 \$/tonnes (12 and 15 \$/GJ) in 2050 due to the lower associated demand, while LNG price increased reaching almost 1200 \$/tonnes (22 \$/GJ) in 2050 due to the higher associated demand. Eventually the dynamics just described reached a convergence as defined in section 4.12 where HFO share stabilised at 20% of the share and LNG share at 80% in 2050.

Another type of dynamic can also be highlighted. The fact that over time HFO share decreased and LNG share increased affected their associated prices. HFO became

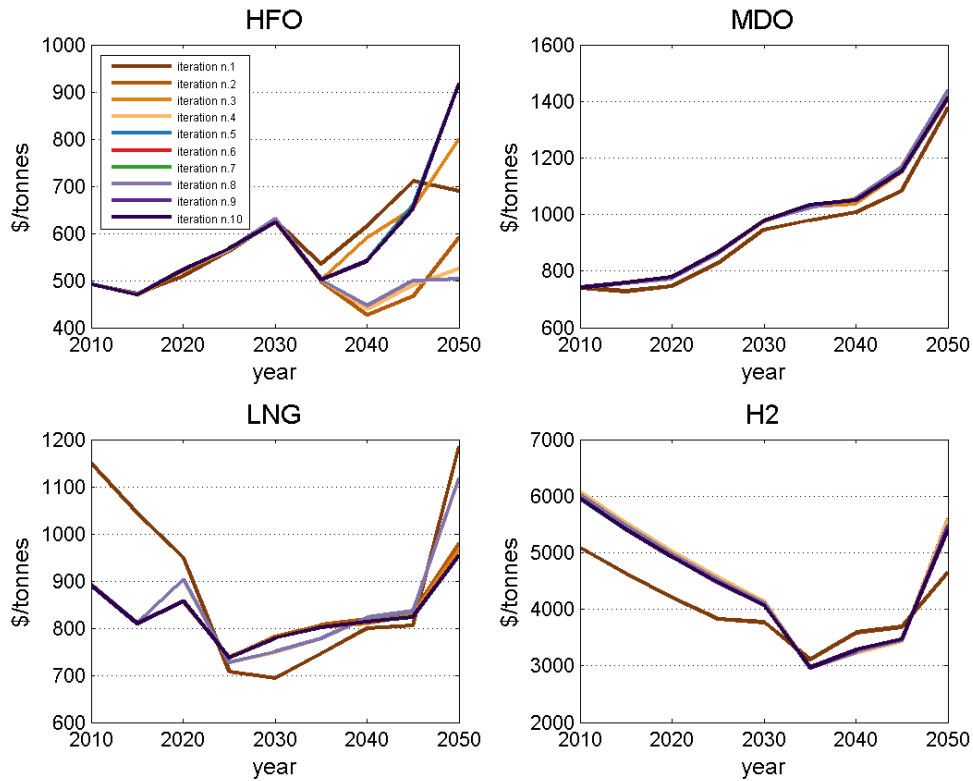


FIGURE 5.15: Convergence of fuel prices TG4D scenario

cheaper and LNG more expensive. This trend continued until a point in which HFO became again competitive compare to LNG as the price difference was reduced. So the model in absence of other more convenient option returned to the option of HFO with scrubber. In fact, HFO share slightly increased after 2040 or 2045 in some iterations, and LNG share decreased at the same time (for instance, iteration 1, HFO increased and LNG decreased after 2045 or iteration 8, HFO increased and LNG decreased after 2040). Another way to explain this dynamic is by looking at the LNG prices and shares by iterations. During the period 2040 to 2050 LNG prices increased in all iterations but with a different slope. The iterations in which LNG prices increased more rapidly, the difference with HFO price decreased and LNG shares decreased as the model returned to the option of HFO with scrubber. In contrast, the iterations in which LNG price increased with a lower slope, the price difference with HFO is large enough to make the option of switching to LNG cost effective. As consequence, LNG share increased and HFO share decreased.

The trend of LNG price have a small peak in 2020 associated with the investment required for new infrastructure to cope the increased demand of LNG from that year.

The price of MDO by iteration did not vary significantly. MDO shares has a similar trend of HFO share.

The fuel mix for TG4D scenario at final iteration is shown in figure 5.16. In this simulation LNG was adopted from 2020. HFO and MDO shares decreased significantly covering in total approximately 20% of the total consumption. The remaining share is only LNG as hydrogen was not adopted in this scenario. The global CO_2 emissions reached a value of approximately 1100 million tonnes in 2050 of which about the 80% is associated with LNG consumption and the other 20% is associated with HFO and MDO consumption.

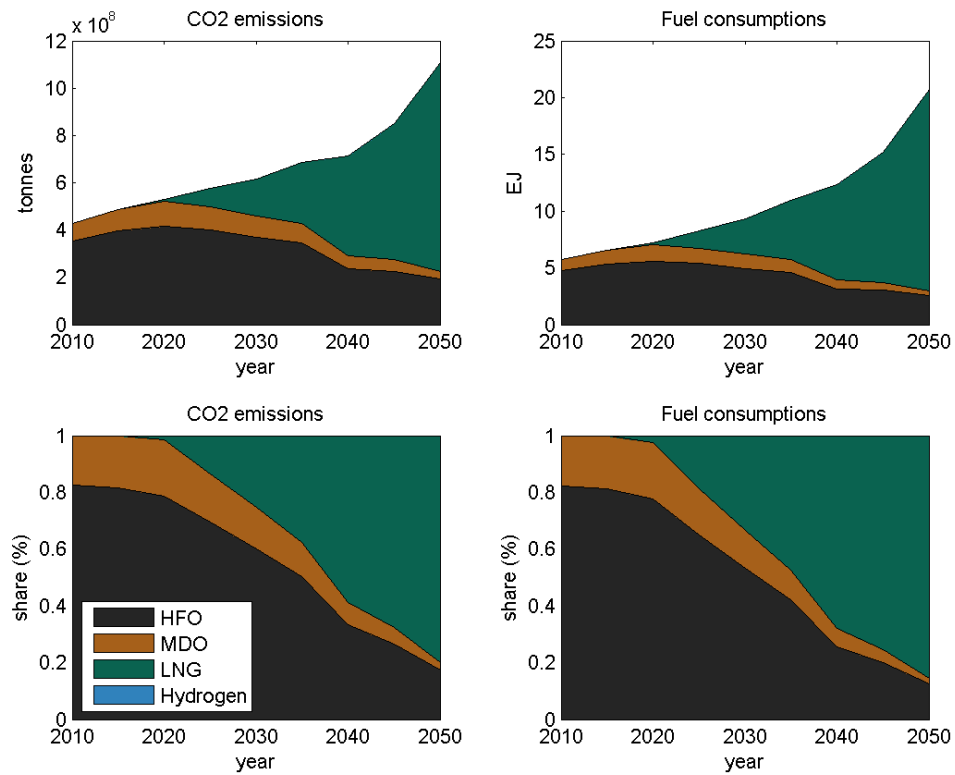


FIGURE 5.16: TIAM-GloTraM fuels shares TG4D scenario

5.6.2 Scenario 2 Celsius degree with TIAM-GloTraM

The iterative process in TG2D scenario achieved the convergence after four iterations. The resulting trade of energy commodities of this scenario is displayed in figure 5.17. It is possible to observe the trajectories of the iterative runs from each commodity group and the trajectory at final iteration for all commodity groups in this scenario. Similarly to the TG4D scenario, there are relatively small differences among the iterative runs

for all commodity groups, which suggest that the influence of a different fuel mix in shipping on the trade of these energy commodity groups are relatively small.

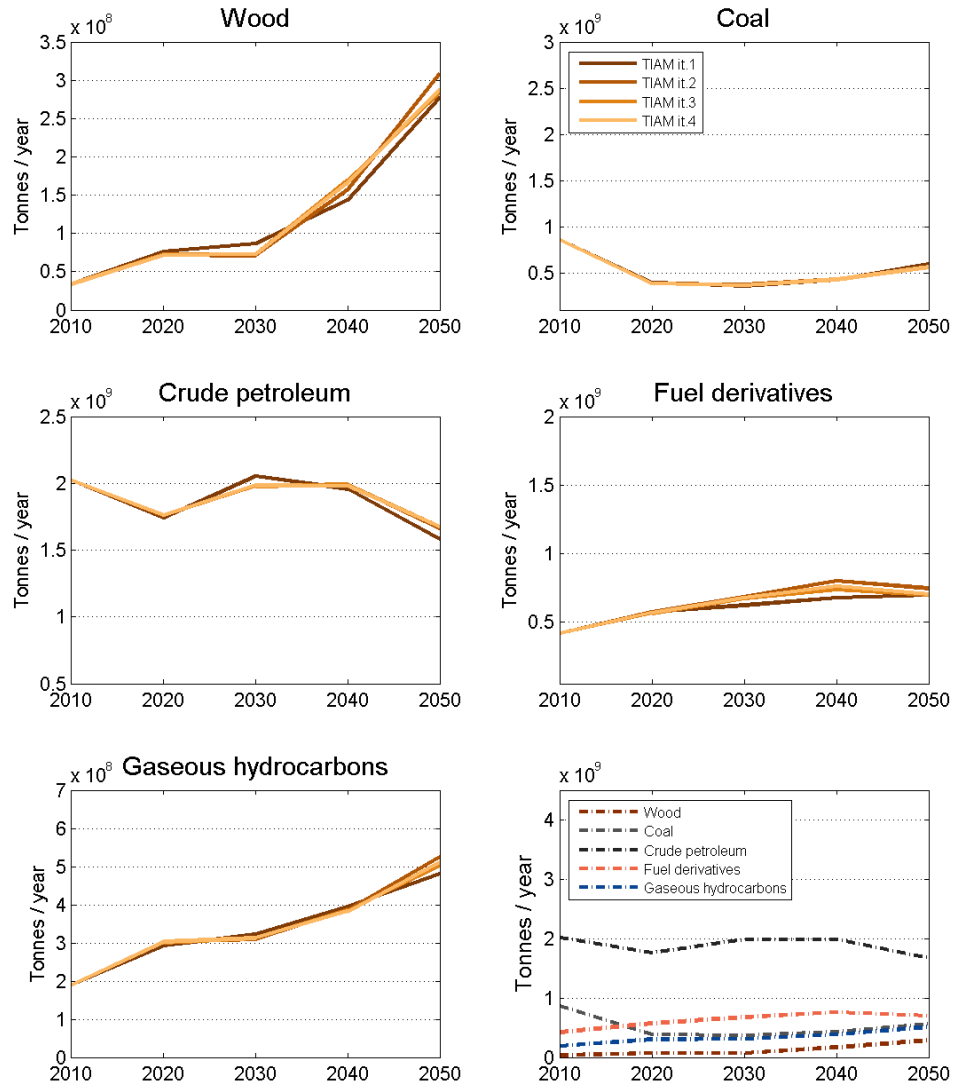


FIGURE 5.17: Convergence of energy commodities trade TG2D scenario

Overall, the resulting trade of energy commodities showed an increased trade of wood, fuel derivatives and gaseous hydrocarbons. The trade of wood increased constantly over time, while the trade of fuel derivatives increased until 2040 and tended to stabilise afterwards. The trade of crude petroleum reached a peak in 2030 and then decreased rapidly. Instead the trade of coal decreased until 2020 and then tended to remain stable. The trade of gaseous hydrocarbons rapidly increased, and reached a value similar to the

trade of fuel derivatives in 2050. In this scenario the trade of energy commodities with high carbon content such as crude oil, coal and part of fuel derivatives declined, while natural gas, biomass and biofuels increased due to the more stringent emission target in comparison with TG4D scenario.

In order to meet 2°C target a carbon price was introduced and it was estimated endogenously. Figure 5.18 displays such carbon price in TG2D at last iteration. It constantly rose between 2025 and 2045 reaching approximately 250 \$/tonnes in 2045. Afterwards it increased more rapidly hitting a peak of almost 450 \$/tonnes in only 5 years.

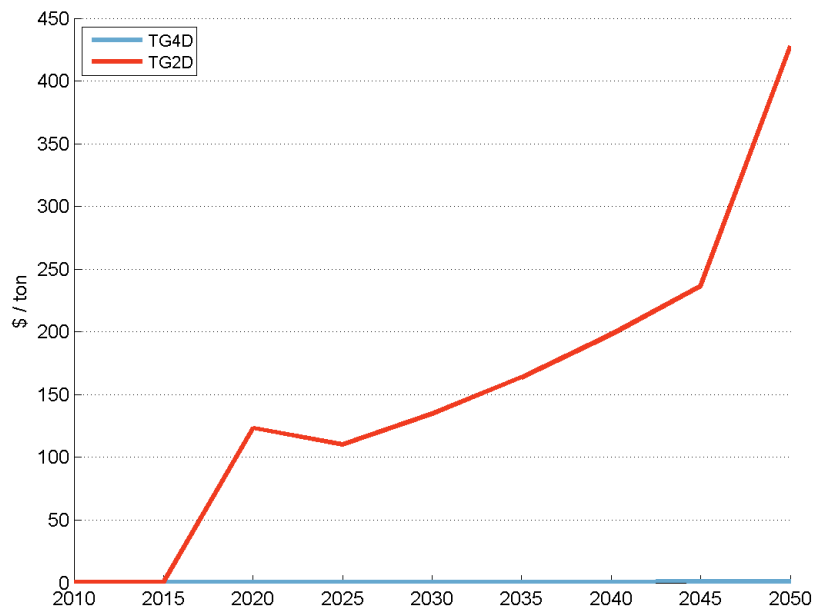


FIGURE 5.18: Carbon prices TG4D and TG2D scenarios in TIAM-GloTraM

Using the soft-linked model, it is possible to analyse the fuel shares and prices per each iteration. Figure 5.19 shows the fuels shares by iterations, while figure 5.20 shows the fuel prices by iteration. At beginning of the simulation, initial conditions of fuel shares were assumed in TIAM-UCL and they are the same used in TG4D scenario. No significant uptake of hydrogen was observed in any iteration as hydrogen prices resulted to be more expensive and the introduction of a carbon price as estimated in the energy system was not enough to find hydrogen a convenient fuel for the shipowner's revenue perspective. Moreover after 2035 hydrogen prices rapidly increased as it was found cost effective in other sectors of the transport sector.

LNG shares showed a similar trend in all iterative runs. It started in 2020 and increased very rapidly until 2040. After 2040 in some iterations the share continued to increase but with a less steep slope. The bigger variance among the iterative runs was observed during the period 2040 to 2050, although LNG prices had a similar trend in all iterative runs. This can be explained by looking at HFO shares in the same period, which show a similar variability due to a difference in HFO prices by iterations (see figure 5.20). When HFO price was low, HFO share increased and LNG decreased, in contrast when HFO price was high, HFO share decreased and LNG share increased. Eventually this dynamic found a convergence after four iteration.

In general HFO shares tended to remain almost constant until 2020, then rapidly decreased until 2040 and continued to decrease more gradually until 2050. Also MDO shares tended to have similar trends among the iterative runs. They slightly increased until 2020, then decreased until 2040 and continued to decrease more gradually until 2050.

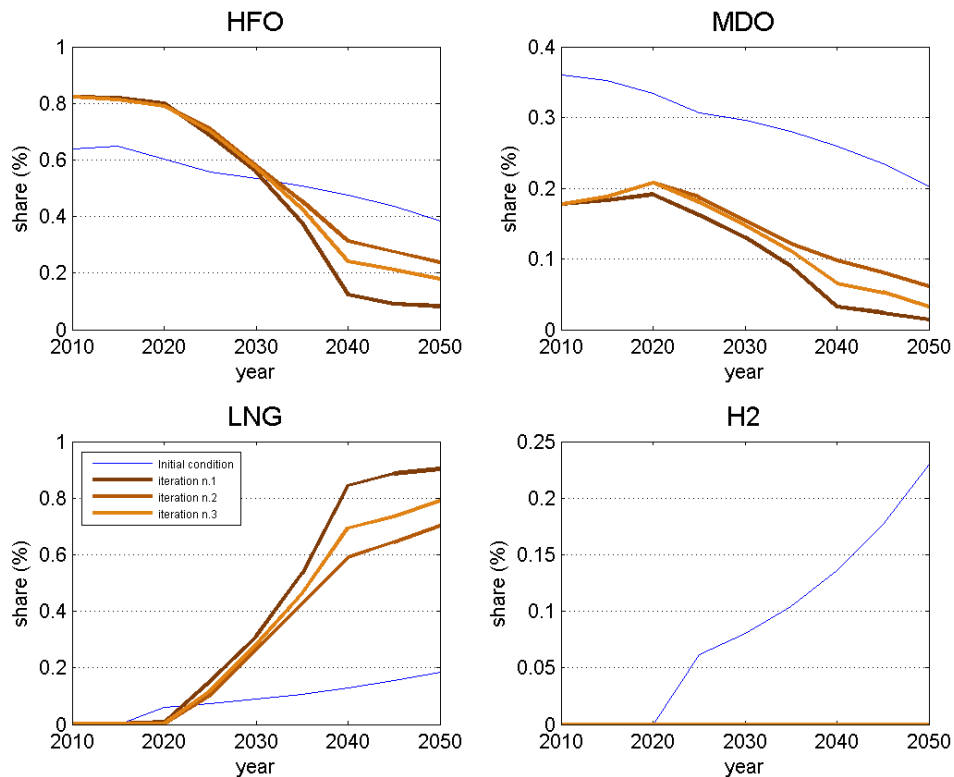


FIGURE 5.19: Convergence of fuel shares in shipping TG2D scenario

Fuel mix in shipping for TG2D scenario at final iteration is displayed in figure 5.21. In this simulation a rapid uptake of LNG was observed starting from 2020. HFO and

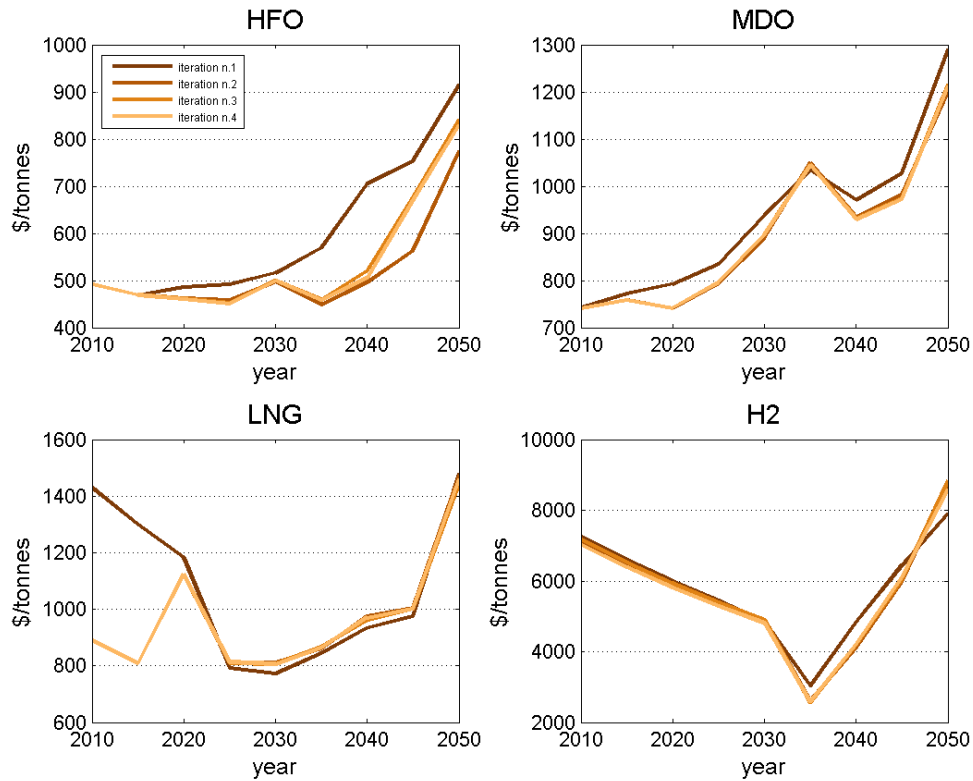


FIGURE 5.20: Convergence of fuel prices TG2D scenario

MDO consumptions decreased until 2040 then remained almost constant, however their shares decreased significantly over the period studied. Hydrogen did not take up in this scenario either. The global CO_2 emissions reached a value over 900 million tonnes in 2050 of which about the 80% is associated with LNG consumption and the other 20% is associated with HFO and MDO consumption.

5.7 Comparing the results of the soft-linking framework

In the previous sections the results of two reference scenarios have been presented. These results have been obtained from the independent runs of TIAM-UCL and GloTraM and from TIAM-GloTraM, respectively. The evidence of how TIAM-GloTraM improves the modelling representation of hydrogen uptake in shipping is provided in this section. In order to discuss this evidence, the results of the key variables are compared. The aim is to demonstrate that TIAM-GloTraM is able to provide a more consistent and detailed explanation of its results, and potentially to unfold emergences that cannot be captured with the independent runs. If so, TIAM-GloTraM is a model with an improved

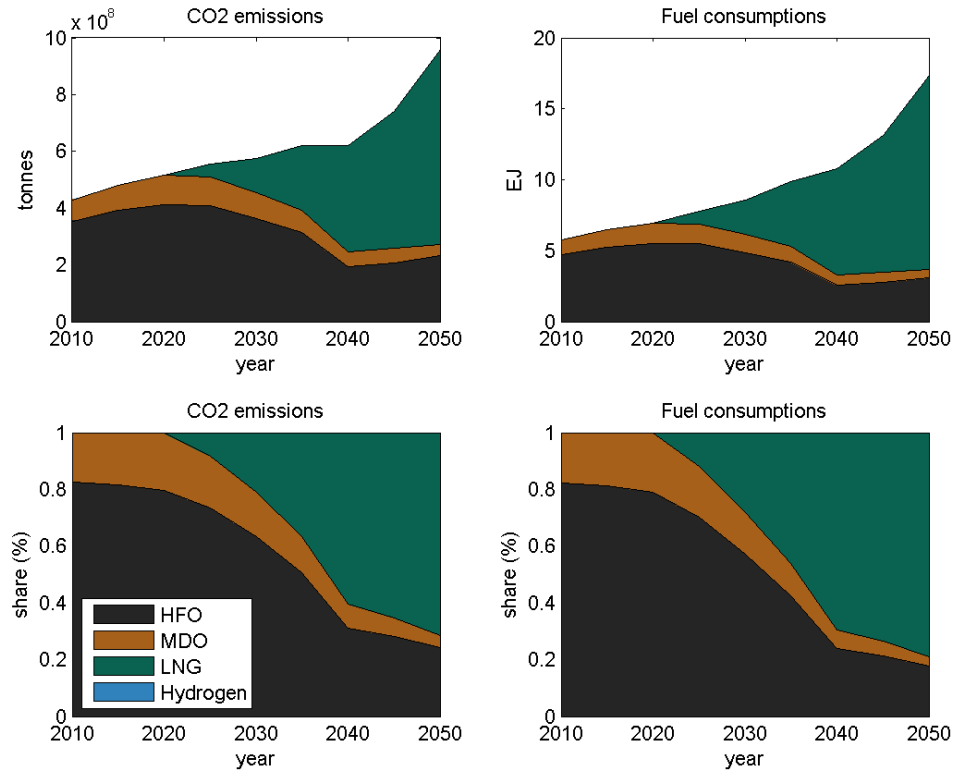


FIGURE 5.21: TIAM-GloTraM fuels shares TG2D scenario

representation of the uptake of hydrogen, and its results are an improvement at the level of their substance.

The key variable that are compared in the next sections are: the shipping transport demand, the fuel and carbon prices and the fuel mix in shipping.

5.7.1 Transport demand

The transport demands of energy commodities among different regions in each simulation are compared in this section. Figure 5.22 shows for each commodity group the trend of the transport demand by scenarios; when available, third party data are also plotted for the base year 2010 and are based on [UNCTAD \(2012\)](#).

Transport demand is an exogenous variable in the independent runs of GloTraM (IG2D and IG4D), instead, it is an endogenous variable in the independent runs of TIAM-UCL and TIAM-GloTraM (IT4D, IT2D and TG4D and TG2D). The trajectories of the trade of energy commodities groups' wood and coal in the scenarios IG2D and IG4D (exogenous trade) is consistently higher than the transport demand obtained

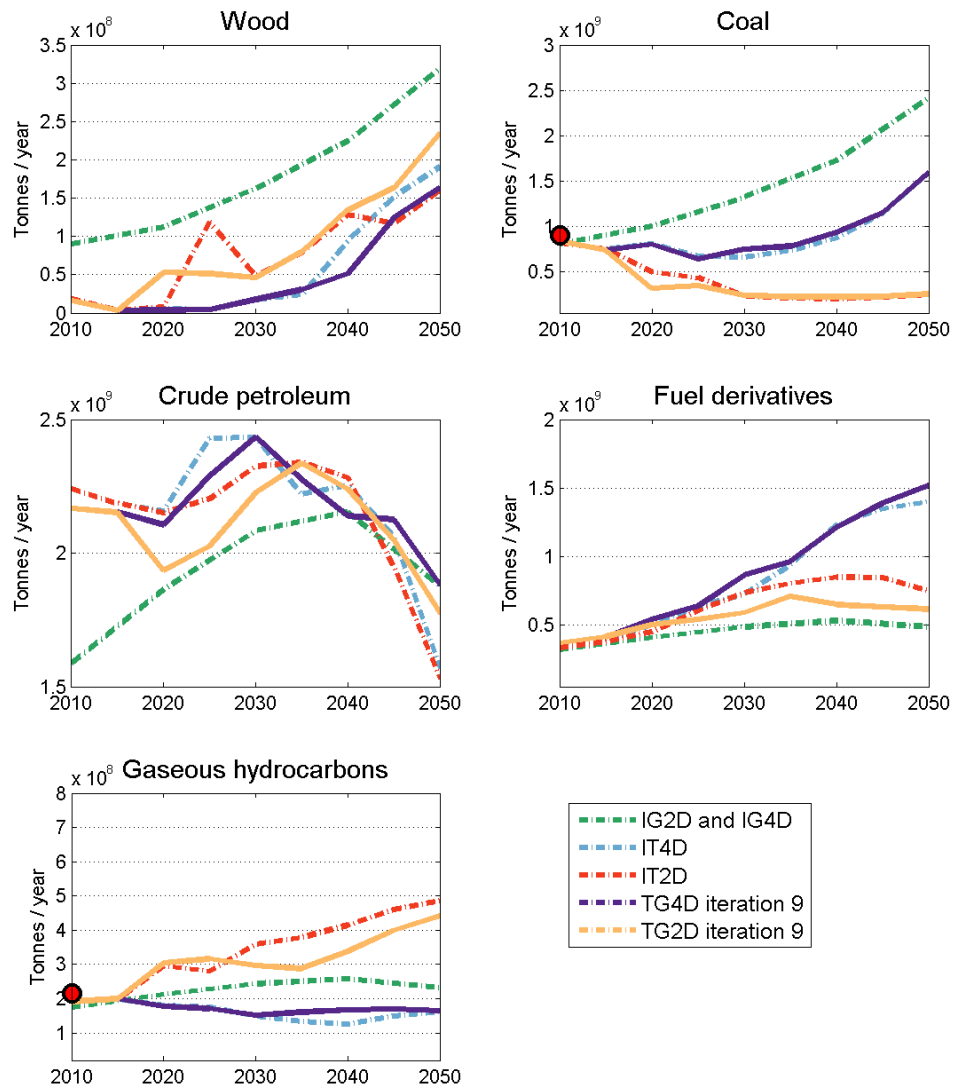


FIGURE 5.22: Transport demand by scenarios

endogenously in the simulations IT4D, IT2D and TG4D and TG2D. The exogenous transport demand refers to a World with a focus on a balance across all energy sources which can favour the trade of biomass and at the same time does not penalise the trade of coal. Instead, the endogenous transport demand shows more remarkably the effects of different emissions reduction policies (4°C and 2°C scenarios). In fact, the trajectories in simulations IT4D and TG4D are similar to each other, as well as for IT2D and TG2D. In the 2°C scenario there is a higher level of trade of commodity group wood than in 4°C scenario. The difference can be associated with the increasing demand of

clean energy sources in the 2°C scenario. In addition, the commodity group wood in the exogenous trade demand includes commodities that are not modelled in TIAM-UCL which explains why the endogenous transport demand for this group is lower from the base year 2010.

The endogenous transport demand (IT4D, IT2D and TG4D and TG2D simulations) shows also the effects of different emissions reduction policies in the trade of commodity group coal. In this case it can be observed a higher level of trade of commodity group coal in the 4°C scenario than the one in 2°C scenario.

The endogenously calculated trade of crude petroleum (IT4D, IT2D and TG4D, TG2D simulations) is generally higher than the one reported in the exogenous transport demand (IG2D and IG4D). All trajectories show a common feature, after an increasing trend they reach a peak and then decline steeply. It can be observed that the peaks occur at different times. For instance, the peak in the exogenous transport demand (IG2D and IG4D) occurred in 2040, while for TG4D and IT4D occurred in 2030. Instead, in TG2D and IT2D the peak occurred in 2035. There might be a number of reasons for such differences that will be analysed later in this section, in general the endogenous transport demand is remarkable different as it is influenced by the global emissions constraints. During the period 2010 to 2020 the endogenously calculated trade of crude petroleum is higher than the exogenous trade due to the calibration of the data that occurs in TIAM-UCL. For this particular period the data are the sum of both crude petroleum and fuel derivatives, however TIAM-UCL takes into account of such misallocation.

The exogenous transport demand assumed in the independent runs of GloTraM for the commodity group fuel derivatives is lower than the endogenous calculated demand in the independent runs of TIAM-UCL and TIAM-GloTraM. Instead, the exogenous trade of gaseous hydrocarbons is half way between the endogenous calculated demands in 4°C and 2°C scenarios. These difference can be associated to the fact that the exogenous transport demand refers to a balanced use of all energy sources, which in this case penalised the trade of fuel derivatives (that include also oil derived fuels) and encouraged the trade of natural gas.

The endogenous transport demand of natural gas in IT2D and TG2D shows an increasing trend in the 2°C scenario, while fuel derivatives increases at a lower rate than the 4°C scenario. In contrast, in the latter scenario, it can be observed that the endogenous transport demand of natural gas declines over time while the demand of fuel

derivatives increases.

The comparison between the exogenous and endogenous transport demands highlights that an exogenous trade demand is based on assumptions that are difficult to correlate with the dynamics that can occur within the energy system. In this case the transport demand is external to the model, and it is only possible to analyse how the transport demand affects the shipping system and consequently the fuel mix. In contrast, the endogenous transport demand is affected by the different emissions reduction targets. For example, it was observed that the trade of coal and gaseous hydrocarbons increases in 4°C scenario and decreases in 2°C scenario.

The endogenous transport demand can also be affected by the fuel mix in shipping. For example, an high uptake of LNG in shipping may affect the trade of natural gas among regions. It also includes the effect that the transport demand can have on the fuel mix in shipping. For example a high transport demand can drive to a high shipping energy demand which may select a fuel rather than another based on the scenarios assumptions. Both models, TIAM-UCL and TIAM-GLoTraM, estimate the endogenous transport demand taking into account these effects. The trade obtained from TIAM-GLoTraM includes the feedback of the fuels mix estimated in GloTraM. The trade obtained from the independent runs of TIAM-UCL includes the feedback of the fuels mix estimated in the energy model itself. Although both models include such a feedback, the way the fuel mix is generated is different. For instance, both simulations IT4D and TG4D report the use of LNG in shipping, and in both simulations, the trade of the gaseous hydrocarbons commodity group is affected by the uptake of LNG.

The benefit of using the soft-linking is, therefore, only in the way the fuel mix is estimated. Although the soft-linking is able to capture the effect of fuel mix on transport demand the difference on the final results on the trade of energy commodities are relatively small. Marine fuels represent a small percentage of the total transport demand, so the complexity of the soft-linking added a relatively small benefit on the representation of such effect.

5.7.2 Carbon price

Another important variable to be examined is the carbon price. Figure 5.23 shows the carbon price for each simulation. The main considerations are:

1. carbon price obtained from the independent runs of TIAM-UCL was used as exogenous input data in the independent runs of GloTraM. So, the simulations IG4D and IG2D use the same carbon prices as of IT4D and IT2D, respectively.
2. the carbon price in IT4D and TG4D simulations are very low and negligible
3. the trajectories of carbon price in IT2D and TG2D simulations are very similar to each other. However, in TG2D carbon price increased more rapidly than in IT2D during the period 2045 and 2050, reaching more than 400 \$/tonnes. Such an increases can be explained by the fact that the higher demand of LNG in shipping which may have affected the global carbon price. Because LNG became more expensive a higher carbon price was necessary in order to make it economical viable for shipping.

In the simulations using TIAM-GloTraM it was assumed that the shipping's carbon price is equal to the global carbon price as estimated in the energy model. However, this assumption does not mean that the carbon price in the independent runs of TIAM-UCL is the same of the one in TIAM-GloTraM as the latter includes the feedback of a different fuel mix derived from the shipping model. As analysed in the last point of the considerations above, this difference provides important evidence of how the model TIAM-GloTraM is able to highlight an effect that was not possible to observe in any other simulation.

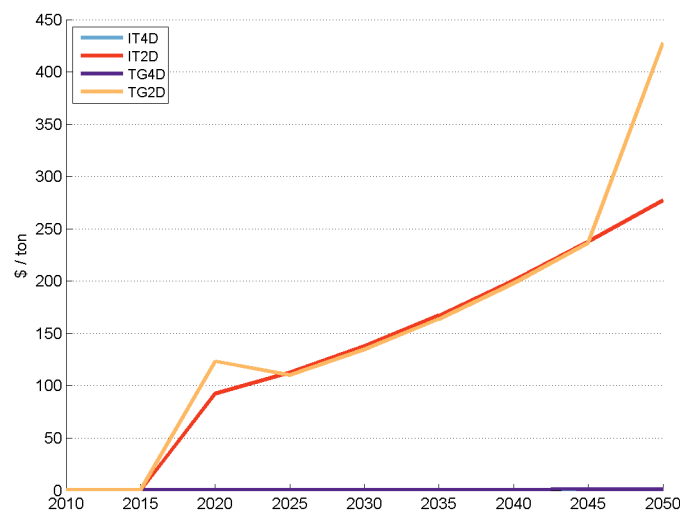


FIGURE 5.23: Carbon prices for each simulations with TIAM-UCL and TIAM-GloTraM

5.7.3 Fuel shares and prices

The main purpose of this section is to compare the fuel shares and prices obtained in each simulation and to highlight the different explanations that can be derived from using different models. First, the fuel shares and prices for the 4°C scenario are compared, followed by the 2°C scenario.

The shares and prices for the 4°C scenario for each fuel are displayed in figure 5.24. The shares of HFO and LNG are significantly different, although they share a common trend. In all cases, HFO share decreased and LNG share increased. The use of HFO remained dominant in IT4D, while in IG4D the uptake of LNG is much higher and its share reached 100% of the mix in 2040. It is important to note that IT4D and IG4D have the same fuel prices, however, while in IT4D fuel prices are depended on the relative fuel shares, in IG4D fuel prices are exogenous and independent on the relative fuel shares.

The iterative process embedded in TIAM-GloTraM reached the convergence when the resulting trend is in the middle between the trend observed in IT4D and the one observed in IG4D. In the simulation TG4D, the trend of HFO price shows a big dip between 2030 and 2035 and rose again afterwards. This trend can be associated to the uptake of LNG, which reached a high level of penetration which causes the drop of HFO price. After 2035, however, HFO found again a market as its price is very low. Therefore, HFO share started to increase and its price too increase again.

MDO price in IT4D resulted to have a similar trend to the one in TG4D, although the prices in the latter were consistently higher than the one in IT4D. MDO share in all scenario tended to decrease and eventually it is zero due to the increasing MDO price influenced also by its demands from other sectors.

In the simulation TG4D, the algorithm used is responsible for hydrogen shares and associated prices. Particularly, when transferring fuel consumptions from GloTraM to TIAM-UCL even though there is no uptake of hydrogen in shipping after 2025, the algorithm adds a small share for hydrogen before sending the shares into the energy system so that hydrogen price for shipping can be estimated. In fact, hydrogen share increased from, $3.7 \times 10^{-2} \%$ in 2030 to $3.8 \times 10^{-2} \%$ in 2050. These shares also represent very small amounts of fuel, and they effect the associated prices. In the simulation IT4D the price is associated with very small amount of uptake of hydrogen in shipping which are allowed since the linear property of the energy model.

The demand of hydrogen from other sectors is not significant until 2045, and only in the last period from 2045 to 2050 hydrogen started to be used in other transport sectors in both simulations and it had an effect on its price, particularly for TG4D simulation.

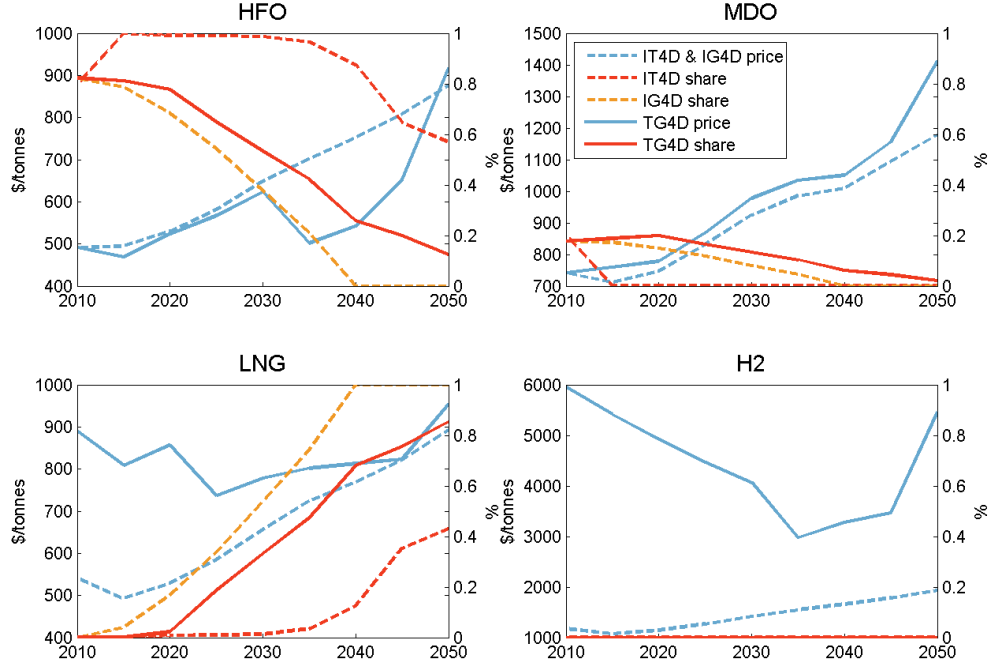


FIGURE 5.24: Fuel shares and prices 4°C scenarios

Fuel shares and prices for the 2°C scenario for each fuel are displayed in figure 5.25. The main observation from all simulations is that HFO and MDO share decreased and LNG share increased. Hydrogen share also in these scenarios is negligible. It is possible to interpret these results differently depending on the model used.

In the independent simulation of TIAM-UCL and in the simulation using TIAM-GLoTraM, fuel prices and share influence each other. HFO and LNG prices are associated with their corresponding shares. HFO price reacted to its decreasing demand, demonstrating a tendency to fall during the period in which LNG share reaches a higher level of market penetration. HFO and LNG appear strictly interconnected each other as they are almost exclusively used in shipping.

Fuel and carbon price obtained from IT2D simulation were used for IG2D simulation. Fuel shares in IG2D depend on the profit maximisation function and the assumed exogenous fuel prices. Under these assumptions LNG share increased and HFO share decreased but at a lower rate than the IT2D simulation. LNG and HFO shares in TG2D were somehow in the middle of the corresponding shares observed in IT2D and IG2D,

confirming that TIAM-GloTraM finds a balance of fuels supply and demand at which correspond to different fuel prices.

The main difference between the independent simulation of TIAM-UCL and TIAM-GloTraM is that in the latter, fuel prices are associated with their fuel shares which are influenced by the technical and operational drivers included in the profit function of a shipowner.

Another dynamic can be highlighted by analysing the shares and prices of MDO and hydrogen. In particular, MDO price increased gradually until 2035 and at the same time hydrogen price reached its lowest point. This can be explained by looking at the demands in other sectors as both fuels are not exclusively used in shipping. For example in TG2D, MDO demand in the global transport sector dropped from 2035 to 2050 from a total share of 43% to 8% in 2050, while hydrogen demand increased in the same period from 0.5% to 20% (similarly it happened in IT2D simulation). So, in the global transport sector hydrogen demand increased after 2035 at the expenses of diesel fuel demand. This had an effect on MDO price which dropped in TG2D simulation and showed a tendency to remain stable in IT2D simulation. Eventually, in the last period (from 2045 to 2050) hydrogen price reached an extremely high value due to its increased demand in bus and trucks, and MDO again found its market and its price started to increase.

The difference price obtained between IT2D and TG2D is due to the fact that in the former the linear property of the energy model allows very small amount of uptake of hydrogen, while in the latter the algorithm implemented does not allow it.

5.7.4 An improved modelling representation of the target system

The aim of this chapter was to explore whether the soft-linking framework enables the explanations of the dynamics between the energy and shipping systems that may not be observed with the independent simulations. The key output were compared among the different simulations in order to test whether TIAM-GloTraM generates new insight into the dynamics of the shipping-energy system and therefore improves the modelling representation of the uptake of hydrogen in shipping. The focus of the comparison was on the interpretations of the results and not on the results itself as the different boundaries of the models prevent a fair comparison of the results. Evidences of new insight were found by comparing the following key output: marine fuel prices and demands, carbon price and fuel mix, the shipping transport demand of energy commodities.

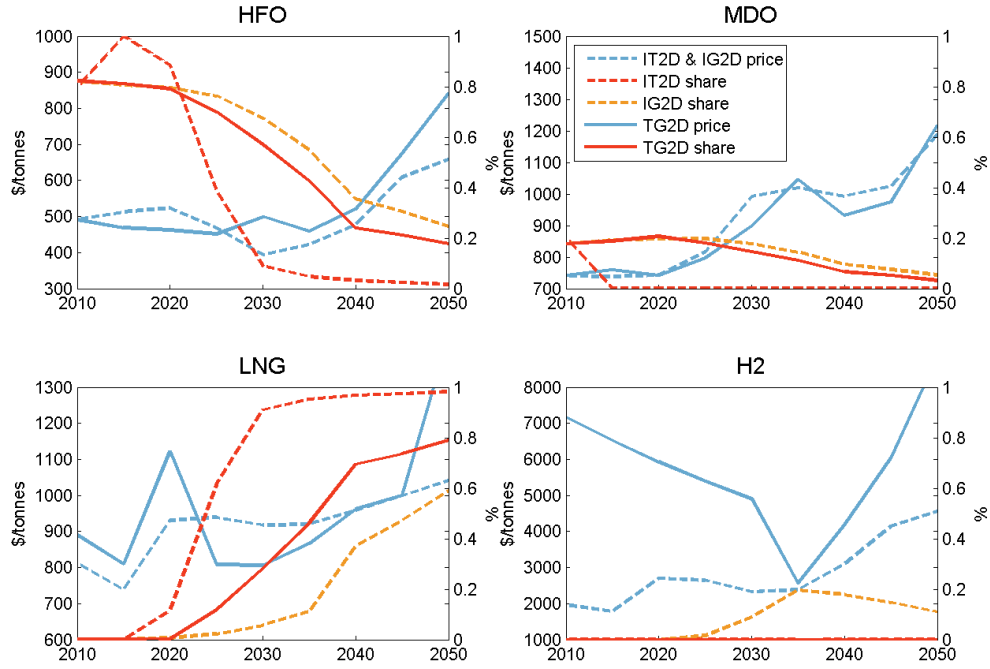


FIGURE 5.25: Fuel shares and prices 2°C scenarios

The first evidence is the fact that in TIAM-GloTraM, marine fuel prices are affected by the associated fuel demands in shipping. An example of this influence can be observed analysing the results of the scenario TG4D (see section 5.6.1). LNG share reached approximately 50% of the total in 2035, and consequently the demand of HFO decreased and its price fell from that year. This effect was not observed in the independent simulations of TIAM-UCL and GloTraM. TIAM-GloTraM, instead, captured the balance of supply and demand of those marine fuels. Such a balance is reached by using the estimated fuel prices of the energy model in conjunction with the estimated fuel demands of the shipping model. The estimation of fuel prices includes factors of the supply infrastructure, the estimation of fuel demands includes factors of the economic, operational, and technical characteristics of the shipping industry. Marine fuel prices are exogenous to the shipping model (GloTraM), and shipping energy demand is exogenous to the energy model (TIAM-UCL). In TIAM-GloTraM, instead, both the fuel prices and the energy demand are endogenous to the model. The fact that these parameters are endogenous and that the results are sensitive to this representation is an improvement of the modelling representation of the marine fuels supply and demand. As a consequence, also the representation of the uptake of hydrogen is improved.

In regard to the fuel price an additional evidence in support of an improved representation of the potential uptake of hydrogen in shipping is that the soft-linked framework overcomes the unrealistic representation of very small technology capacity. The linear property of TIAM-UCL makes the uptake of very small amount of hydrogen possible, which for example, could signify that the corresponded hydrogen prices is not representative of a real economy. This can be considered unrealistic in some scenarios (see IT4D and IT2D scenarios in section 5.4). The algorithm used in the soft-linking framework, instead, prevents such representation correcting hydrogen price every time there is an unrealistically small uptake of hydrogen. In TG2D and TG4D scenarios, it can be observed that hydrogen price (varying from 3 to 9 \$/kg) is consistently corrected and therefore it is always higher than the corresponded price in IT2D and IT4D scenarios (varying from 1 to 5\$/kg).

Another evidence of new insight generated with TIAM-GloTraM can be found by comparing carbon price and fuel mix among the simulations. For example, it was found that carbon price in the TG2D scenario made LNG more attractive in shipping in comparison with HFO and MDO; the increased demand of LNG in shipping also increased the associated price. In order to maintain the economical viability of LNG in shipping, the global carbon price increased too (see section 5.6.2). This dynamic was not observed in IT2D as TIAM-UCL does not include a feedback loop of marine fuel mix demand on carbon price. It was not observed in IG2D as GloTraM in this instance uses an exogenous carbon price. TIAM-GloTraM, instead, includes the effects of the marine fuel mix on the carbon price (whether it is global or in-sector) which improves the modelling representation of the uptake of marine fuels. As consequence, also the representation of the uptake of hydrogen is improved.

The use of TIAM-GloTraM generates a transport demand of energy commodities by ships that respond not only to the different target emissions (4°C and 2°C scenarios) but also to the possible effect of a difference fuel mix in shipping. In scenario TG2D, for instance, it can be observed the effect of using LNG in shipping on the trade of natural gas among regions (see section 5.6.2). The global energy systems energy mix (and therefore transport demand scenarios), were only minimally sensitive to the mix of energy sources used in the shipping industry, the dominant source of variation in the global energy system remains the temperature target. Therefore, there is not a clear benefit in using TIAM-GloTraM in comparison with TIAM-UCL for this particular

parameter, although the modelling representation of the uptake of hydrogen is more completed in TIAM-GloTraM as it includes the effect that the use of hydrogen may have on the shipping transport demand. Both models (TIAM-GloTraM and TIAM-UCL), however, have an improved modelling representation than GloTraM, in which the transport demand is exogenous to the model.

It can be concluded that the soft-linking framework is able to model the supply and demand balance of the selected marine fuels, taking into account two important aspects simultaneously. On one side, the profitability of marine fuels within the shipping system, on the other side, the costs of supplying these fuels to the ships. These aspects improve the representational capacity of TIAM-GloTraM to represent the uptake of marine fuels. Therefore, TIAM-GloTraM can be considered an improvement in the substance of modelling hydrogen in shipping, and it can be used to explore possible emergences into the energy-shipping system.

Chapter 6

Exploring the implication of using hydrogen in shipping

This chapter addresses the second research question: what can the framework TIAM-GloTraM tell us about the potential of using hydrogen to fuel international shipping? If hydrogen would be used in shipping what would be the main economic and environmental implications? Therefore, this chapter examines the circumstances in which it would be possible to see an uptake of hydrogen in shipping.

Following the establishment in chapter 5, that a soft-linked model enables a more realistic representation of the shipping-energy system interaction, such circumstances are analysed using the developed modelling framework TIAM-GloTraM. In order to explore on appropriate shipping mitigation strategies of CO_2 emissions, it has been introduced a scenario different from the ones explored in the previous chapters. In this scenario the shipping sector is constrained to emit a certain amount of CO_2 until 2050. The economic and environmental implications of the use of hydrogen are addressed by the analysis of the results under this scenario. In order to provide credibility of the results, the viability of hydrogen in shipping is tested with a robustness analysis. The findings of sensitivities cases are examined to provide further insights on the potential of hydrogen to fuel international shipping.

This chapter is organized as following: section 6.1 introduces and justifies the concept of applying a carbon budget in shipping. Section 6.2 examines the consequences of the decarbonisation of the shipping sector and examines the main drivers for the use of hydrogen in shipping. Section 6.3 analyses the environmental implications of using hydrogen focusing on shipping CO_2 emissions. Section 6.4, instead, analyses the economic implications. Finally in section 6.5 the robustness of the results are tested with the robustness analysis.

6.1 Introducing a carbon budget in shipping

Emissions reduction regulations are being implemented or under debate in many countries. Following the Paris Agreement at the COP21 under the UNFCCC (United Nations Framework Convention on Climate Change) framework, it is recognised that all economic sectors should identify appropriate sectoral mitigation strategies of GHG emissions in order to hold the increase in global temperature “well below 2 and aiming for 1.5 degree”. Countries have committed themselves to achieve a decarbonisation trajectory with a

peak of GHG emissions as a priority and substantial reduction of annual GHG emissions afterwards. Although shipping was not included in the Paris Agreement, shipping emissions are becoming a concern as all scenarios for the projected shipping emissions provided in (Smith et. al., 2015) do not see a downward trend. Since 2009 the IMO has considered whether international shipping should be subject to an explicit CO_2 emission reduction target. During the MEPC68 the Marshall Islands provide the justification to establish a GHG emission reduction target for international shipping, forecasting that the sector could constitute between 6% and 14% of total anthropogenic carbon dioxide emissions in 2050 MEPC.1/Circ.6851 (2015). During the MEPC69, instead, the ICS proposed that the IMO should agree to develop an Intended IMO Determined Contribution on behalf of the international shipping sector as soon as possible, so that the shipping industry will account for a "fair share" of the total CO_2 emission in the future. Establishing CO_2 reduction commitments is therefore believed to be the way forward.

In the previous chapter we used the framework TIAM-GloTraM in order to estimate projections of fuel mix in shipping under a scenario in which the average global temperature rise is constrained to be below 2 degree Celsius (TG2D). Under this scenario the uptake of hydrogen was not observed in shipping. However, the underlying assumption in this scenario is that the shipping sector is not committed to a CO_2 emissions reduction target and it is allowed to buy unlimited offsets of CO_2 emissions from the rest of the economy. The global energy system is acting as single entity to mitigate the emissions, so it is assumed a global carbon market in which carbon credits will flow to the sector with the lowest mitigation costs first. As consequence the resulting sectoral fuel selection are based on the maximisation of the social welfare as defined in the objective function in TIAM-UCL. This simplification of the real world system is acceptable if the modelling framework is utilised to analyse the use of primary energy sources in order to meet the 2-degree temperature rise target. It is, instead, less useful when such type of simplification is adopted to identify fuel selection and associated emissions trajectory that can occur in specific economic sectors such as the shipping sector.

Emissions reduction regulations for a specific sector can affect the uptake of fuels in different ways. Speculation that accounts for a "fair share" for shipping is therefore required. The introduction of a scenario with a CO_2 reduction target is justified by the need to include in the modelling framework TIAM-GloTraM a mechanism that enable a decarbonisation pathway in shipping in accord with a defined "fair share".

The definition of an appropriate "fair share" for shipping is under debate, however a simple starting point is to assume that the current shipping emissions share is preserved in the future. The same assumption has been used under the 2-degree global warming scenario in the Shipping in Changing Climates research project (Smith and Wrobel, 2015). This can be seen as an appropriate mitigation strategy which is proportionated to the "well below 2 and aiming for 1.5 degree" global decarbonisation trajectory. Therefore, the new scenario is introduced which not only ensures that the average global temperature rise is constrained to be below 2 degree Celsius, but also so the shipping industry is restricted on the total amount of GHG that can be emitted until 2050 to a certain budget. The new scenario is named TG2D-CB. The hypothesis is that hydrogen could take up as marine fuels under these new circumstances.

Under the scenario 2 degree, the framework TIAM-GloTraM calculates the global cumulative CO_2 emissions over the period 2010 to 2100 to be 1474 $GtCO_2$. The international shipping sector accounted for approximately 2.3% of the global CO_2 emissions in 2010 (Smith et al., 2015). Assuming that future shipping emissions share will be consistent with such a share it is possible to estimate a CO_2 shipping budget. The carbon budget is calculated as a proportion of the global cumulative emissions, resulting in 34Gt over the time period from 2010-2100. A number of different shares could have been used, however for the sake of this research only one representative value is explored and such a value is considered to be appropriate.

In TG2D scenario, however, at base year 2010 shipping emissions represents 1.2% of the total which is lower than the 2.3% reported in Smith et al. (2015). This underestimation derives from the fact that in this thesis only five ship types were included, and that the shipping model was effected by an unbalance between the supply (shipping) and demand (transport demand) at base year which caused an overestimation of ships that were laid up in that year with consequent under estimation of emissions. In view of this underestimation the carbon budget used in this thesis has been scaled taking into account that at base year the emission calculated from the shipping model represent approximately the 55% of the one provided in Smith et al. (2015). The CO_2 shipping budget, therefore, resulted to be 19Gt.

The shipping carbon budget allows the calculation of a "target trajectory" at which corresponds an equivalent cumulative emissions. Figure 6.1 displays the global CO_2 emissions reduction trajectory, and the shipping CO_2 emissions trajectory in the scenario

without carbon budget. It also displays the target trajectory that ensures consistency with CO_2 shipping budget of 19Gt. The new scenario TG2D-CB looks at bridging the gap between the shipping emissions and the so defined target trajectory.

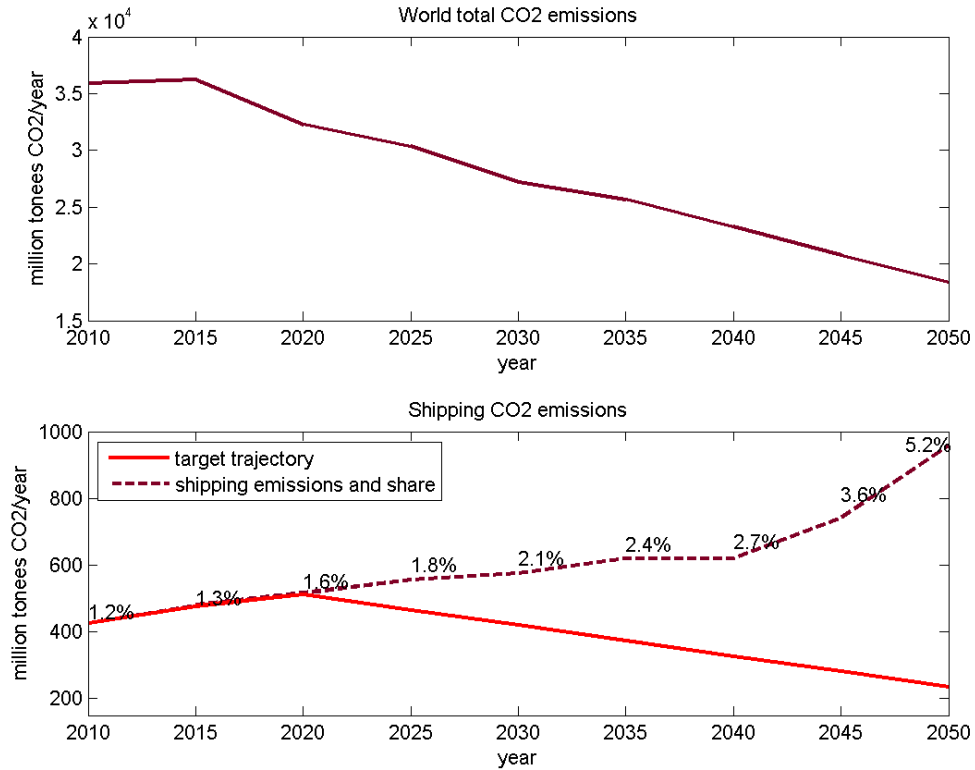


FIGURE 6.1: World's total CO_2 emission (top); shipping CO_2 emissions and shares (as percentages of the world's total emissions) (bottom dotted line) and target trajectory (bottom red line)

6.1.1 Implementing a shipping market-based measure in TIAM-GloTraM

The shipping sector might comply with the CO_2 budget in different ways. By incorporating in the modelling framework TIAM-GloTraM a market-based measure (MBM) mechanism, the amount of emissions that the shipping sector emit is ensured to be under the budget. The introduction of an emissions cap guarantee a decarbonisation pathway through the implementation of a carbon pricing and a system for addressing revenue deployment.

A carbon price specific for shipping is introduced in the framework TIAM-GloTraM which adjust the cost-benefits available in the model to enable take-up and in-sector emissions mitigation measures. Shipping carbon price is estimated through the re-iteration of GloTraM's modelling steps. In each iteration if the gap between the target

trajectory and the net shipping emissions is not bridged, the shipping carbon price increase proportional, and the GloTraM's modelling steps are repeated until the gap is bridged. These iterations are embedded into the soft-linking framework, so that each time information is exchanged between TIAM-UCL and GloTraM. The latter is re-iterated until the constraint on carbon budget is satisfied. The information estimated in the shipping model is then exchanged back to TIAM-UCL. By implementing such a MBM mechanism the framework TIAM-GloTraM is characterised by two iterative processes. The first iteration process is between TIAM-UCL and GloTraM, the second is the re-iteration of GloTraM's steps.

The MBM assumes that the revenue from carbon pricing is allocated in different proportions for out-sector and in-sector purposes. In this scenario it is assumed that 40% of such revenue is allocated to developing countries in order to compensate them for negative costs incurred from introducing a MBM (rebate mechanism). A further 50% of the revenue is allocated to the international shipping sector; the 80% of this revenue is assumed to be used within the shipping sector, while the remaining 20% to purchase emission credits in economic sectors other than the international shipping sector (emission offsetting out-of-sector). The final 10% of the revenues from carbon pricing is assumed to be allocated to the Green Climate Fund to finance further mitigation activities, climate change adaptation or technology transfer, and/or to other purposes. Table 6.1 provides details of the MBM. This should only be considered an example of possible ways of distributing the revenue, as speculation is required to identify a foreseeable implementation of an MBM for the shipping industry.

TABLE 6.1: Assumed proportions of the revenue deployment due to the carbon pricing

Purposes	proportion (%)
Rebate mechanism	40%
Out-sector offset purchase	10%
In-sector re-investment	40%
Green Climate Fund	10%

6.2 The decarbonisation of the shipping sector

This section presents the results for the shipping sector under the scenario with a CO_2 emissions reduction target. First, the emissions trajectory is presented with the associated shipping fuel mix by ship type. Second, the fuel selection is analysed by looking at key drivers. Finally the uptake of hydrogen is presented by ship type. The results are analysed to determine the circumstance in which it would be possible to see an uptake of hydrogen in shipping and what would be hydrogen's role in shipping. This will provide an answer to the first part of the second research question regarding the potential of using hydrogen to fuel international shipping.

6.2.1 Shipping with a carbon budget constraint

The results for the scenario with a carbon budget in shipping (TG2D_CB) are obtained after the modelling framework TIAM-GloTraM reaches the convergence. This is achieved after 5 iterations between TIAM-UCL and GloTraM. Each iteration the shipping model GloTraM achieves the compliance with the defined carbon budget after a number of "re-iterations" of GloTraM's steps. So, in addition to the iterations of the soft-link, there are also separate re-iterations of GloTraM occurring during each iteration.

The introduction of the MBM enabled a decarbonisation pathway, which was achieved with the contribution of CO_2 offsetting and in-sector technical and operational emissions abatement measures. Figure 6.2 shows the decarbonisation of the shipping sector by ship type under the carbon budget constraint of 19Gt. The figure also displays the total shipping operational emission trajectory (global fleet), the total target trajectory, the trajectory of the tonnes of CO_2 emissions offsets and the net emission trajectory obtained as operational emissions minus offsets.

The graph in figure 6.2 highlights the contribution of CO_2 offsets and the effect of in-sector measures on the net shipping emissions trajectory. In particular, shipping emissions are projected to increase until 2030. During this period the gap between the target trajectory and operational emissions was mainly bridged by CO_2 offsets. During the period from 2030 to 2040 a rapid decarbonisation was observed which can be associated mainly to container and gas carrier ship types. The shipping emissions were reduced as new buildings and retrofitted ships emit less. The contribution of in-sector measures reduced the need to purchase CO_2 offsets during such period. Instead, during

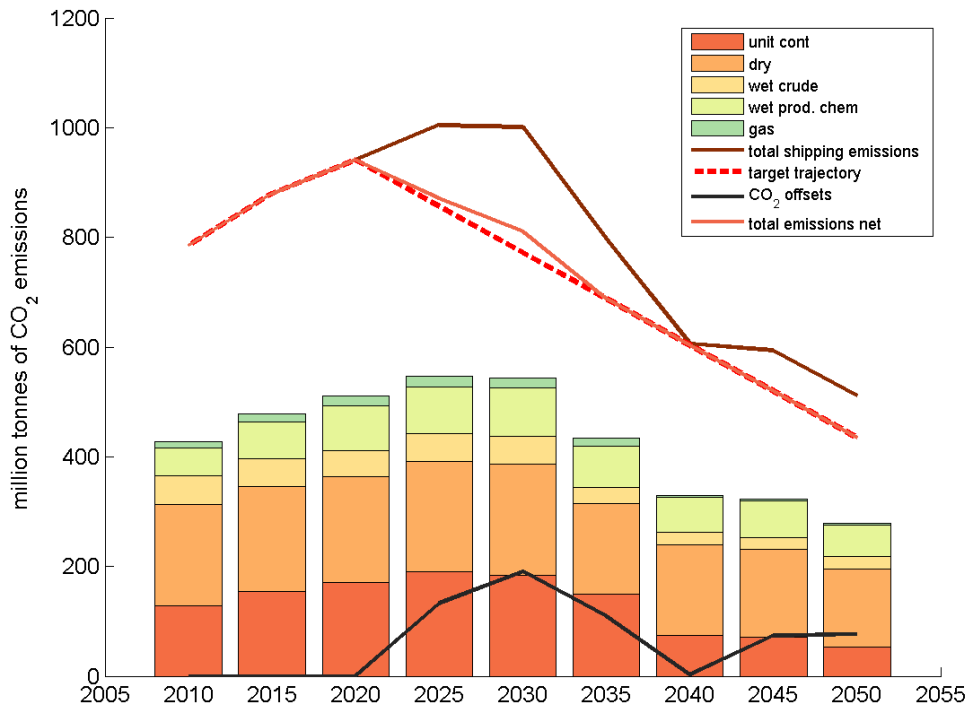


FIGURE 6.2: Decarbonisation of the shipping sector in TG2D-CB scenario. Total emissions trajectory, target trajectory, CO₂ offsets and net emissions trajectory

the last decade 2040 to 2050, the reduction of operational emissions was not sufficient to meet the target trajectory so offsetting started to increase again.

All ships types contributed to the reduction of operational emissions from 2030. In particular, gas carrier type reduced operational CO₂ emissions of 86% from 2030 to 2050. During the same period unit container reduced the CO₂ emissions approximately of 71%, while wet crude of 57%, wet product chemical of 34% and dry of 29%.

Based on the results of this scenario, the shipping sector would be able to buy CO₂ offsets from other sectors during the period 2010 to 2030. This may ensure the sector to meet the target trajectory in that period and at the same time invest in technical and operational emissions abatement measures. The effect of the latter would be observed from 2030 when the operation shipping emission would reach a peak. From 2030 shipping would be required to dramatically decrease its operational emissions. Some ship types may find it more economically convenient to decarbonise. For example, container and gas carrier types might be the ones with the greatest opportunity to reduce their emissions, followed by wet and dry types. In long term from 2040 to 2050, meeting the defined target trajectory could mean a further challenge for the sector and the contribution of

offsetting might become again of significant importance.

The cumulative emissions in this scenario is in line with the constraint on carbon budget. The decarbonisation pathway can be explained by looking at the fuel mix. Figure 6.3 displays the fuel mix share by ship type and it can be observed that across ship types the fuel mix show a similar trend. The energy demand of conventional marine fuels such as HFO and MDO, reduced over time, while LNG and hydrogen demand increased. LNG was used from 2020 and its share tends to remain stable from 2030 to 2050, while hydrogen was taken up in shipping from 2030 in all ship types. Hydrogen in combination with fuel cells have no operational emissions associated, as a consequence, shipping emissions appeared to be reduced.

Container and gas carrier types are the ships that showed more uptake of hydrogen. Hydrogen share for those types reached in 2050 about 80% and 90% respectively, which can be associated with the greatest decarbonisation observed in these types. The uptake of hydrogen was also significant in the other ship types. Its shares in 2050 were approximately 50% for dry and wet crude, and 60% for wet product chemical type.

In conclusion, this results show that in order to meet the carbon budget constraint, low carbon system such as hydrogen in combination with fuel cells might be required to lower down the operational emissions and to comply with the target trajectory. On this view hydrogen would play a key role for the decarbonisation of the shipping sector as its potential would be associated with the compliance of a CO_2 emissions reduction target. For some ship types it might be more economically convenient to switch to hydrogen such as for container and gas carrier types.

6.2.2 Drivers and choices in a decarbonised shipping sector

In a decarbonised shipping sector, a number of different drivers influence the model's decisions. The results of the scenario TG2D-CB are analysed in this section in order to determine how such key drivers have influenced the uptake of hydrogen. The main drivers that are analysed are: transport demand, carbon price, fuel price, and the competitiveness of fuel/machinery options.

A dominant driver for the observed energy demand trend in shipping is the transport demand. The model projected an increasing transport demand for the majority of ship types modelled. As a consequence, the energy demand increased. Figure 6.4 shows the

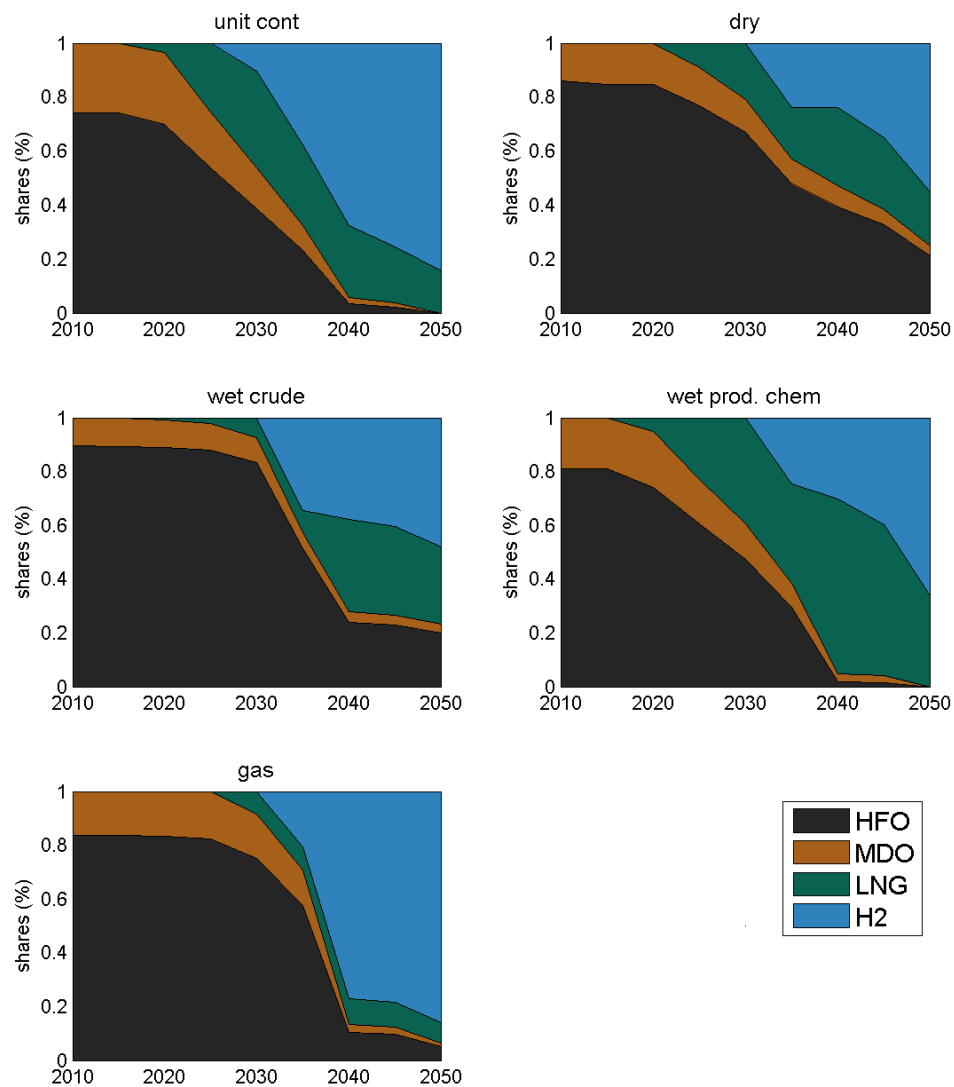


FIGURE 6.3: Fuel mix in TG2D_CB scenario by ship type.

transport demand by ship type on the top and the total shipping energy demand by fuel type on the bottom. A decreasing in trade is projected only for wet crude due to the low demand of crude commodities. A reduction by 12% is observed from 2010 to 2050. In contrast a significant increasing is observed for unit container which transport demand increased by 500%. Overall, the energy demand increased in accordance with the transport demand by 180% from 2010 to 2050. During this period hydrogen accounted for about 30% of the cumulative energy demand.

The need to meet an increased transport demand means, therefore, that the shipping

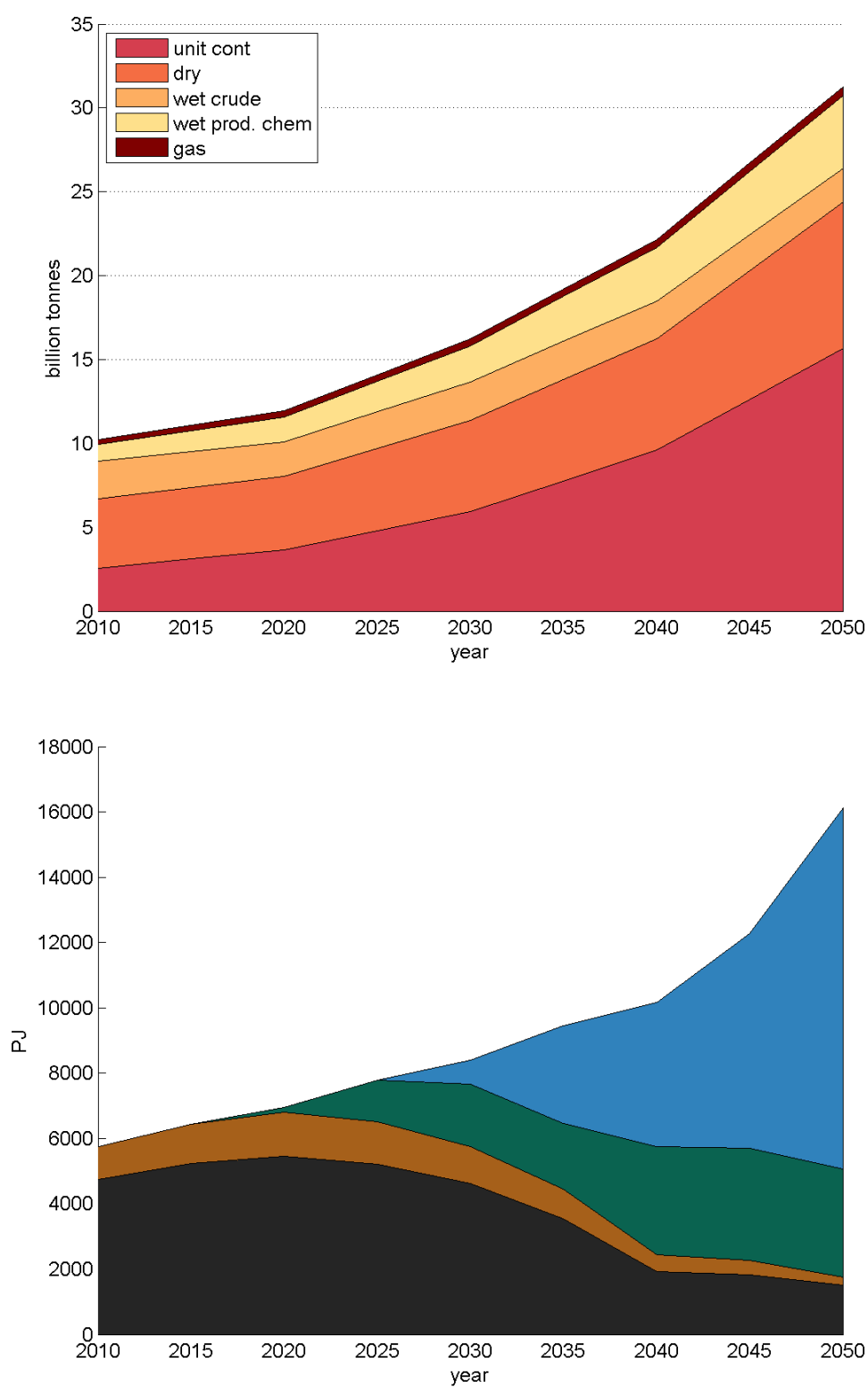


FIGURE 6.4: Transport demand by ship type (top), energy demand by fuel type (bottom) - scenario TG2D_CB

sector would require more energy. Such energy demand would be associated with a fuel mix in which hydrogen has a growing demand.

In addition to the transport demand, another important driver in a decarbonised shipping sector is the carbon price. The shipping carbon price is set to reach the given CO_2 trajectory, taking into account both in-sector and out-sector abatement options. If the shipping carbon price is higher than the global carbon prices, then it is reasonable to purchase offsets. This dynamics, however, is limited at 20% of the revenue generated as there is the need to make sure the carbon price causes some in-sector decarbonisation, and to avoid the risk that all purchasing of the emissions credits occurs outside of the shipping industry. The resulting shipping carbon price for the scenario TG2D_CB is presented in figure 6.5. As a comparison, the figure also shows the global carbon price. In a decarbonised shipping sector carbon price is required to be approximately 250% higher than the global carbon price in 2050.

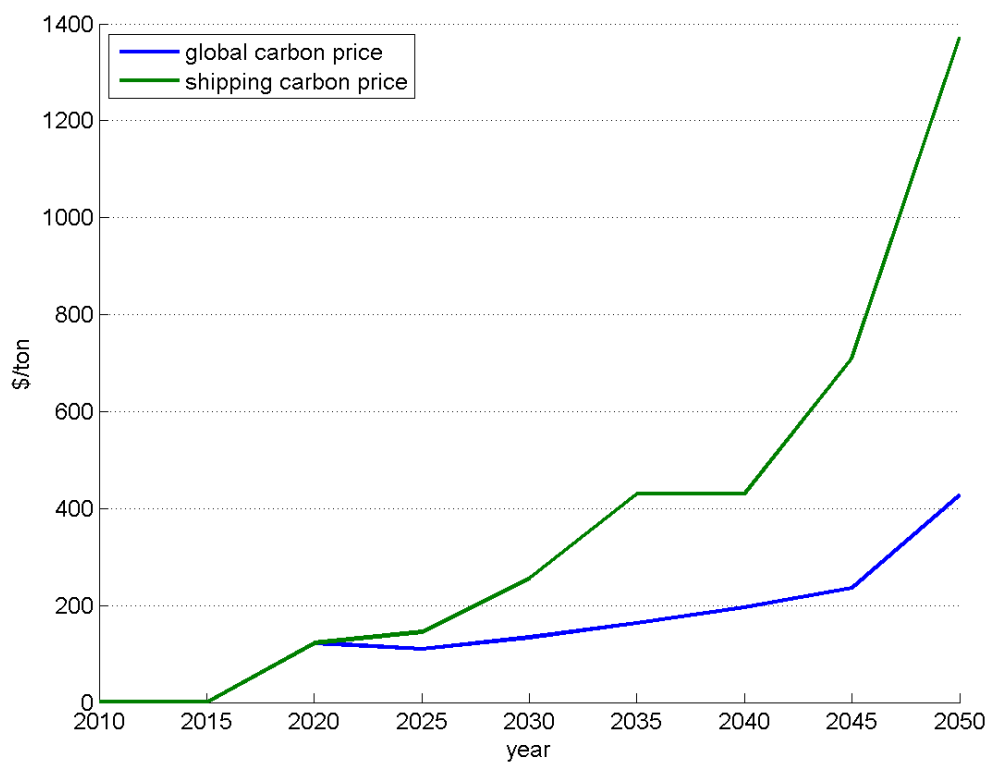


FIGURE 6.5: Comparison between shipping carbon price and global carbon price in TG2D_CB scenario

The trend of carbon price puts an increasing penalty on fuels with high carbon content. Therefore, ships that use conventional fuel such as HFO and MDO would pay

additional costs. As a consequence, there would be a clear advantage for fuel with lower carbon content such as LNG and hydrogen.

As for carbon price, also fuel prices are endogenously estimated in the modelling framework. The trend of fuel prices is another important driver and is associated with the demand generated in the model. Figure 6.6 shows fuel prices in TG2D_CB scenario. LNG price is comparable to the MDO price in terms of \$/tonnes. HFO is consistently the cheapest fuel, while hydrogen is the most expensive. Hydrogen price during the period 2010 to 2035 decreased by 100% from 6000 to 3000 \$/tonnes, while it increased in the year following by 180% reaching more than 8000 \$/tonnes in 2050.

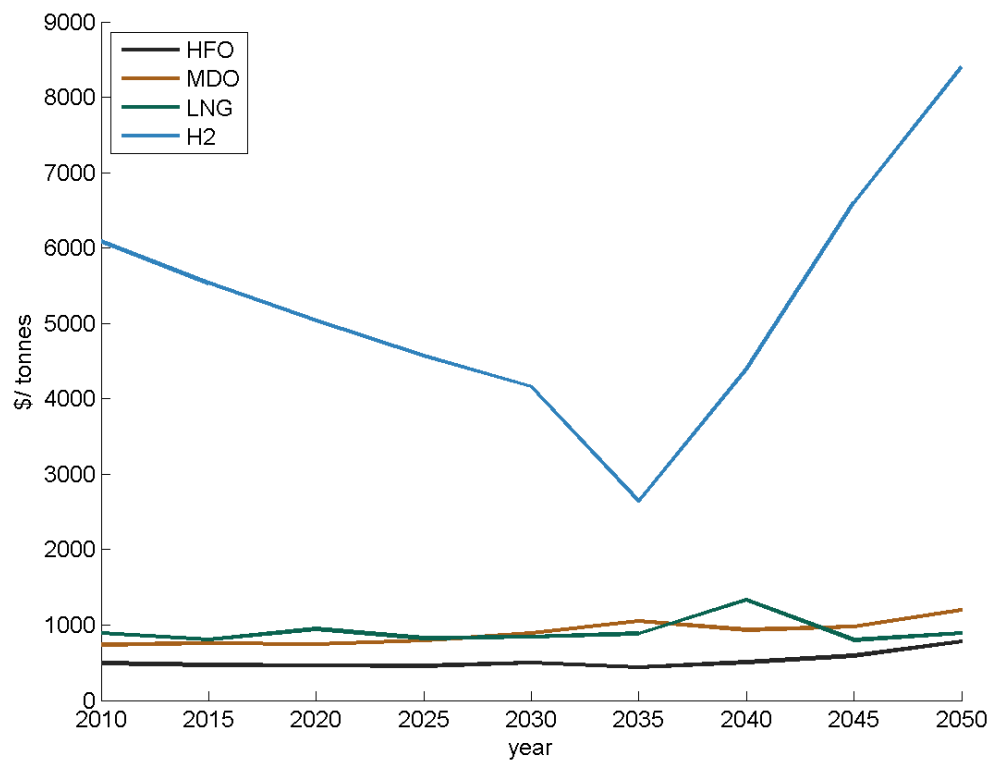


FIGURE 6.6: Fuel prices in TG2D_CB scenario

During the period 2010 to 2035 hydrogen price would gradually decrease as it is assumed that high associated with the development of the supply infrastructure would eventually reduce although it might be that hydrogen first introduced would be where infrastructure cost is lowest. In contrast, the increasing hydrogen demand during the period 2035 to 2045 can explain the significant and rapid increasing of hydrogen price in that period. The growing share of hydrogen demand in shipping can also explain the drop of LNG price during the period 2040 to 2045.

An additional important factor is the price difference among marine fuels. In particular the difference between hydrogen price and other marine fuels prices is an important drive for the selection of hydrogen in shipping. For example, the peak of LNG price in 2040 reduces the gap with hydrogen price in that year, although in general after 2035 the gap between hydrogen price and other fuel prices increases over time.

The carbon and fuel prices are part of another driver which in this thesis has been called the competitiveness factor. As explained in the previous chapters the shipping model simulates the choices for new buildings and retrofits and for the technical and operational emissions abatement measures assuming that the most profitable solution will be selected. One way to explain the selection criteria of main machinery and fuel type is by looking at the competitiveness of each fuel/machinery option. The competitiveness factor is intended to be indicative of the relative advantages of the fuel/machinery options modelled. Such a factor is expressed in $\$/kWh$ and it is defined by the formula 6.1 as indicative “price per unit of shaft output power. The lower the factor, the higher the competitiveness of fuel/machinery option.

$$C_{jy} = (p_{fiy} + (Cf_i * Cp_y)) * sfc_j \quad (6.1)$$

where:

- C_{jy} is the competitiveness factor of the main machinery and fuel combination j at year y
- p_{fiy} is the price of fuel i at year y
- Cf_i is the carbon factor of fuel i
- Cp_y is the shipping carbon price at year y
- sfc_j is the specific fuel consumption of the main machinery and fuel combination j

The competitiveness factor is calculated for the baseline ship design (the technical and operational specification of the 2010 fleet), so such factor is not exhaustive in explaining the fuel and machinery choices as the ship’s technology and operational specification vary over time. Figure 6.7 shows the competitiveness factor of some of the key fuel/machinery options that are considered to be indicative for each fuel type.

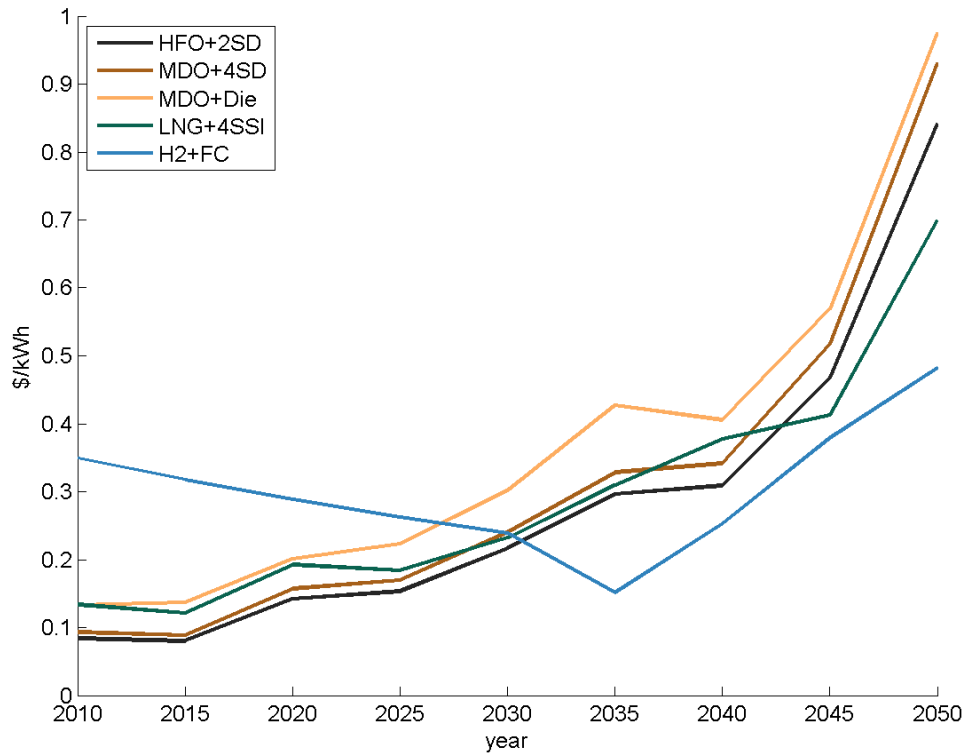


FIGURE 6.7: Competitiveness of fuel/machinery options

During the period 2010 to 2025 the use of HFO with 2SD engine appeared to be the most competitive, while the use of LNG with 4SSI started to reduce the gap with HFO and MDO options. Hydrogen was the less competitive due to the high hydrogen price. During the period 2025 to 2030, the combination of a decreased hydrogen price (approximately 4000 \$/Tonne), and carbon price (approximately 200 \$/Tonne), and greater efficiency of fuel cells system made the option hydrogen with fuel cells the most competitive. During the period 2030 to 2050 the hydrogen's option maintained its advantage mainly thanks to an increasing carbon price.

6.2.3 Hydrogen demand by ship type and size

Under the assumption of a carbon budget in shipping, hydrogen appeared to be used from 2030. As explained in the previous section a number of factors influence the selection of fuel, however the peculiar characteristics of specific ship type and size categories also might have an effect on the uptake of hydrogen. Figure 6.8 shows hydrogen shares for each ship type by size categories.

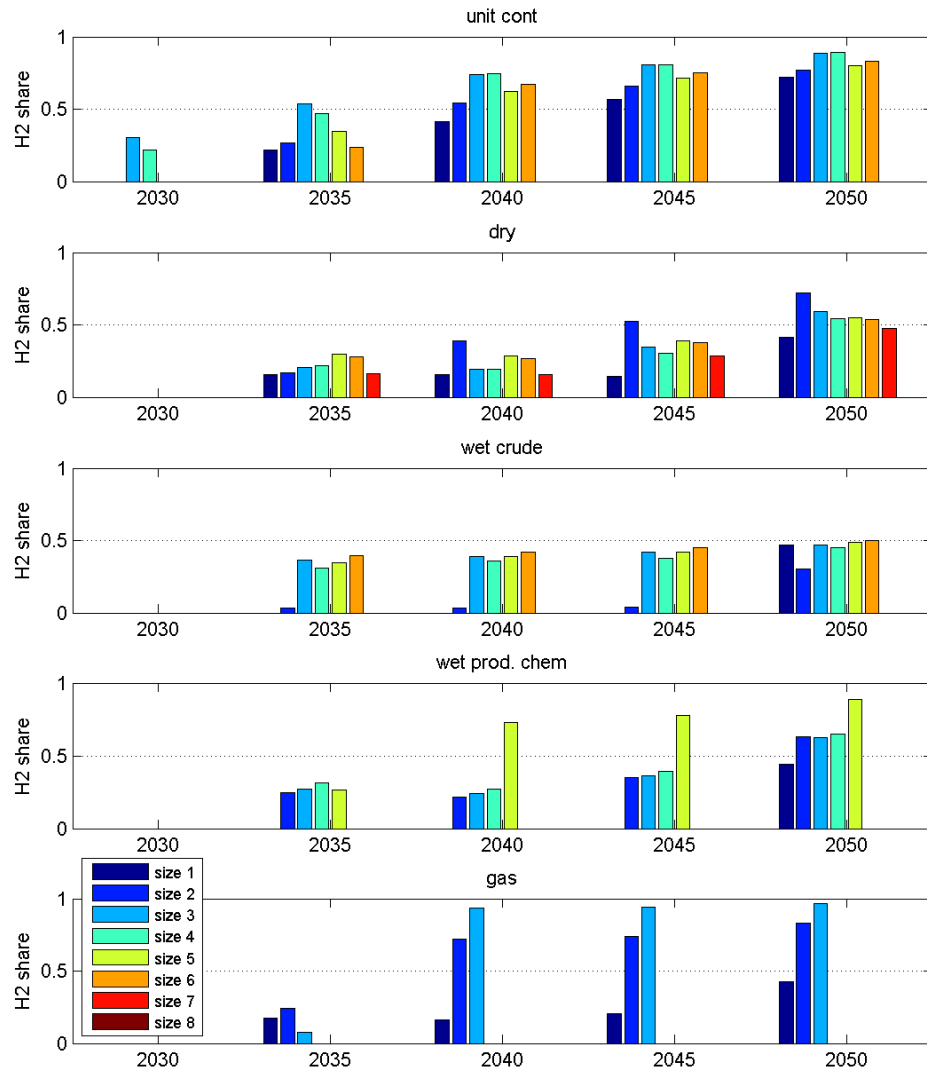


FIGURE 6.8: Hydrogen share per ship type by size category ranging from the smallest size 1 to the largest size 8 in wet crude

The category unit container switched more rapidly to hydrogen when compared to other ships types; for middle size category (3 and 4) the share of hydrogen on total energy demand reached already 20-25% in 2030. Afterwards the uptake of hydrogen was observed in all size categories of unit container type. The middle sizes categories (3 and 4) remained the categories with higher hydrogen share in comparison with the other sizes categories over time, suggesting that for smaller ship types the impact of hydrogen storage volume on the ship's payload capacity penalised the hydrogen uptake in these categories. In contrast, for bigger ships the impact of high investment cost with

the main machinery could have penalised the uptake of hydrogen.

In the category ship type dry, instead, the uptake of hydrogen was observed in all size categories from 2035. In 2050 the share of hydrogen on total energy demand by size appeared to be over 50% in almost all size categories. Similar to the container, in this case the smallest and largest size categories seems to be penalised, however hydrogen seems to be very competitive in ship type dry of category size 2 from 2040. In the category wet crude, hydrogen share by size appeared quite similar across the categories except for small size (1 and 2). Only in 2050, the share for small size reached values similar to the other size categories. Hydrogen in the wet chemical and gas carrier categories appeared to be systematically more convenient in large ships rather than small ships. In particular, gas carrier fleet appeared to switch almost completely to hydrogen.

The analysis of the uptake of hydrogen across different ship type and size categories highlights the fact that such a fuel could be more or less economically competitive across the different categories. There is not a common pattern among such categories. The smallest and biggest unit container and dry ships could be penalised by the high volume required to store hydrogen on board. The same would also be for small ships of wet chemical and gas carrier types. Large unit container and dry ships would also be penalised by the high costs associated to large engine/equipment. In contrast, large wet chemical and gas carrier types don't seem to suffer these costs. They would convert almost the complete fleet with hydrogen in 2050.

In general, it can be concluded that the observed differences between categories could be explained by a combination of different factors. Costs and space requirements could be some of the key factors but also transport demand, fuel price and carbon price could influence the profitability of a particular type and size category. A detailed analysis across categories is left to further research effort.

6.3 Environmental implications of using hydrogen in shipping

This section focuses on the main environmental implications of using hydrogen to fuel international shipping. In this thesis, the focus is mainly on emissions implications, other possible environmental implications are not addressed. The main implications that will be discussed are the following: the effect on the decarbonisation pathway by

ship type, the effect on total shipping emissions share, the effect on hydrogen supply and consumption in a decarbonised energy system. This will provide an answer to the second part of the second research question.

6.3.1 Decarbonisation by ship type

In a decarbonised shipping sector the trend of emissions emitted by ship type decreases over time. Figure 6.9 shows the shipping CO_2 emissions by ship type. Container ships are by far the principal emitter until 2040. They drastically decreased their emissions from 2030 becoming the second emitter during the period 2040 to 2050. The emissions of wet chemical products and dry showed a tendency to remain constant, although after 2030 they started to decrease slightly. The emissions of gas carrier ship type also showed a tendency to decrease over the period 2030 to 2050. The emissions of wet crude ship types do not appear to increase and then start to decrease after 2030. This trend can be associated with the decrease of transport demand for crude commodities.

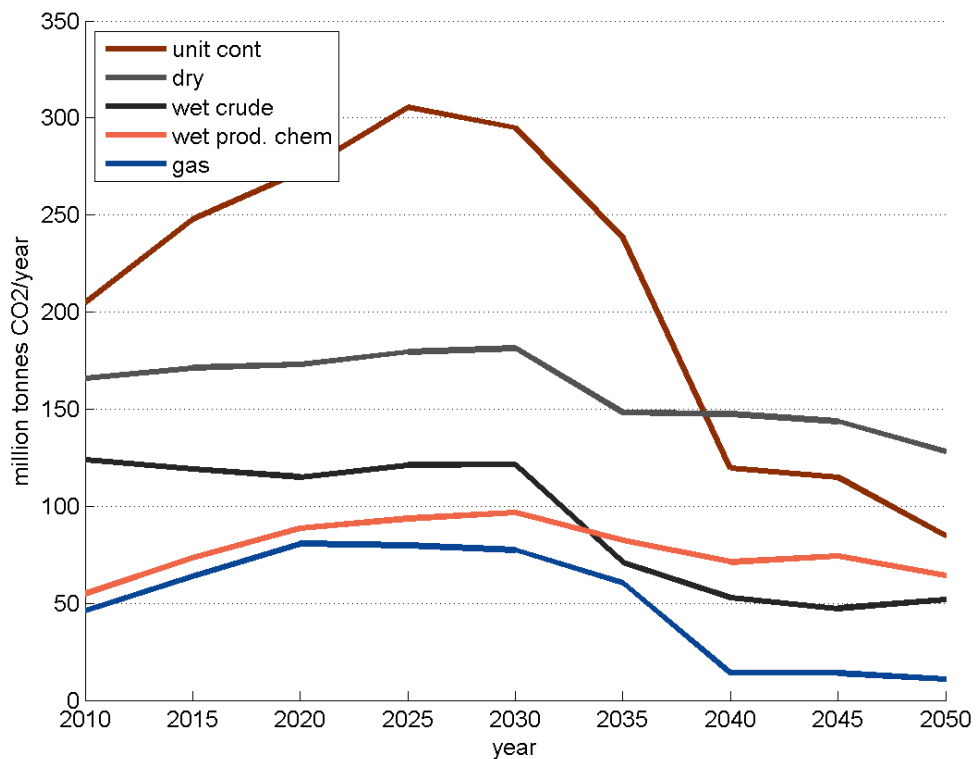


FIGURE 6.9: CO_2 emissions by ship type category in the TG2D.CB scenario

Transport demand by ship type represents one driver for the observed CO_2 emissions trends, however, the dominant driver is the carbon intensity of the fleet. One way

to observe this is by looking at the operational emissions by unit of transport work (EEOI) and at the averaged carbon factor of the fleet. Variations in the EEOI can result from changes in a number of parameters such as: composition of the fleet, capacity utilisation, design and operating speeds, the use of other energy efficiency technology and operational interventions, and fuel choice. Figure 6.10 on the bottom, shows the trends EEOI by ship type. A drastic reduction is observed over time across all types.

In this thesis, the composition of the fleet and capacity utilisation is held constant across time. The use of other energy efficiency technology and operational interventions, along with the changes of design and operating speeds had an effect on the trajectory of the EEOI. However, these other parameters would have a secondary impact in comparison with the fuel choice. If the trends of design and operating speeds between the scenario TG2D and TG2D_CB are compared, they show a great similarity. The same is for the uptake of energy efficiency technology and operational interventions. This means that the switch to alternative fuels with low operational emissions remains the principal explanation for the observed shipping emissions reduction.

Fuel choice drives the changes in the carbon intensity of the fleet as fuels with low or zero carbon content reduce the average carbon factor of the fleet. The reduction of the averaged carbon factor is one of the dominant driver of the observed EEOI trend. Figure 6.10 on the top shows the averaged carbon factor by ship type over time. In general, all types drastically reduce this factor after 2030. Container and gas carrier ships that have the highest hydrogen share reduced their carbon factor by 83% and 67% respectively from 2010 to 2050.

Focusing on the selection of fuel choice, these results show the effect of the use of hydrogen on the average carbon intensity of the fleet.

6.3.2 The effect on the shipping emissions share

A comparison of the results obtained from the 2 degree scenarios with and without a shipping carbon budget (TG2D and TG2D_CB) can be useful to analyse the differences between a future fleet with or without the use of hydrogen.

Despite the fact that both scenarios TG2D and TG2D_CB simulated a decarbonisation of the energy system that ensure an average global temperature rise below 2°C, the shipping emissions and the associated share have different trajectories. Figure 6.11

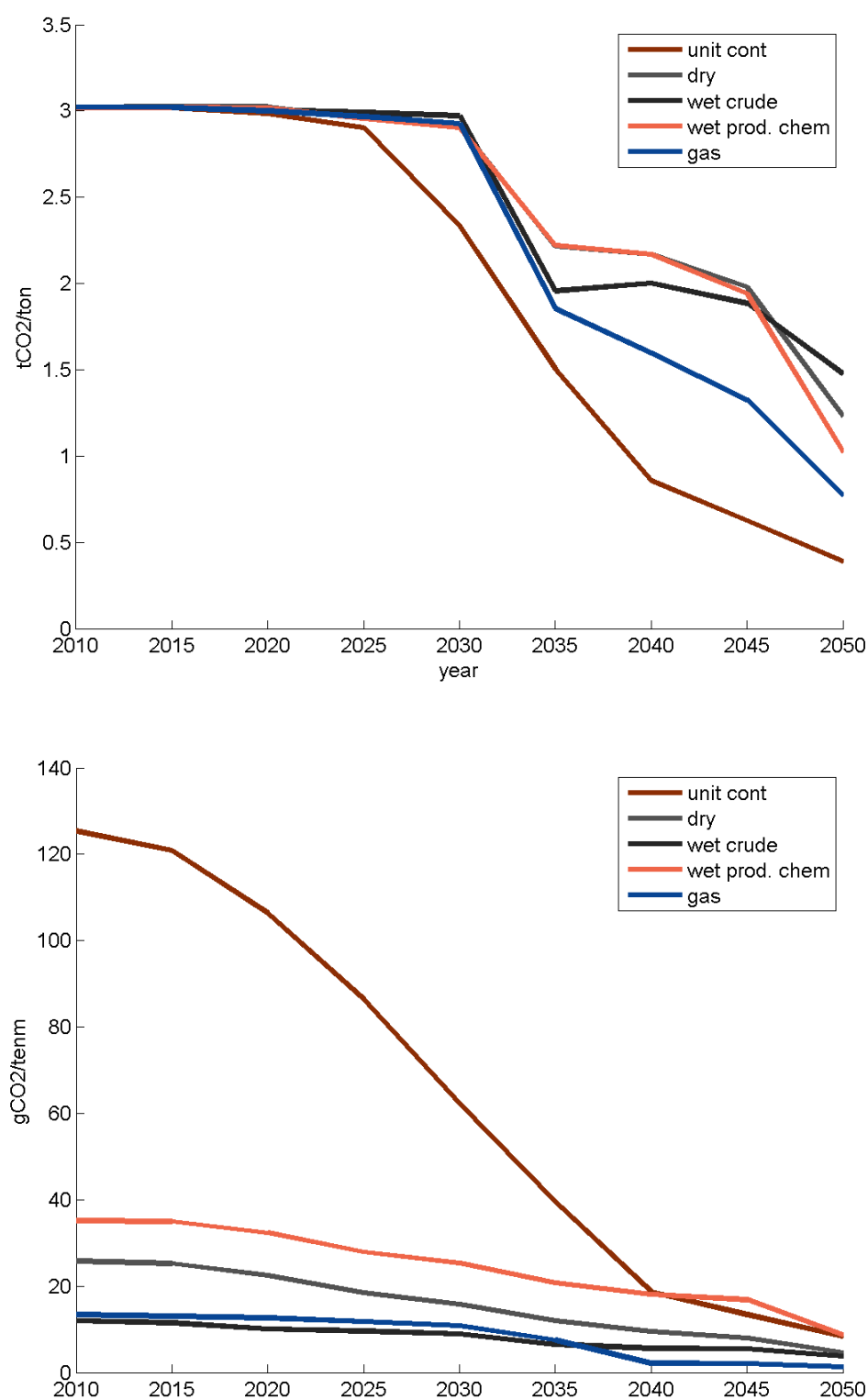


FIGURE 6.10: Average carbon factor by ship type (top), EEOI by ship type (bottom)

displays the shipping CO_2 emissions and annual shares on the global CO_2 for TG2D and TG2D_CB scenarios. In TG2D, the global CO_2 emissions declined over time, while

the contribution of shipping emissions increased reaching 5.2% of the total in 2050. The shipping CO_2 emissions increased from approximately 450 million tonnes in the base year 2010 to approximately 1000 million tonnes. In TG2D_CB the contribution of shipping emissions increased similar to the one in TG2D until 2025. Afterwards the CO_2 emissions started to decrease reaching 2% of the total in 2050.

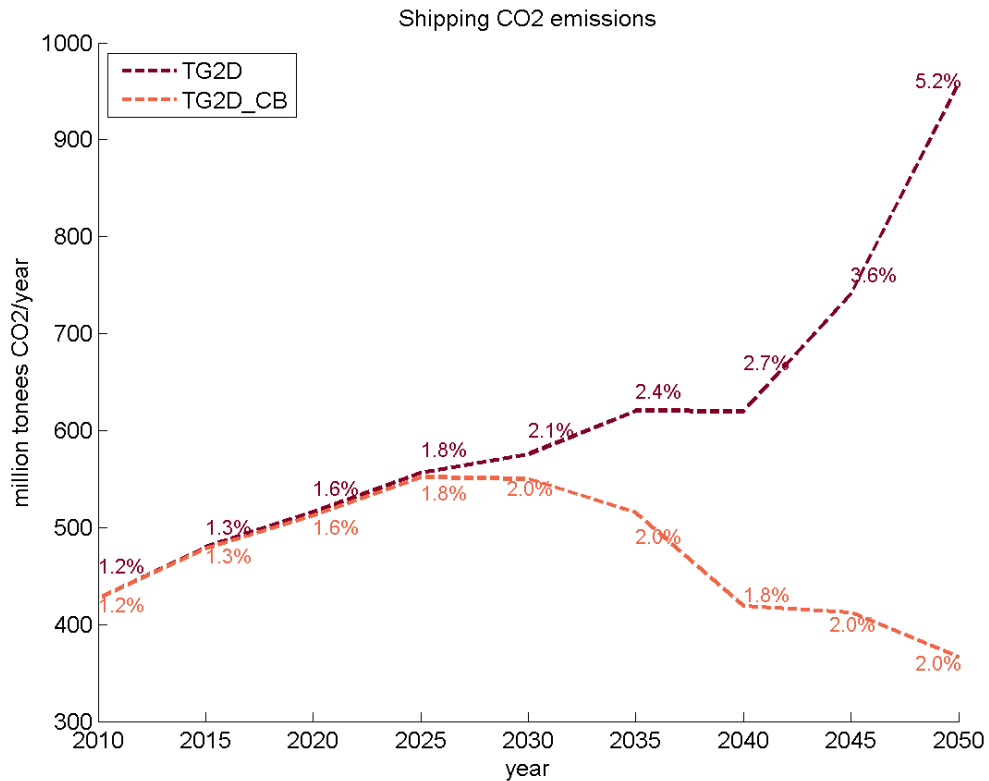


FIGURE 6.11: Shipping CO_2 emissions and annual shares of the total CO_2 for TG2D and TG2D_CB scenarios

Figure 6.12 shows the shipping operational CO_2 emissions by fuel type.

The trajectory of the shipping emissions share in the scenario with a carbon budget in shipping is associated with the decarbonisation of the rest of the energy system. It is possible to link the response of the shipping system with the responses of the other main economic sectors in order to analyse the emission implications of using hydrogen in shipping within the context of a decarbonised energy system.

Under the assumption that the global energy system acts as a single entity to mitigate emissions, carbon credits flow to the sector with the lowest mitigation costs first. So the sectors in which mitigation measures can be applied in the most cost-effectively manner will decarbonise first. Figure 6.13 on the top shows the annual CO_2 emissions by sector.

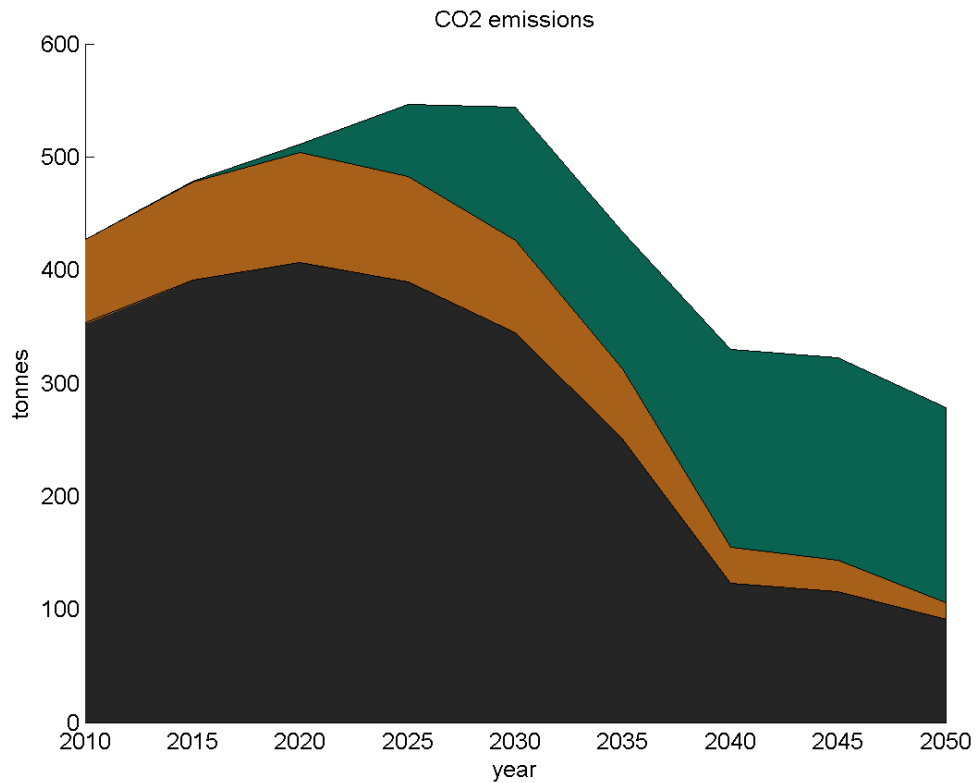


FIGURE 6.12: Shipping operational CO_2 emissions by fuel type in TG2D-CB scenario

From 2010 to 2035 the electricity power sector is responsible for the majority of decarbonisation, reducing its share from 31% to 7%. The electricity sector would be affected by a significant change switching to clean technologies such as renewables. The carbon intensity reduction of this sector is seen as the least cost option during the first 25 years of the examined period which should ensure an optimum use of primary energy sources in order to meet the 2C-temperature rise target.

From 2035 to 2050 the CO_2 sequestration technologies become of significant importance. The access to CO_2 emissions sequestration technologies and to “clean” electricity contributes to the global decarbonisation. During this period the transport sector (excluding shipping) also decarbonises thanks to the availability of clean electricity, reducing its share from 30% to 28%. Sectors such as industry also contributes to the decarbonisation.

Focusing on the transport sector, figure 6.13 on the bottom shows the annual CO_2 emissions for all transport modes indexed to their value in 2010. With respect to the value in 2010, the shipping emissions trajectory shows a similar trend in comparison with the decarbonisation trajectory of car category. However, truck (HGV, LGV) and

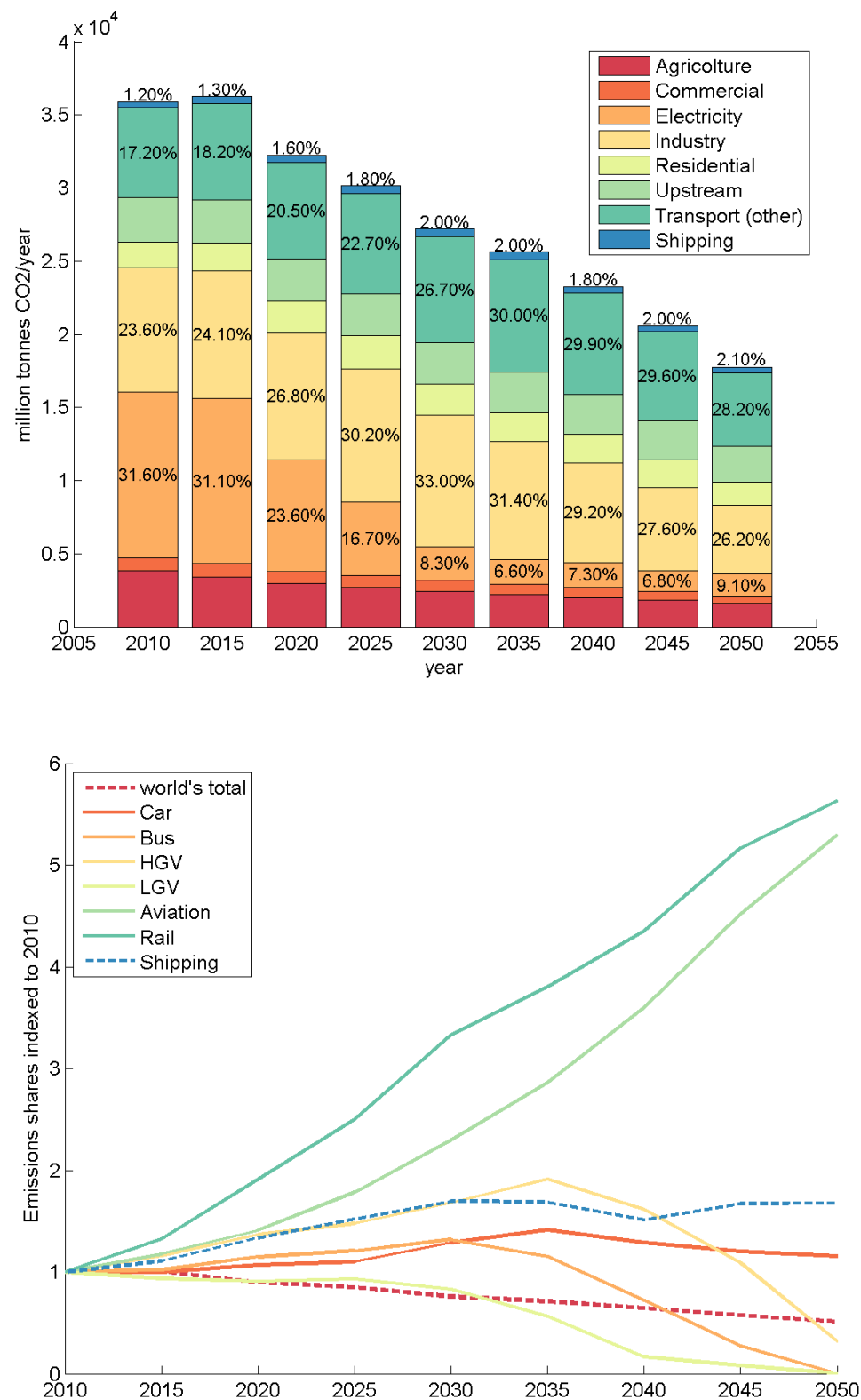


FIGURE 6.13: Emissions by sectors in TG2D_CB scenario(top). Annual CO₂ emissions for all transport modes indexed to their value in 2010 (bottom)

bus categories drastically reduce their emissions from 2030/2035. Bus and LGV reduce their emissions to almost zero. All together, they are responsible for the decarbonisation of the transport sector during this period. In comparison with the global decarbonisation trajectory the latter categories start to decarbonise later than other sectors (e.g. electricity).

Aviation and rail emissions increase over the period 2010 to 2050. These sectors are difficult to decarbonise from the point they are in 2010. While rail does not account for a significant share of the emissions emitted by the transport sector, aviation does. It is expected that the two sectors will offset CO_2 emissions over the period 2010 to 2050.

Within the transport sector, the car, truck and bus mode categories would start to adopt clean technologies from 2035. As an example, figure 6.14 presents the fuel share mix in car, bus and truck transport modes categories. Car appears to switch gradually to electric based vehicle, while bus switches to fuel cells vehicles with hydrogen. In category bus, for example, hydrogen takes up from 2035 and until 2050 its share reaches almost 100% in this category as shown in figure 6.14. In category truck instead a significant share of hydrogen starts in 2040 and increases to about 50% in 2050, while for the category car hydrogen share is quite low being constant around 3% over the period 2040 to 2050. Hydrogen in large vehicles like the categories truck and bus could be favoured as for those categories battery electric vehicles may be unsuitable.

The decarbonisation of the other sectors made available offsets of CO_2 . This means that during the first period 2010 to 2030 shipping would be in competition for CO_2 offsetting. The main competitor in the transport sector would be aviation. However, the purchasing of CO_2 offsets would not be sufficient to meet the target trajectory meaning shipping emission share would therefore increase in that period (see figure 6.13).

Under the assumptions that the purchasing of emissions credits outside of the shipping industry is limited to a certain share, some in-sector decarbonisation would be required. Shipping carbon price would have to be higher than the global carbon prices, to make it reasonable to purchase offsets and to enable the uptake of emissions reduction measures. As consequence, the increasing carbon price adjusts the cost-benefit evaluation and hydrogen can become economically viable from 2030. Switching to hydrogen would reduce the operational shipping emissions and the associated shipping emissions share during the period 2030 to 2050 (see figure 6.13).

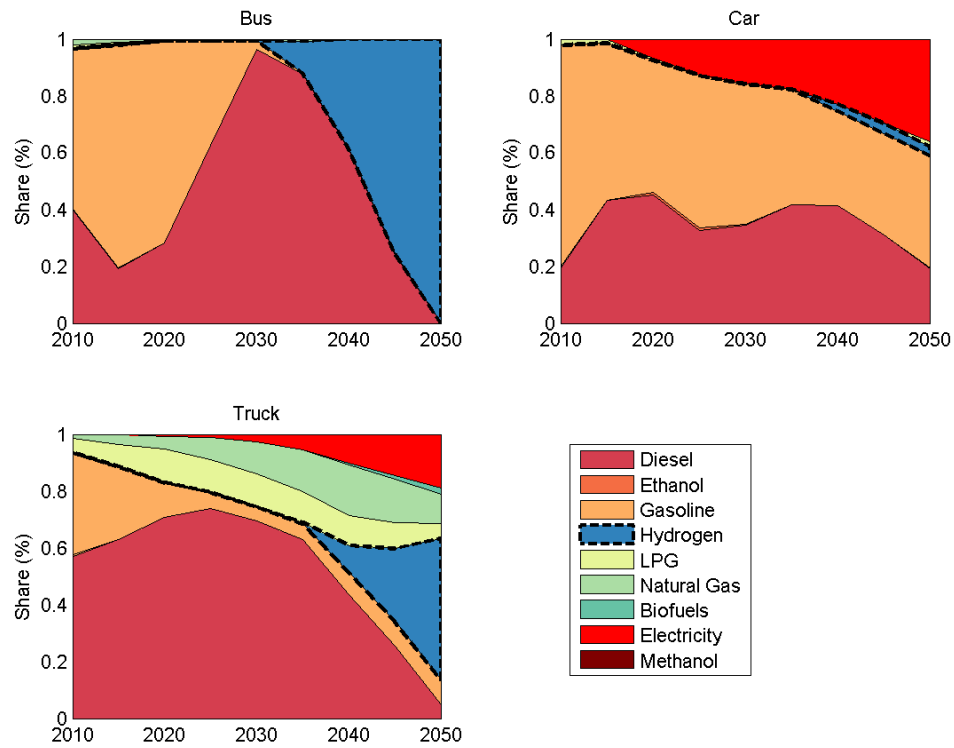


FIGURE 6.14: Hydrogen share by mode in TG2D_CB scenario

6.3.3 Hydrogen supply and consumption in the decarbonised energy system

The use of hydrogen in shipping affects the supply and consumption of hydrogen in the decarbonised energy system.

The supply of hydrogen includes the production, the transportation and distribution. Figure 6.15 on the top shows the breakdown of hydrogen production. Hydrogen was produced mainly with SMR with CCS and biomass gasification with CCS production plants. Such production technologies covered almost the entire production (up to 80%), while the rest was produced from SMR without CCS and coal gasification with CCS production plants. In this scenario the production in absolute value reaches about 38000 PJ in 2050.

Hydrogen was produced in large centralised plants, and it was transported in pipeline and distributed in gaseous form for industry, mix with gas and upstream, and at refuelling stations for bus, car and trucks. A certain amount of hydrogen was liquefied in large plants close to the production site, and transported over long distance with trucks.

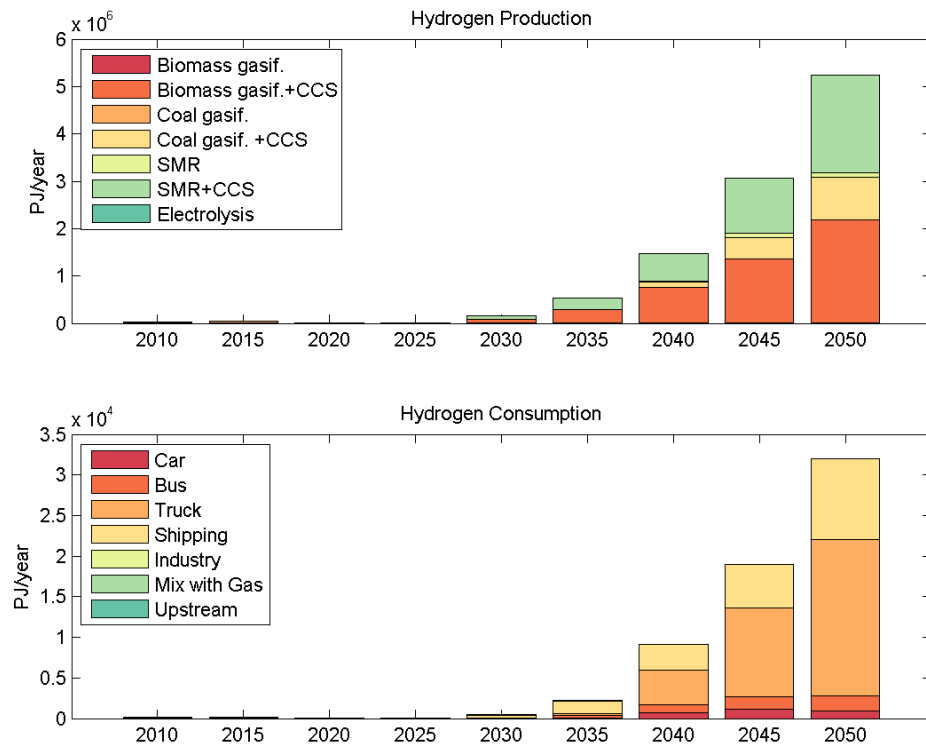


FIGURE 6.15: Hydrogen production and consumption in TG2D_CB scenario

Afterwards the liquid hydrogen was distributed to refuelling station at port terminals to meet the shipping demand.

The described supply refers to a global aggregated level. The actual configuration in specific port would depend from many local factors. The analysis of the best hydrogen supply at ports level is out of the scope of this thesis.

The most attractive use of hydrogen within the context of a decarbonised energy system would be mainly as fuel for the transport sector. The bottom graph in figure 6.15 shows the breakdown of hydrogen consumption. Hydrogen started to be used in shipping from 2030 representing approximately 70% of the total consumption. From 2040 hydrogen consumption for truck rapidly increased and overcame the shipping consumption. In 2050 hydrogen in shipping represented 30% of the total consumption.

The use of hydrogen for shipping contributed, therefore, for a significant part of the total consumption. The supply associated with the hydrogen been used in shipping had also emissions implications. In this thesis upstream emission are defined as all emissions of industrial activities from the point of resource extraction to the point of distribution of a fuel. The model does not allow a clear separation of the upstream emissions for

each end user technologies. An attempt of associating the upstream emissions per each marine fuel was undertaken by allocating emissions of each process proportionally to the energy use of each technology. This first attempt provided an estimate of the upstream emissions by marine fuel type and the upstream emissions associated with the use of hydrogen in other sector as shown in figure 6.16.

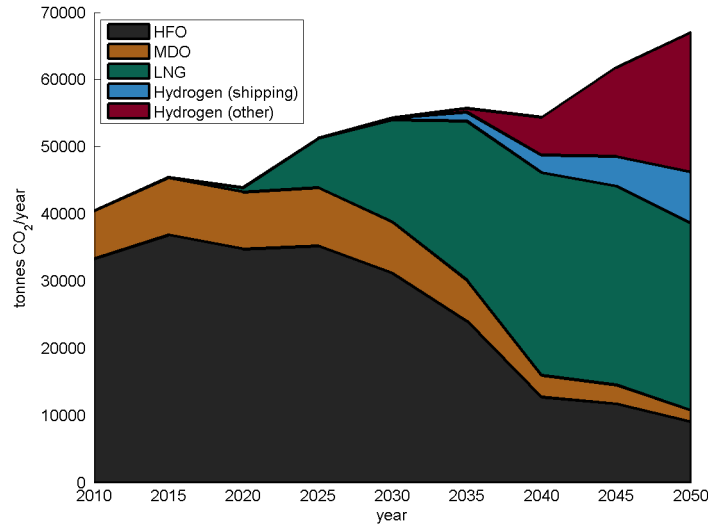


FIGURE 6.16: Hydrogen and other marine fuels upstream CO_2 emissions in TG2D_CB scenario

While at base year the emissions are dominantly associated with HFO, in 2050 the upstream emissions for the use of LNG in shipping accounts for the majority of the share. Instead, the upstream emissions associated with hydrogen in shipping are relatively low. Also the contribution of the emissions associated with the use of hydrogen in other sectors appears to be relatively small. A possible interpretation would be that the emissions of hydrogen production with fossil fuels such as natural gas and coal was reduced by the use of CCS technology.

It is important to highlight that in this thesis upstream CO_2 emissions are only estimated and they are not considered in the objective function of the shipping model. In other word, it is assumed that the shipowner will take his decision only by considering operational CO_2 emissions. On the other hand, the energy model estimates the upstream CO_2e emissions for all hydrogen production and they are passed to the climate module, which makes sure that the global mix of technologies is in line with the climate target.

6.4 Economic implications

This section focuses on the main economic implications of using hydrogen to fuel international shipping. This will provide an answer to the second part of the second research question of this thesis. The main economic implications that will be discussed are hydrogen price, profitability of hydrogen powered ship and the revenue deployment associated with the carbon pricing.

6.4.1 Hydrogen price

One of the main economic implication is the hydrogen price. Such a price is derived endogenously from the estimated costs of production and the estimated hydrogen demand. The cost of producing hydrogen can vary among regions, therefore there are some differences in price among different regions. Similarly, hydrogen demand is different among regions and this depends on the assumptions used to estimate regional shares (see section 4.11). Figure 6.17 on the top shows hydrogen regional prices for shipping.

Hydrogen price for shipping would be different from the price of hydrogen for other sectors. Figure 6.17 on the bottom shows a comparison among hydrogen prices in different sectors. The model provides a price when the fuel is actually used in a sector, this is why hydrogen price in shipping appears in 2030. the cheapest hydrogen was observed for car category. The difference between the price for car and for ships is almost consistent over the period. Hydrogen price for car resulted to be approximately 50-60% lower than the price for ships. The price of hydrogen for shipping would be the most expensive due to the extra costs assumed with the delivery and bunkering of hydrogen at ports.

The trends of hydrogen price among sectors are very similar during the period 2030 to 2050. It decreased until 2035 and increased rapidly afterwards. The increasing price is due to the fact that hydrogen was produced mainly from biomass and natural gas which became more expensive over time under this 2 degree scenario. Both commodities were found more expensive while the ratio of biomass and natural gas used in production did not change significantly.

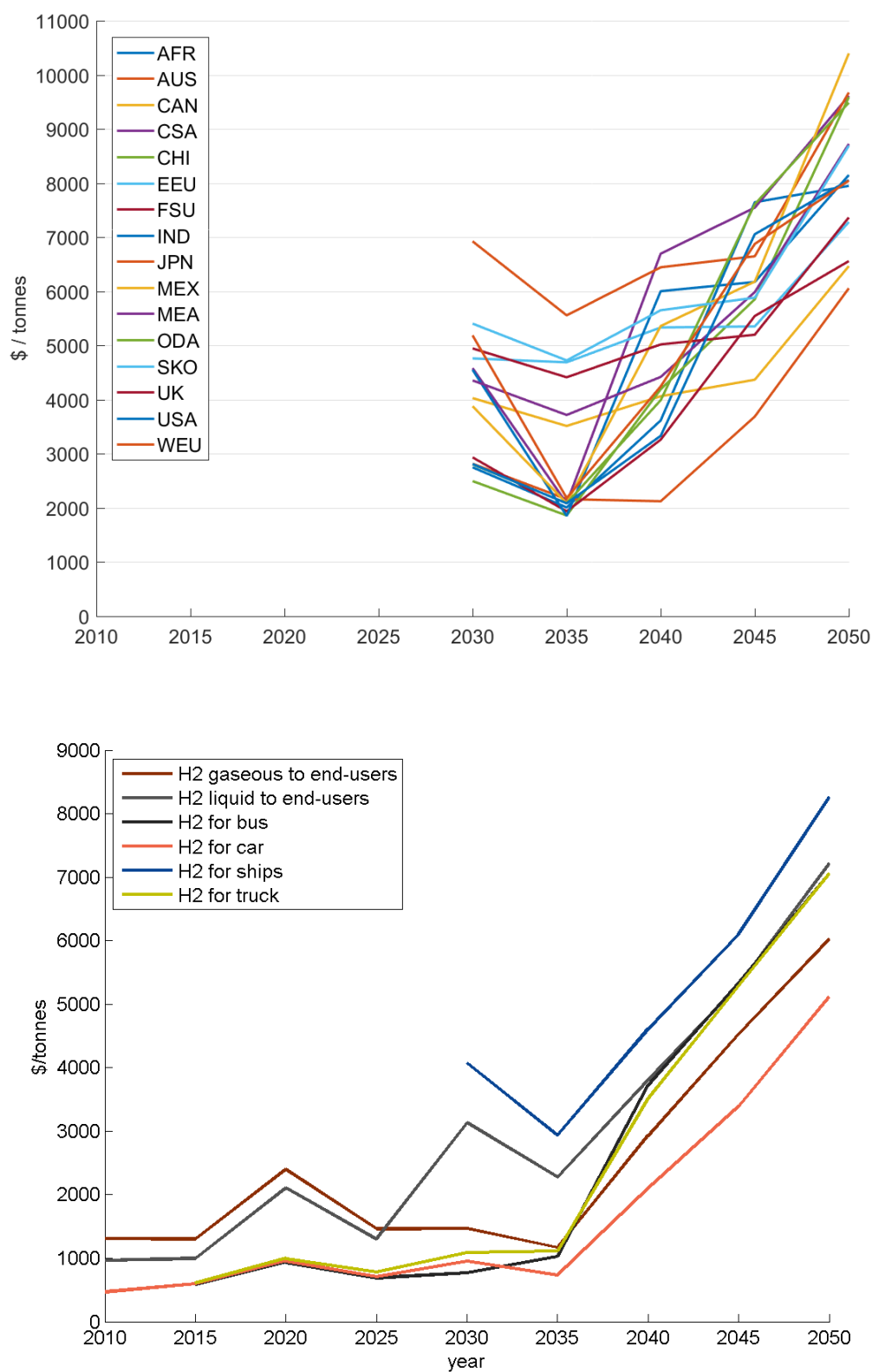


FIGURE 6.17: Weighted average and regional hydrogen price (top). Hydrogen price by sector (bottom)

6.4.2 Profitability of hydrogen ships

Another economic implication is the effect on the profitability of ships by type and size categories. Based on the model's output ships powered with hydrogen and fuel cells would become more profitable in most of the cases during the time. For example, figure 6.18 displays the profits indexed to the values in 2010 of container ship type for the smallest size category (size 1) and for a large size (size 4). Only the key fuel/machinery options are plotted as they are considered to be indicative for each fuel type option. The estimated profits are different from the competitiveness factor explained in section 6.2.2 as in this case ship's technology and operational specification changes are included in the calculations.

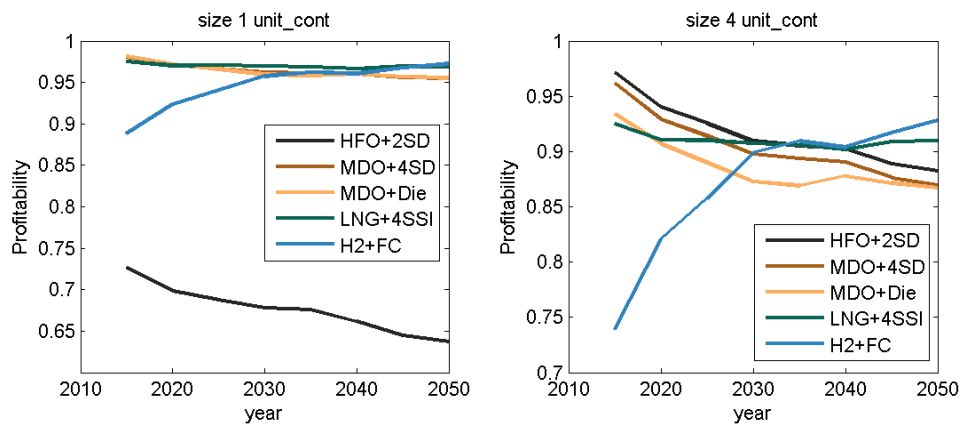


FIGURE 6.18: Profitability of fuel/machinery options

The results showed that the profitability of machinery options that use HFO in small containers (size 1) were lower than the other options. Over time hydrogen became more competitive and it appeared to be one of the most profitable from 2040 in close competition with LNG's option.

Instead, the profitability among fuel/machinery options of the large size category is very different. For the machinery options that use MDO and HFO the profits decreased over time, while for the options with LNG and hydrogen it showed a tendency to increase. From 2010 to 2030 hydrogen with fuel cells increased rapidly overtaking the other main fuel/machinery options. During the period 2045 to 2050 LNG's options started to decrease slightly while hydrogen with fuel cells option was more profitable over time.

6.4.3 Revenue deployment

Another economic implication regards the deployment of the carbon pricing's revenue. As discussed previously the uptake of hydrogen is observed because the introduction of a high carbon price. The cost-benefit is adjusted so that emissions reduction measures such as the switching to hydrogen becomes economically viable. The increasing shipping carbon price generates high budgets for the MBM mechanism. Such a mechanism assumes that the revenue generate from a carbon pricing are deployed on rebate mechanism (40%), on Green Climate Fund (10%), on in sector investments, and on out sector purchase of CO_2 offsets. Figure 6.19 shows the global and shipping carbon pricing as well as how the revenue from this pricing is deployed.

The estimated budget for CO_2 offsets appears to be not sufficient to ensure that the shipping emissions match with the target trajectory. The shipping carbon price goes up rapidly over time to enable the uptake of emissions reduction measures. The portion of the budget for in-sector reinvestment is assumed to be used for infrastructure and supply chains to enable the fuel to be supplied at ports prices and for grandfathering of vessel investigation. However, the reinvestment portion is essentially treated as external and not affecting of any system responses. The necessary decarbonisation is achieved as the carbon price "forces" the sector to use hydrogen to decarbonise, however costs on the sector would be high due to a high shipping carbon price.

6.5 Testing the viability of hydrogen's potential in shipping

This section examines the viability of hydrogen in shipping by performing a robustness analysis of the results of the scenario TG2D_CB. In addition, the findings of sensitivities cases are examined to provide further insight on the potential of hydrogen to fuel international shipping.

One conclusion from the scenario with a carbon budget in shipping is: if the dynamics of supply and demand of hydrogen in shipping are similar to the ones in the model TIAM-GloTraM, then there are circumstances in which the shipping industry could be keen to invest in hydrogen powered ships based on the maximization of the shipowner's profit,

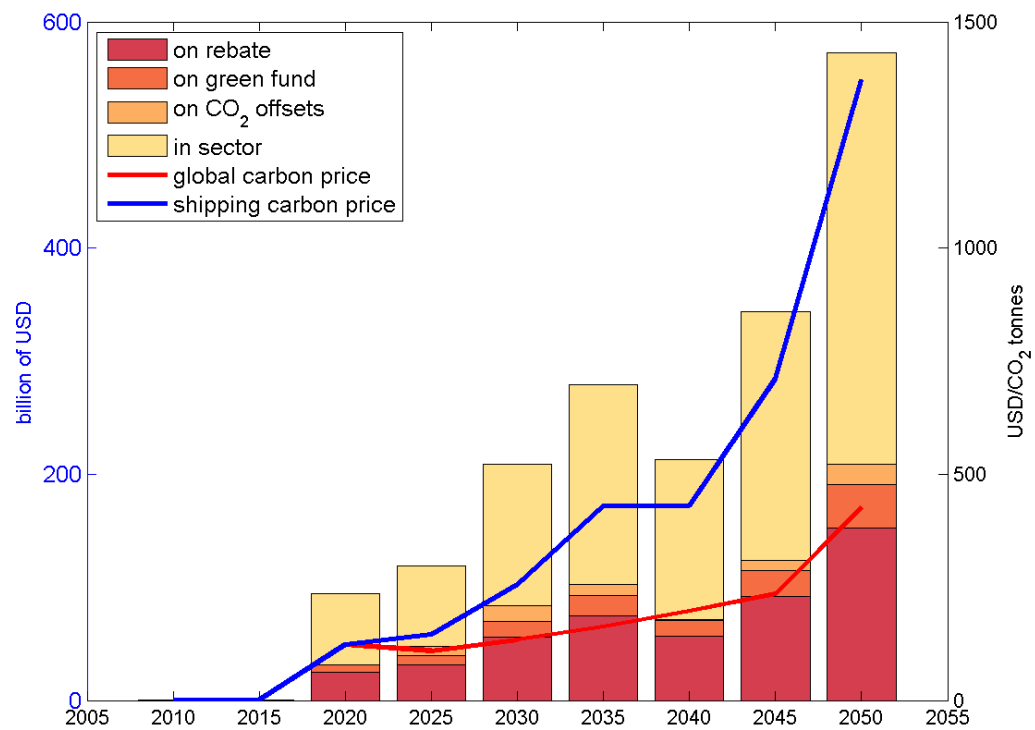


FIGURE 6.19: Carbon pricing and revenue deployment

and compliance of a defined carbon budget. If so, how uncertain is this result and what are the factors mostly responsible for the uncertainty?

This type of question sits in line with the definition of a sensitivity analysis according with [Saltelli and Annoni \(2010\)](#). The sensitivity analysis can *"explore how the impacts of the options you are analysing would change in response to variations in key parameters and how they interact"*. In other words, it quantifies the output variability and describes the relative importance of each input in determining this variability [Campolongo et. al. \(2011\)](#).

According with [Song et. al. \(2013\)](#), there are a wide range of sensitivity analyses (SA) methods; two broad categories are local SA and global SA. An example included in the first category is the local one-at-a-time (OAT) sensitivity which explores the sensitivity of a model output to a given input factor. This method should be used only if all factors in a model produce linear output responses. On the other hand, in a global SA the entire parameter space of the model is explored simultaneously for all input factors. Different techniques have been developed for the global SA and the advantage of using them is that they provide not only information about the effect of a factor but also regarding

the interaction among the factors.

The development of complex computer simulation models such as TIAM-GloTraM involve numerous choices and simplifications. Sources of uncertainty can be for example the parameter input variability, model algorithms and structure, and the model calibration. In addition, TIAM-GLoTraM calculates several outputs depending on a very large number of input parameters. Often the output responses are not linear and moreover each simulation requires significant computational time. As recognized also in [Campo-longo et.al. \(2011\)](#), for such complicated type of model the estimation of quantitative sensitivity measures could be infeasible. Since the uncertainty and sensitivity analysis are not in the scope of this thesis, a possible sensitivity analysis is left to further work. Instead the focus is on a *robustness analysis* as defined in [Weisberg \(2012\)](#).

The objective of this type of analysis is to determine which aspects of the model make trustworthy predictions or can reliably be use in explanations. The purpose is to understand the relationship between a given uncertain input factor and the model outputs. The interest is not on the quantification of the uncertainty and so on the relative importance of each input factor, but rather on the robustness of the inference by testing if the model is excessively depended on fragile assumptions. Since there are a large number of assumptions the main focus in this analysis is only on assumptions associated to hydrogen related technologies that have been introduced in this thesis.

Generally the steps of the robustness analysis are: first step, the examinations of a group of similar but distinct models looking for a robust behaviour. Second step, the finding of the core structure that gives the robust property. Third step, the investigation of the limits of the robustness ([Weisberg, 2012](#)). In this analysis of the results only the third step is applied, as it is assumed that the robust behaviour is that hydrogen is up taken as a future fuel for specific ship type in a scenario with a carbon budget. The objective is to investigate the limits of such theorem.

It is important to distinguish between finding a robust theorem and confirming a theorem. According with [Weisberg \(2012\)](#), the robustness analysis cannot confirm on robust theorem as it is based on the manipulation of the model and it is not based on empirical data from observations and experiments, that are, the only ones that can provide a confirmation. However it identifies hypotheses whose confirmation derives from the confirmation of the framework used. In addition, it can help to discover situations in which the robust theorem can be defeated [Weisberg \(2012\)](#).

6.5.1 Analysis of the input assumptions

The investigation of the limits of a robust theorem can be performed with three different types of analysis as defined in [Weisberg \(2012\)](#): parameter, structural and representational. The parameter robustness analysis examines what changes when the value of a parameter is varied. The structural analysis examines what happens if new mechanistic features are added or excluded to the model. The representational analysis examines what happens if features of the model have new representational framework.

The parameters analysis tests if changes to a parameter of the model changes the behaviour of the model. There are a larger number of parameters that can be of relevant importance on the uptake of hydrogen. For example, all the parameters associated with the supply of hydrogen (e.g. costs and emissions factors of each production plant, transportation and distribution options) could influence the mix of technologies selected and therefore also the price of hydrogen. Other parameters that are not associated to hydrogen related technologies could also be of importance for the uptake of hydrogen. For example, the time of period of the NPV, or the economic parameters that simulate how revenue is passed between the shipowners and operators could influence the selection of the most profitable options and therefore the uptake of hydrogen.

In this analysis only a limited number of parameters were chosen in order to have a manageable number of scenarios. The parameters chosen are identified as the ones that are deemed to have greatest significance on the uptake of hydrogen. They are: investment cost of hydrogen production plants from biomass, volumetric density of hydrogen storage system, hydrogen storage system and fuel cell investment costs, fuel cell efficiency, carbon budget. Table [6.2](#) provides the list of the selected parameters, the value used in IT2D-CB, and the new value used in parameters analysis.

A common and normally adequate approach on how to choose new values of a parameter is to specify values within equal sized intervals and select a level for each parameter that encompass the range of possible outcomes for that variable, or at least the "reasonably likely" range [Pannell \(1997\)](#). A possible approach is to select the maximum and minimum levels, however it is a subjective choice of the modeller to define what constitutes "reasonably likely" range [Pannell \(1997\)](#).

In this thesis the parameter space was sampled in reasonable values and speculations were made on both extremes of the space. As the scope is to test how robust is the

inference of the uptake of hydrogen in TG2D_CB scenario, only values that would likely test such inference were explored. For instance, only more expensive hydrogen storage technologies are tested as cheaper technologies are likely to have a positive effect on the uptake of hydrogen in shipping. In addition, as the space of reasonable values increase, it can become computationally expensive to explore on a relatively high number of values, therefore for each parameter only the values in table were explored which are considered a justifiable limit.

TABLE 6.2: Parameter robustness analysis (PRA)

Parameter	Unit	Value used in TG2D_CB	Value used for PRA
Large biomass gasification	$US\$2010/GJ/yr$	42.9	115.5
Large biomass gasification+CCS	$US\$2010/GJ/yr$	45.32	122
Medium biomass gasification	$US\$2010/GJ/yr$	47.85	174.9
Decentralised biomass gasification	$US\$2010/GJ/yr$	140.8	220
Vol. density H2 storage	$Kg(f)/m^3(s)$	38	27
H2 storage cost on board	$$/Kg$	71	333
FC cost	$$/KW$	830	1670
FC efficiency	%	55 %	65%
Carbon budget	Gt	19	28

The first parameter is the investment cost of hydrogen production plants from biomass. Since it was observed that hydrogen is significantly produced from biomass, there is an interest to test if hydrogen is still a valuable option if the cost of producing it with biomass increases, and what type of change we can observe. This parameter is subjective to a discount rate over the period studied; the table above provides only the value estimated at base year 2010 and are derived from the value in the UKTM-UCL model.

The volumetric density of hydrogen storage system on board ships is the second parameter; its value is highly uncertain, in addition in this thesis the power density of fuel cell has not been taken into account so it makes sense to explore a situation in which more space is required on board. A lower value based on the volumetric density of gaseous hydrogen storage system can explore the potential changes on the loss of cargo capacity when adopting hydrogen and fuel cells technologies on board.

Both hydrogen storage system and fuel cell investment costs are based on the values in [Dodds and McDowall \(2012\)](#). Such values are relative low compared to others found in the literature, therefore there is an interest in exploring higher costs associated to these technologies. The values used in PRA are based on a number of sources as reported in figure 4.5.

Finally, fuel cell efficiency can be improved with the recovering of the heat; a better efficiency could be favourable for fuel cells in combination with LNG rather than in combination with hydrogen. So, there is uncertainty regarding the effect of a higher fuel cells efficiency on the uptake of hydrogen in shipping. It is reasonable, therefore, to explore higher value then the one used in TG2D_CB. The value used in PRA is based on the range proposed in [Ludvigsen and Ovrum \(2012\)](#).

A final important parameter is the carbon budget. In TG2D_CB scenario it is set to 19 Gt for the fleet analysed in this thesis. It corresponds to 55% of the total carbon budget (34 Gt), which may ensure the shipping sector to account for about 2.3% of the global CO_2 emissions. There is, however, the potential for shipping being allowed a greater share of emissions because of the sensitivity of developing country impacts of shipping CO_2 mitigation. It is difficult to define on how greater could be the share of emissions and such estimation is considered out of the scope of in this thesis. However, in order to explore the potential for shipping being allowed a greater share, a value of 3% of share has been considered appropriate. Taking into account only the fleet being analysed (which is assumed to account for the 55% of the emissions), the carbon budget to be used in this analysis of the results is 28 Gt.

Other parameters associated with hydrogen exist in the model and together with these there may be other parameters that can change the behaviour of the model such as the ones associated with the economic assumptions in GloTraM or with the biomass availability in TIAM-UCL. Due to the scope of this analysis these further explorations are left to future effort.

Differing from the parameter analysis is the structural robustness analysis which examines what happens if a new mechanistic features is added to or excluded from the model. This can be seen as the setting of a new scenario where a new set of technologies or regulations are introduced. There are many cases that could be explored however in this analysis the focus is only on one new feature: the exclusion of land-based carbon capture storage technologies (CCS). The CCS technology is crucial in meeting

the emissions target and several energy models have demonstrated the significant impact that such technologies could have [Anandarajah et. al. \(2013\)](#). Since in TIAM-GloTraM hydrogen can be produced in large plants with or without CCS there is an interest in understanding what type of changes would be seen if this technology is excluded.

Another example of structural analysis in TIAM-GLoTraM is the addition of biofuels in shipping. This would be an interesting test as a significant share of hydrogen is produced with biomass, so it would be important to understand if biofuels could take over hydrogen uptake in shipping. This is left to future effort due to the reasons explained in section 4.7.

Final type of robustness analysis is the representational analysis. It examines what would change if a features of the model has a new representational framework. An example is the assumption used for the representation of where ships trading between each couple origin and destination regions would refuel, see section 4.11. It can be interesting to explore what would change if instead of using fixed shares of fuel sales per region a different representation will be used. This type of modification requires further modelling effort that are not considered strictly related to the scope of this thesis, therefore such type of representational analysis is left to future work.

Summing up, this section has provided the objective of this analysis of the results which is the investigation of the relationship between given uncertain input factors and the model output. The analysis is carried out by a parameter and structural robustness analysis. Table 6.3 provides a summary of the simulations that were used for such analysis. Next sections provide the results and a comparison of the results obtained from these simulations.

TABLE 6.3: Simulations for the parameter and structural robustness analysis

Name	type	Factor
TG2D_Fc	parameter	FC cost
TG2D_Ff	parameter	FC efficiency
TG2D_IT	parameter	Carbon budget
TG2D_Sc	parameter	H2 storage cost on board
TG2D_Vl	parameter	Vol. density H2 storage
TG2D_BioC	parameter	Investment cost of hydrogen production plants from biomass
TG2D_nCCS	structural	CCS technology

6.5.2 The robustness of hydrogen's potential in shipping

The most important output of the robustness analysis is that in all "sensitivity" cases the modelling framework selected hydrogen among other options. Hydrogen is present despite the fact that the robustness analysis explored on variations of the input factors that could have discouraged the use of hydrogen in shipping. This confirms that in a decarbonisation system, hydrogen has the potential to be used in international shipping. The constrain of a carbon budget forces the shipping system to decarbonise and the model always finds hydrogen as part of the solution for the decarbonisation. The cumulative amount of fuels used by scenario during the period 2010 to 2050 is shown in figure 6.20.

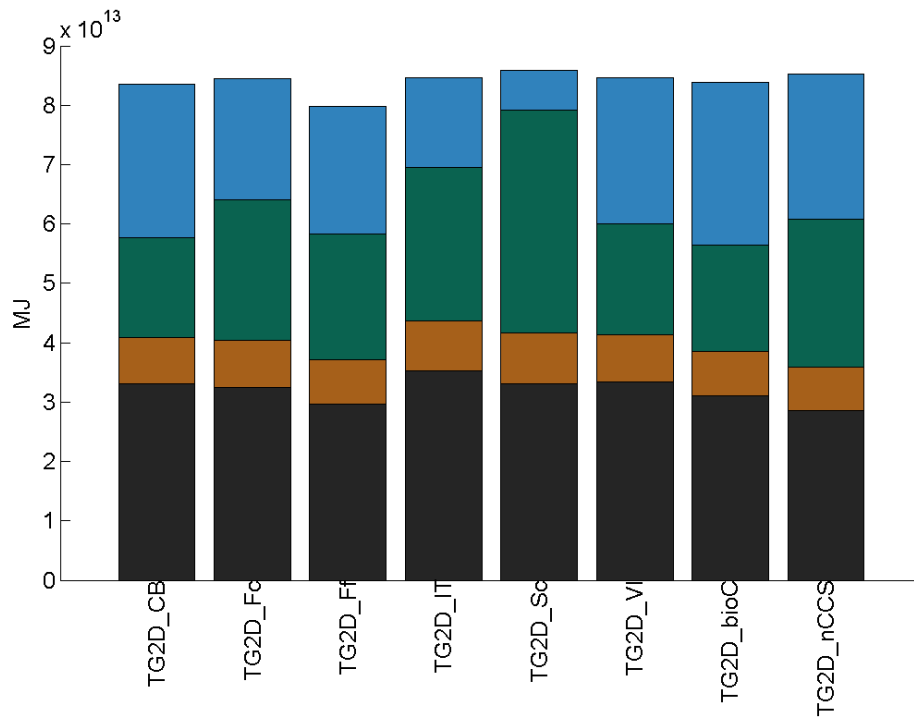


FIGURE 6.20: Fuel mix in shipping by scenario over the period 2010 to 2050

In relative terms the majority of the sensitivity cases used hydrogen for approximately 30% for their cumulative energy demand. In the scenario with high cost of fuel cells system (TG2D_Ff), hydrogen represents the 27% of the energy demand, while in the scenario with high costs of hydrogen production plants from biomass (TG2D_bioC) it represents the 33%. Within this range are the scenarios TG2D_Vl, TG2D_Ff and

TG2D_nCCS which are respectively the scenarios with high volumetric density, with high fuel cell efficiency and with no availability of CCS.

The remaining scenarios have significant differences in comparison with the reference scenario TG2D_CB. High cost of fuel cells and hydrogen storage systems would have a visible impact on the uptake of hydrogen. The scenario with high cost of storage system TG2D_Sc, for example, presented the lowest amount of hydrogen used in shipping among all scenarios representing about 8% of the cumulative energy demand. The scenario TG2D_IT which has a higher carbon budget, also includes hydrogen in its fuel mix (about 24% of the total energy demand), although, as expected the uptake of hydrogen is lower than the one in the reference scenario TG2D_CB .

Small differences among scenarios can be observed also in absolute terms. For example, the high efficiency of fuel cells in (TG2D_Ff) is the reason why the energy required by the shipping system is lower in comparison with the other scenarios.

6.5.3 Analysis of the sensitivity scenarios

The analysis of the sensitivity scenarios can highlight the differences of the key environmental and economic implications and their relationship with the given set of uncertain input factors by scenario. For example, variations of the input factors can affect the shipping emissions and the associated emissions share. The combinations of these effects would have an impact on the dynamics between the energy and the shipping systems and ultimately on the uptake of hydrogen in shipping. In view of this, the following sections examine in more detail three main topics by scenario: the decarbonisation pathways, the hydrogen supply and the key economic implications.

6.5.3.1 The sensitivity of the decarbonisation pathway

The decarbonisation pathways of the shipping sector by scenario are very similar to each other in the majority of the robustness scenarios. The combined effects of both trajectories, operational emissions and offsets of emissions, ensures the meeting of the defined target trajectory and therefore of the carbon budget. Figure 6.21 shows on the top the decarbonisation trajectories (operational CO_2 emissions) and on the bottom the offsets of CO_2 emissions purchased by year for each scenarios. If the shipping emissions are high as in the case of scenarios TG2D_Sc and TG2D_IT, then the shipping industry

would buy high level of CO_2 offsets in order to meet the carbon budget. The trends are also correlated; when the system drastically reduces its emissions, for example, during the period 2030 to 2040 in scenarios TG2D_Ff, TG2D_Vl and TG2D_CB, then the offsets of CO_2 decreases proportionally. In general it can be observed that the only scenario in which the shipping emissions are consistently below the reference scenario is TG2D_bioC, while TG2D_nCCS and TG2D_Ff present periods in which are below and period in which are above the trajectory of TG2D_CB scenario. The emissions trajectories of the remaining scenarios are consistently above the one of TG2D_CB scenario.

The emissions trajectory is correlated to the trend of the fuel mix. The fuel mix for each scenario is displayed in figure 6.22. As expected, the greater use of hydrogen, the lower the operational emissions and vice versa. For example, in scenarios TG2D_IT and TG2D_Sc do not present a significant drop in shipping emissions, as the amount of hydrogen used was relatively low and instead a consistent uptake of LNG was observed. In the scenario with high cost of fuel cells (TG2D_Fc), instead, the adoption of hydrogen started in 2035 (five years later than in the reference scenario) with a relatively low amount; in view of this, considerable high operational emissions can be observed in that year.

The changes made to the input factor's values as defined in the robustness analysis have also had an effect in terms of shipping emissions as share of total world CO_2 emissions. Figure 6.23 shows the trends of such shares for each scenario. Clearly, in scenarios TG2D_IT and TG2D_Sc the share increases over time meaning that the rest of the energy system is decarbonising faster than the shipping industry. The latter relied to a greater level on offsetting in order to comply with the carbon budget constraint. In scenario TG2D_Fc, the delayed adoption of hydrogen makes the shipping's share reaches a peak in 2035 rather than 2030 as in the reference scenario.

In the scenario TG2D_nCCS the shipping's share is higher than the reference scenario TG2D_CB. One can expect that the share in TG2D_nCCS would be lower because the significant uptake of LNG and hydrogen, and the phasing out of HFO and MDO. In fact, the emissions share in this scenario can be associated to the different global emissions decarbonisation trend. Other sectors of the energy system adopted cleaner technologies without CCS technologies earlier so that the global emissions declined at a higher degree until 2020, and at a lower degree after 2020. In view of this the global emissions during the period 2040 to 2050 are higher in absolute terms in TG2D_nCCS scenario than in

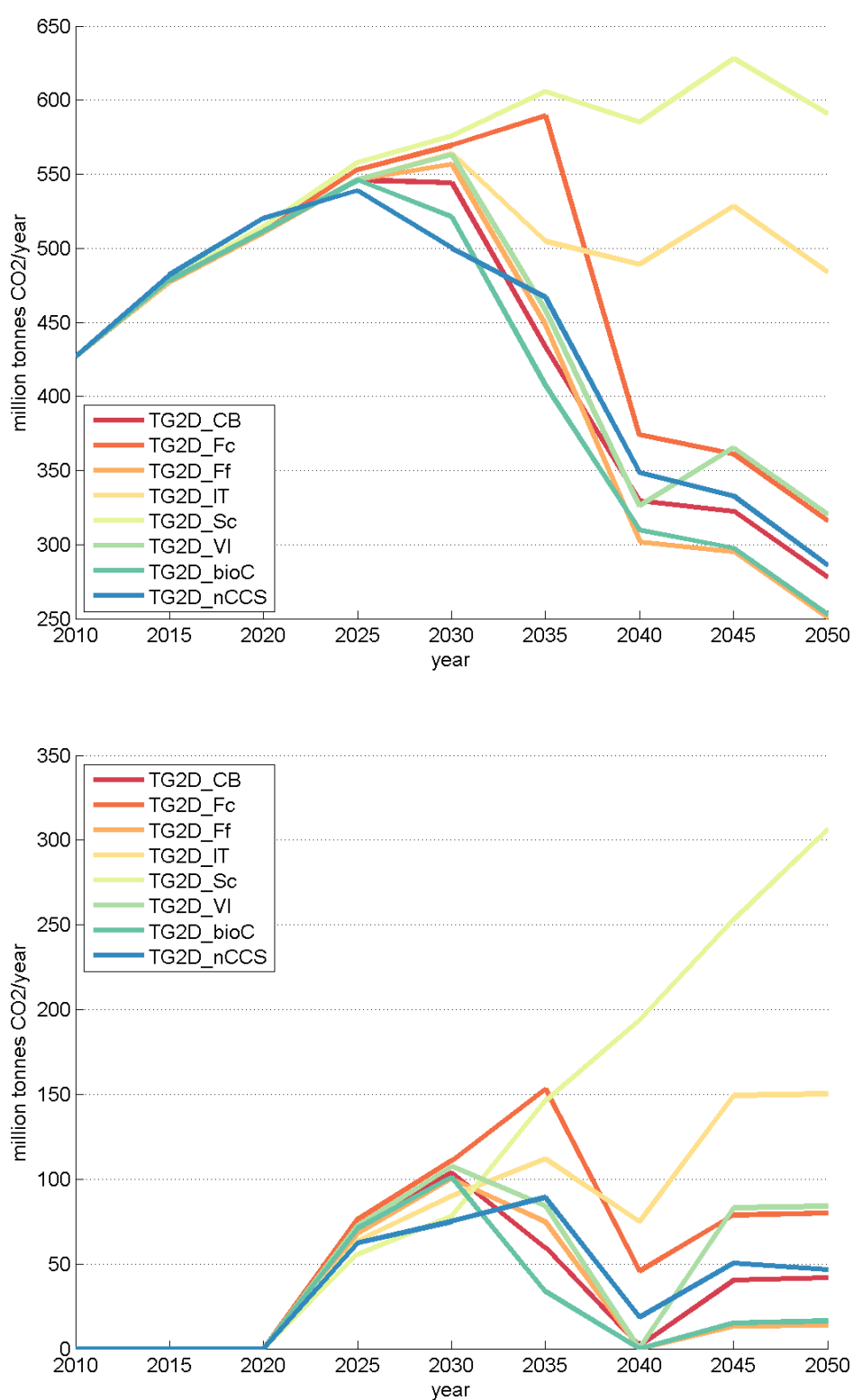


FIGURE 6.21: Shipping's operational emissions trajectory by scenario (top). Offsets of CO_2 emissions trajectory by scenario (bottom)

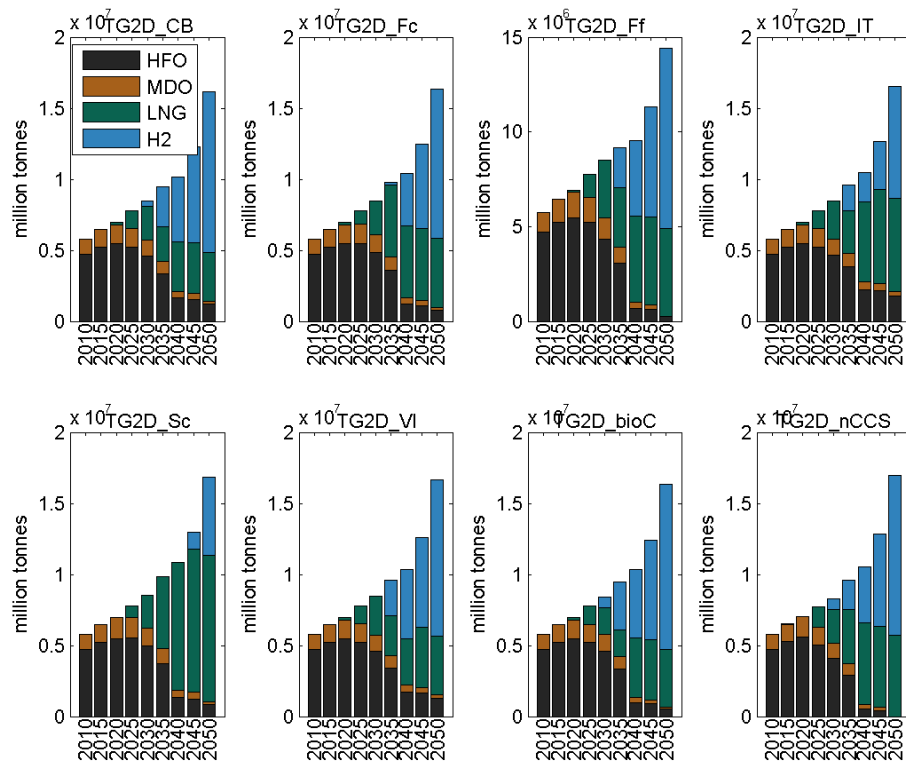


FIGURE 6.22: Fuel mix trends by scenario

any other scenarios. The shipping's share, therefore, cannot decline under a certain level, although shipping stopped the use of HFO and MDO.

6.5.3.2 The sensitivity of hydrogen supply

Another important implication due to the variations of the input factors is on the hydrogen production and consumptions within the global energy system. Hydrogen production is of particular interest as it would eventually affect hydrogen production costs and its relative price and demands. Figure 6.24 shows the cumulative production of hydrogen in PJ over time per production technologies by scenario. Most of the scenarios maintain a similar breakdown to the one observed in the reference TG2D_CB. Hydrogen was produced mainly with SMR with CCS and biomass gasification with CCS. Significant changes are observed, instead, in scenarios TG2D_bioC and TG2D_nCCS. The higher cost of biomass production technology favoured the uptake of SMR technology with CCS covering almost all production. The absence of CCS technology, instead, created a situation in which hydrogen is produced almost evenly with biomass gasification and electrolysis.

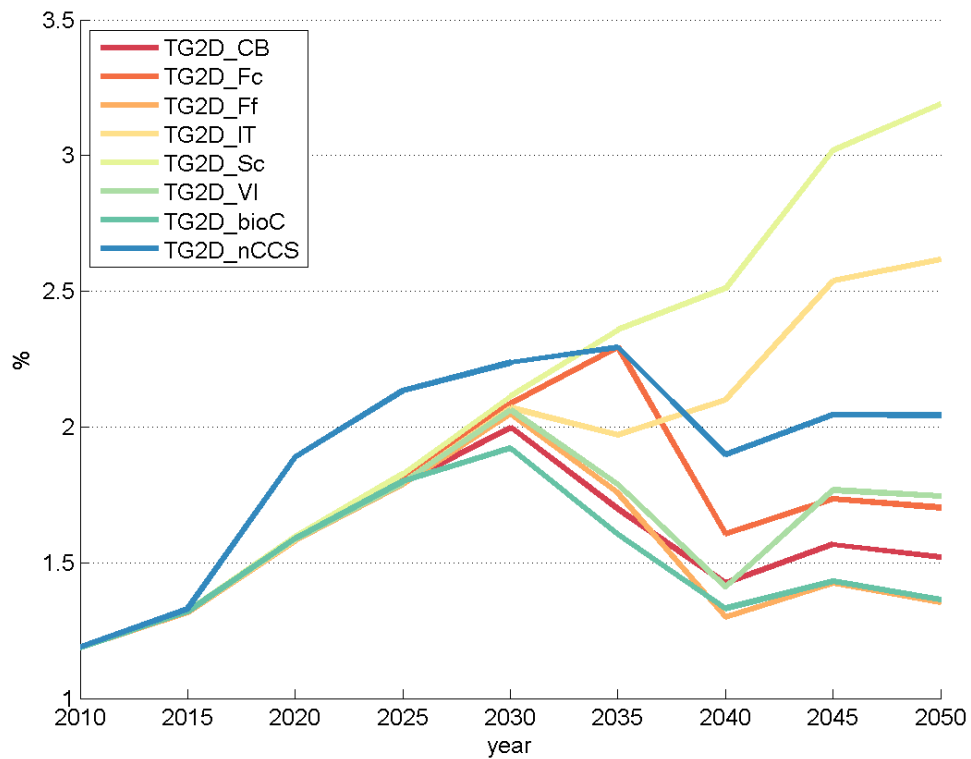


FIGURE 6.23: Shipping emissions as share of total world emissions

The change in hydrogen production technologies would be in line with the decarbonisation of the global energy system. This means that the production of hydrogen might adapt to different conditions, however the emissions associated with that would be counterbalanced in other parts of the energy system. An analysis of the associated upstream emissions due to different configuration of the hydrogen's supply (including transportation and distribution) could reveal the relative impact of different solutions. This is, however, left to further research effort.

Hydrogen end users consumption can also be affected by changes to the input factors. Figure 6.25 shows the cumulative hydrogen consumption of the main end users by scenario over the period 2010 to 2050. The total amount of hydrogen used in absolute terms changes by scenario. The category truck is the main user in the majority of the sensitivity scenarios, followed by shipping, car and bus categories.

The high cost of hydrogen storage system in scenario TG2D_Sc, decreased the consumption of hydrogen in ships which represented approximately 13% of the total. In contrast, the high cost of biomass production technologies in scenario TG2D_bioC decreased the hydrogen consumption in other sectors but not in shipping as it becomes

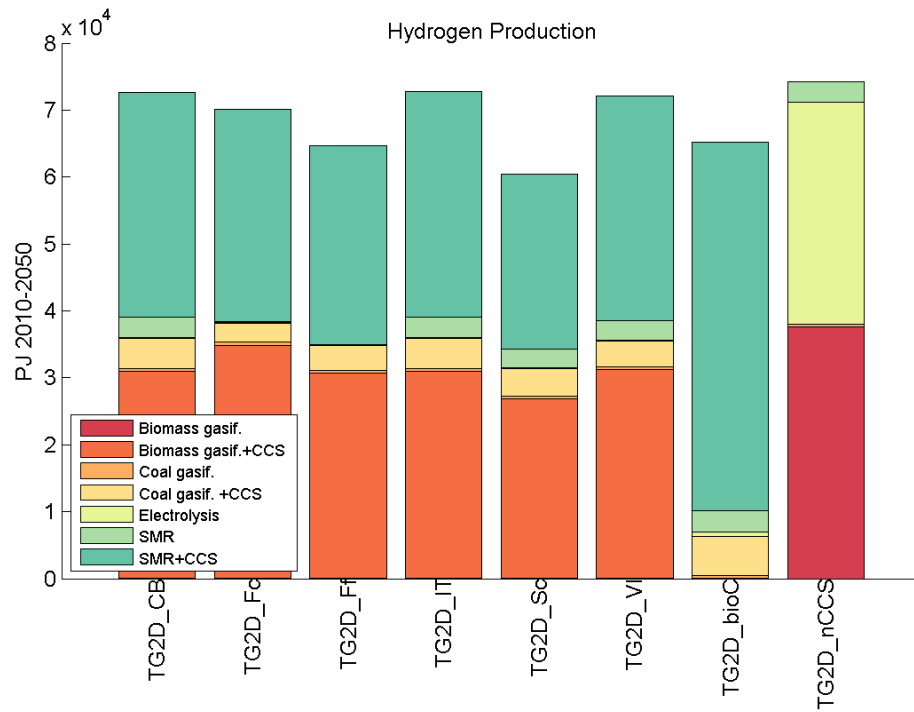


FIGURE 6.24: Cumulative hydrogen production technologies by scenario

the main consumer over time representing approximately 45% of the total hydrogen consumption. The use of hydrogen in ships for the other robustness scenarios ranges between 26-36% of the total.

The observed differences in hydrogen consumption by sector in the robustness scenarios can be associated to the diverse hydrogen demands' response, which in turn depends on the changes on the option's cost-effectiveness and the changes on hydrogen price.

6.5.3.3 Economic implications by scenario

Hydrogen price also varies among the sensitivity scenarios. Due to the changes in the estimated costs of production and the estimated demand, the trend of hydrogen price also changed. Figure 6.26 on the bottom presents the trend of such price by scenarios. In the majority of the cases, hydrogen reached its lowest value in 2035 and then increased afterwards. There are, however, some differences. For example, hydrogen prices in scenario TG2D_Fc decreased until 2030 and then fluctuated until 2040 and showed a tendency to increase afterwards. In contrast, in scenario TG2D_nCCS the lowest point is reached in 2030, and the price is significantly higher than all the other scenarios. This

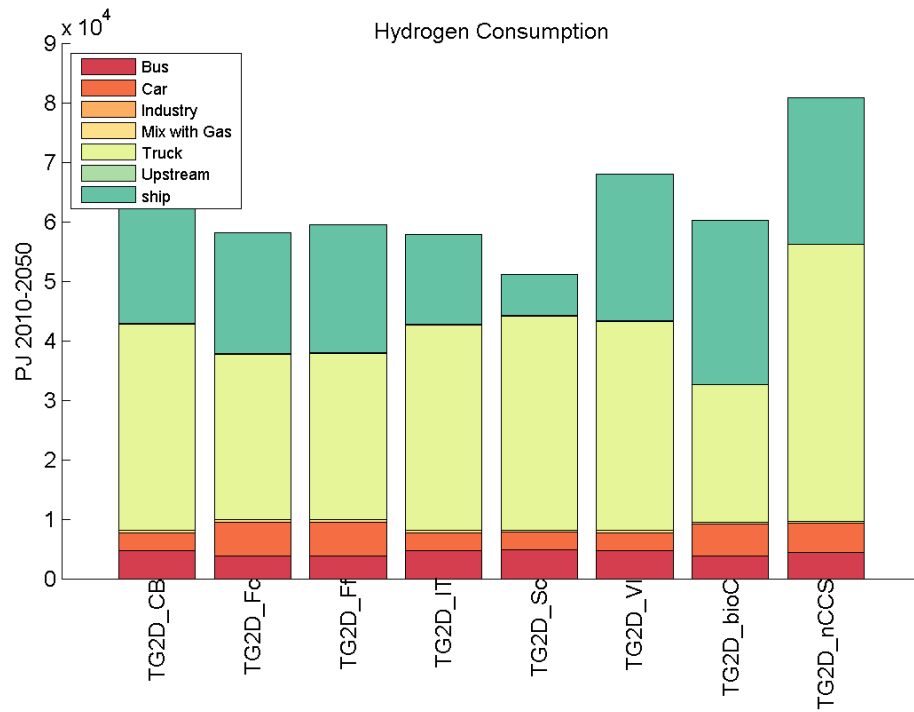


FIGURE 6.25: Cumulative hydrogen end-user consumptions by scenario

means that switching to hydrogen might be more expensive in this case as the use of more expensive hydrogen production technologies would cause its price to increase.

At the base year 2010, hydrogen price is different among the sensitivities scenarios as it is derived from the price estimated at the year in which it starts to be used in shipping. For example, in the scenario in which hydrogen takes up from 2030, the price in that year is used to extrapolated backwards until the base year 2010. This was explained in more detail in section [4.10.2](#).

Shipping carbon price is another important output of the model and its trend changes due to the variations to the input factors. Figure [6.26](#) on the top shows the trends of carbon price by scenario. All scenarios have a very similar trend and prices per year, except for the scenario TG2D_nCCS. In this case the values are significantly higher reaching almost 1500 \$/tonnes in 2050, although the trend remained similar to the other scenario. The absence of CCS technology can explain the very high carbon prices as emissions reduction measures need an extra economic incentive in order to be cost effective and compete with conventional technologies.

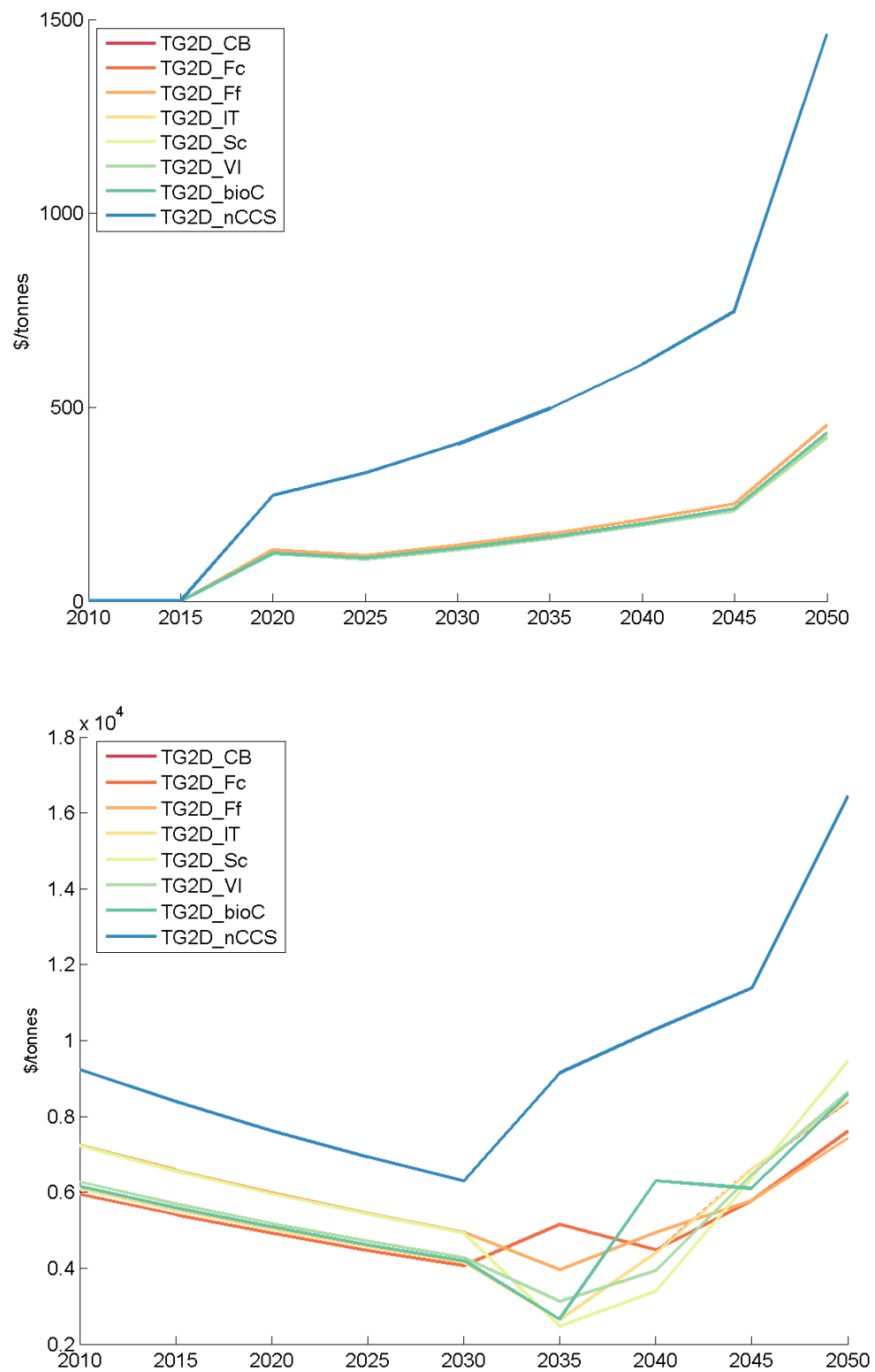


FIGURE 6.26: Shipping carbon prices trends by scenario (top). Hydrogen prices for shipping by scenario (bottom).

6.5.4 Variability of hydrogen adoption

The changes introduced with the robustness analysis affected the way the modelled factors influence each other. As consequence, in each sensitivity scenario a different trend of the uptake of marine fuels was observed. Hydrogen adoption over time is one of the observed effects. This section highlights and consolidates the key dynamics that might emerged in each of the robustness scenario and what this meant for the adoption of hydrogen in shipping.

In the scenario with high cost of fuel cells technology (TG2D_Fc), for example, the following dynamics could emerge. The increased investment cost of hydrogen solution would decrease the uptake of hydrogen. In view of this, shipping emissions would increase and therefore also the gap with the target trajectory. Such a gap in turn would push the purchasing of CO_2 offsets during the period 2030 to 2035, delaying the deployment of hydrogen in shipping. Despite that, the condition in 2040 would find hydrogen as the most convenient option, therefore, its uptake would start to increase from that year. Such dynamic is very similar to what could be observed in the scenario with high cost of hydrogen storage technology on board (TG2D_Sc). In this case, a significant negative impact on the uptake of hydrogen would be observed until later in 2045 when hydrogen would be a convenient option for some specific ships. As consequence, the level of offsets of CO_2 would increase over time in order to comply with the carbon budget restriction.

An increasing in fuel cells efficiency in scenario TG2D_Ff reduces the operational cost of the hydrogen solution with a consequent high uptake of hydrogen. As consequence in this scenario it could be observed a rapid phasing out of HFO and MDO uses in shipping. In view of that, during almost over the period 2010 to 2050 the shipping emissions in this scenario are lower than the reference scenario TG2D_CB.

In TG2D_IT scenario the different carbon budget effects the gap between the shipping emissions and the target trajectory, although the dynamics and the resulting fuel mix trend remains very similar to the reference scenario. In TG2D_VI scenario, instead, the only effect is the increased operational cost of hydrogen solution in shipping which does not seems to have generated a significant difference with the reference scenario TG2D_CB.

In TG2D_bioC the fact that biomass production technologies are more expensive changed the way hydrogen is produced. Hydrogen production plants based on SMR

with CCS technology would be the most convenient. The uptake of hydrogen in other sectors would decrease because other low carbon options would be used (e.g. electricity from renewable). The shipping section, instead, would not find other convenient options and hydrogen would remain an attractive solution. Moreover, price difference between hydrogen and LNG and MDO from 2035 would be very small at an energy base, which means that hydrogen could become more economically attractive. In this scenario, hydrogen would take up from 2030 reaching higher value than the reference scenario TG2D_CB in 2050.

The absence of CCS technology in TG2D_nCCS scenario had two main effects. The first effect is that the way hydrogen is produced may have changed as biomass gasification and electrolysis would become the most cost-effective solution. The second effect is that the energy system would require a very high carbon price in order to stimulate the use of cleaner technologies and to meet the target of 2 degree temperature increase. So, the global emissions trajectory would be different from the other robustness scenarios. It may decrease more rapidly than the other scenarios during the period until 2025 and at a lower degree afterwards. The uptake of hydrogen in shipping would still be observed, however the trajectory of the shipping carbon prices and shipping emissions share would be different in comparison with all the other scenarios.

Chapter 7

Discussion and concluding remarks

This thesis has focused on understanding and exploring the potential and implications of using hydrogen to fuel international shipping. The literature review highlighted that a key gap in the current literature was the absence of analysis that combines sufficient resolution of the shipping system within a representation of the global energy system. This led to the identification that further insight could be gained through soft-linking two models which simulate the shipping and the global energy systems, respectively. As a consequence the structure of this thesis was:

1. First, to develop and deploy a soft-linked modelling representation of the shipping-energy system. This was used to test whether it generates significant new insight into the dynamics of the shipping-energy system putting a particular focus on questions regarding hydrogen and the fuel mix in shipping.
2. Second, to deploy that modelling framework under a plausible scenario in which significant uptake of hydrogen occurs, and create new knowledge from that deployment in what the implications might be for the competitiveness of hydrogen over LNG and current marine fuels in shipping and how robust these implications are.

This chapter is organized as following: the first section consolidates the most important findings of this thesis. The second section examines how the findings should be interpreted, highlighting general conclusion remarks and limitations that may restrict such remarks. Finally, the third section provides recommendations for future research based on further questions that this thesis has raised.

7.1 The findings of this thesis

This section provides a consolidation and a review of the most important findings and whether or not they support the original hypothesis. Such findings can be divided into two parts: the first part includes the findings associated with the development of a new approach for the evaluation of the potential use of hydrogen in shipping. The second part includes the findings associated with the analysis of scenarios in which an uptake of hydrogen in shipping occurs. When possible this section also provides evidence of whether the findings agree with the conclusions of other researchers.

7.1.1 Modelling the energy-shipping system

In this thesis two existing models, TIAM-UCL and GloTraM, have been soft-linked through a code written in Matlab which automates the interactions between them. The developed method to soft-link the two models is based on procedures that were also used in other studies. An important feature of such a method is that it ensures the consistency between the two models (see chapter 4). The original hypothesis was that a soft-linked framework of an energy and a shipping model would have an improved modelling representation of the potential uptake of hydrogen in shipping. The results of this thesis lend support of this hypothesis as there are a number of important pieces of evidence which suggest that TIAM-GloTraM improves the modelling capacity for simulating the supply and uptake of hydrogen in shipping. Evidence of the modelling improvement has been provided by comparing the results of the framework TIAM-GloTraM and the independent simulations of TIAM-UCL and GloTraM. The evidence was found in: the ability of the model to simulate the equilibrium between marine fuel prices and demands, the ability of the model to capture the dynamics between the carbon price and the shipping fuel mix (how these outputs influence each other), the ability to generate fuel price projections that overcome the limitation of the linear property of the energy system model, the ability of capturing the dynamics between the transport demand among regions and the fuel mix evolution of the global fleet. More details of this evidence was provided in section 5.7.4.

The comparison between the independent and the soft-linked simulations of a specific set of scenarios represents a case study in which the developed framework has taken a step in the direction of evaluating the potential of hydrogen to fuel international shipping. The comparison has highlighted the capability of the framework of modelling the investment decision for ships powered by hydrogen in conjunction with the development of a hydrogen supply infrastructure with a more robust approach compared with the energy and shipping models. It is difficult to compare this type of finding with other researchers as the development of similar soft-linked model (energy-shipping system) has not been found in the existing literature. However, the fact that the model TIAM-GloTraM is able to endogenouse a number of variables is in agreement with the best practice to include in a model the most important variables and dynamics of the intended target system (Weisberg, 2012).

7.1.2 The use of hydrogen in shipping

The second research question of this thesis was regarding the circumstances in which hydrogen could become part of the future marine fuel mix and its key implications. So, the linked model TIAM-GloTraM has been deployed under a plausible scenario in which significant uptake of hydrogen occurs. The simulation of a number of scenarios then provided several findings that highlight the conditions that would favour the uptake of hydrogen and the most important associated implications.

The robustness analysis undertaken in this thesis confirmed that hydrogen could be present among the marine fuel mix in all sensitivity scenarios considered. Therefore, to some extent the option of hydrogen in a decarbonised shipping sector appeared to be robust in relation to the uncertainty associated with specific key factors analysed in this thesis.

In conclusion, the key circumstances for the potential uptake of hydrogen that were found in this thesis are: the introduction of an emissions cap and a MBM mechanism in shipping, a hydrogen price ranging between 4-8 \$/kg and competitive investment costs of hydrogen technologies on board ships (fuel cells and hydrogen storage technologies), and finally the supply of hydrogen mainly based on natural gas and biomass with CCS technology or electrolysis in case of an absence of CCS. The main implication of a switch to hydrogen is that shipping emissions could be reduced significantly over time.

7.1.2.1 A shipping emissions regulation

Under the scenario in which there is a shipping carbon budget of 34 Gt until 2100 and a MBM mechanism that adjusts the carbon price according with such budget, hydrogen became a competitive option for the majority of ship type and size categories. In this scenario the switch to hydrogen was mainly driven by an increasing carbon price in shipping, from zero to approximately 1400 \$/tonnes during the period 2010 to 2050. Although hydrogen price increased, the fuel became competitive as it did not have any associated carbon costs. In contrast, under the scenario (TG2D) in which the shipping carbon price increased from zero to 430 \$/tonnes during the period 2010 to 2050, hydrogen was not economically viable. Due to the high hydrogen price and investment costs of hydrogen related technologies (fuel cells and hydrogen storage system), the business case for hydrogen powered ships was not competitive. The comparison of these

two scenarios (TG2D and TG2D_CB) leads to the conclusion that the first important condition necessary to see hydrogen used in shipping would be a shipping emissions regulation that consists in: the introduction of a carbon budget of 34 Gt, and a MBM that deploys an increasing carbon price reaching about 1400 \$/tonnes in 2050.

The MBM mechanism introduced in the scenarios of this thesis limits the amount of budget used to purchase CO_2 offsets to a certain share of the total revenue generated with the carbon pricing. This implies that there are two other conditions that may be necessary to see the uptake of hydrogen in shipping. The first is that other sectors would have to decarbonise more to make CO_2 offsets available in a global carbon market, the second is that in a future emission regulation the amount of offsets the shipping sector will be able to purchase has to be limited as a high level of offsetting means less incentive to reduce the operational emissions of ships, and therefore to the uptake of low carbon fuel such as hydrogen. Based on the results of this thesis such limit would be about 10% of the total revenue.

7.1.2.2 Hydrogen costs

Under the scenario with a carbon budget in shipping, hydrogen is projected to range between 4 to 8 \$/kg. In general, such estimate is relatively in line with other recent estimates of hydrogen price which range from 0.9 to 11 \$/kg (SBA, 2014; IEA, 2015; Ohira, 2016; Michalski and Bunger, 2016), depending on assumptions about the production technologies. This projected price could be another important condition for the use of hydrogen in shipping as hydrogen price influence the ship's profitability. For example, in the scenario (TG2D_CB) hydrogen in combination with fuel cells was found as the most profitable option in several ship type and size categories from 2030 (see section 6.4.2).

Under this scenario (TG2D_CB) hydrogen was found more suitable for middle size container and dry ship type, and small size wet chemical and gas carriers types than small or very large unit container and dry ships which could be penalised by the high volume required to store hydrogen on board. In large ships, the high costs associated with large engines and equipment could also penalise the use of hydrogen. The analysis of the sensitivity scenarios have highlighted that high costs of fuel cells and hydrogen storage systems could have a significant impact on the uptake of hydrogen in shipping. High investment costs of fuel cells could reduce the uptake of hydrogen up to 20%, whereas,

high costs of hydrogen storage system up to 74% in comparison with the reference scenario (TG2D_CB). This implies that the assumptions of the projected investment costs for marine fuel cell systems of about 830 \$/kW, and for liquid hydrogen storage technology of about 71 \$/kg would be another important condition for the use of hydrogen in shipping.

7.1.2.3 The supply of hydrogen

Another important premise for the use of hydrogen in shipping regards its supply infrastructure. Based on the results of this thesis, hydrogen production with SMR in combination with CCS and biomass gasification with CCS could cover up to 80% of the global production. This combination of production technologies finds support also in other studies in which see the global hydrogen production system, initially based on fossil fuel such as natural gas, and progressively shifting toward renewable sources ([Mueller-Langer et. al., 2007](#); [Barreto et. al., 2003](#)). This thesis also found that electrolysis could be used to produce hydrogen under the assumption of an absence of CCS technology (see scenario TG2D_nCCS in section 6.5). In this scenario, the absence of CCS technology affected the decarbonisation trajectory of the other sectors which reduced their emissions at a high rate in order to account for the emissions that will not be captured with CCS. the take-up of hydrogen in shipping was still observed for the decarbonisation of the sector, however, a means to produce hydrogen with low emissions impact was required such as biomass gasification and electrolysis (with electricity produced in a way that is in line with the climate target according with TIAM-UCL). The total hydrogen production was approximately 50% from electrolysis plants. The use of other technologies for the production of “greener hydrogen” have been under investigation in other studies. The use of electrolysis, for example, is another common option that is often found to have high potential in the future ([McDowall and Eames, 2007](#)).

The scenarios analysed in this thesis highlighted that hydrogen could also be supplied in other sectors of the global energy system. This is also of relevant importance as the investment for hydrogen supply infrastructure depends also on the demands of other sectors. In the scenario with a carbon budget in shipping the total amount of hydrogen produced in 2050 was about 30% used in shipping and 60% used in trucks, and the remaining 10% used in other sectors. The amount of hydrogen that was found

to be used in shipping in 2030 was about 70% of the total hydrogen consumption, however, the demand for road transport modes such as the truck category increased rapidly and overcame the shipping demand in the long term. The main use of hydrogen was, therefore, found in the transportation sector. This is in accordance with many studies (SBA, 2014; Ekins, 2010; Mansilla et. al., 2012), although, a recent growing interest is on the use of hydrogen to provide back-up power for the electricity grid (SBA, 2014; DOE, 2014).

In all scenarios of this research hydrogen was found to be suitable for large vehicles like ships, trucks and buses. The role of hydrogen for the long-term decarbonisation of these categories is also highlighted in Anandarajah et. al. (2013) which is in line with a common conclusion that large vehicles might be more suitable for the use of hydrogen.

7.1.2.4 Main implications

The introduction of a carbon price would increase the profitability of a hydrogen powered ship, this effect would favour a switch to hydrogen which would reduce the emissions of the sector over time significantly. Under the scenario with a carbon budget of 34 Gt in shipping, hydrogen's share of the total fuel demand for container and gas carrier types reached about 80% and 90% in 2050 respectively, whereas, its shares was approximately 50% for dry and wet crude, and 60% for wet product chemical type in 2050. Such a penetration of hydrogen within the marine fuel market reduced the average carbon factor of the fleet, as well as the average carbon intensity. The changes in the carbon intensity of a fleet can be observed by looking at the trend of EEOI. For example, the averaged EEOI for container type changed from 125 to 15 $gCO_2/tenm$ during the period 2010 to 2050 (see section 6.3.1).

As a comparison, the uptake of hydrogen from 2030 under the scenario with a carbon budget is in disagreement with the findings of (Taljegard et. al., 2014), which sees hydrogen to be chosen from 2070 under a base case scenario with 400 ppm CO_2 global concentration constraint which could be a result from the fact that the GET model allows overshoot (over 400 ppm) during the century and therefore the carbon constraint is not as strict in 2030-2050 compared to the TIAM-GloTraM model. It is, instead, in line with the findings of (Argyros et. al., 2014) which sees the uptake of hydrogen in 2030 under a scenario with a more aggressive emission reduction policy combined with a moderate hydrogen price.

The introduction of hydrogen would also enable the reduction of the shipping emissions share. The total shipping CO_2 emissions in the scenario with a carbon budget were found to be 367 million tonnes in 2050. As a consequence, the contribution of the shipping emissions in a decarbonised energy sector decreased. The emissions of the analysed fleet as a percentage of the total CO_2 emissions came to 2% in 2050. As a comparison to the scenario in which the uptake of hydrogen does not occur, the total operational emissions continued to increase. The shipping CO_2 emissions reached 958 million tonnes in 2050, and as a consequence, the contribution of the shipping emissions in a decarbonised energy sector increased. The emissions of the fleet analysed as percentage of the total CO_2 emissions came to 5.2% in 2050.

7.2 Interpretation and limitations of the results

This section provides a critical analysis of the findings of this thesis, examining how the findings should be interpreted. It generalises from the findings and highlights the limitations that restrict the extent to which the findings can be generalised. This section comprises of two main parts: the first part focuses on the findings and limitations with regard to the method used to study the uptake of hydrogen in shipping, while the second part focuses on the findings and limitations in regard to the projected uptake of hydrogen and what this means for the shipping industry.

7.2.1 Modelling the interactions between two systems

The successful case study of TIAM-GloTraM has demonstrated that the soft-linked version of the models TIAM-UCL and GLoTraM has an advanced modelling representation of the energy-shipping interaction. This leads to two types of interpretations: one is on the utilisation of the method used to develop the soft-linked model, another is on the extension of the modelling representation to a wider target system.

A standard procedure for linking two models was not found in the literature and current studies have used different techniques and referred to the same terminology of soft-linking. If sectoral models (e.g. the shipping model) are involved in the linking process it becomes even more difficult as the way they would be linked would be technically different depending on the type of model. A part of the literature review undertaken in this thesis has, however, given the opportunity to detect a number of common key

steps among the studies that have focused on the linking process for pedagogic reasons, and the studies that have undertaken practical experiments. In this thesis, these steps have been categorised in more general procedures and applied for the development of TIAM-GloTraM. The successful case study of TIAM-GloTraM, means that the method used to soft-link TIAM-UCL and GloTraM could be used as an example in future studies that aim to represent the interaction between two different systems. More generally, the key steps and challenges highlighted in this thesis could be taken into account when developing a method to soft-link any two models.

The second type of interpretation regards the extension of the modelling representation to a wider target system. There are at least two possible extension that can be derived from the case study of this thesis. Essentially, the developed soft-linked model opens the door to a new modelling representation of any alternative fuels in shipping. Conceptually, the framework adds a greater level of sophistication to the study of alternative fuels. It could be extended to represent a wider range of fuels taking into account the parameters that influence the investment decision for ships in conjunction with the parameters of the development of a supply infrastructure.

In addition, the interaction between the energy and shipping system as modelled in TIAM-GloTraM could be extended to other transportation modes. In practice, it could be assumed that such modelling of the global energy system (that selects the most cost-effective options to achieve an emissions target) and the shipping system (that selects the most profitable options based on signals from the global energy system), is representative of the real world phenomena of the interaction between the energy and any transportation mode.

There are, however, limits that restrict such interpretations of the successful case study of TIAM-GloTraM. The most important is that TIAM-GloTraM cannot be validated. The confirmation of the findings is associated with the confirmation of the framework itself, which cannot be currently assessed since the only way to validate the findings is a comparison with reality, which is impossible for future scenarios. So it's not possible to know if this is a correct modelling representation of the real world behaviour. Obviously, this is an important limitation which affects all findings of this thesis.

Another limitation regards to the modelling representation of the energy-shipping interactions. The fact that the two models have two different theoretical behaviours can limit the derived interpretations. In effect, the energy model is constrained to use the

fuel mix derived from the shipping model. Such constraint applied to a single sector of the energy model has implications on the other sectors, as the latter receives the signals from a single sector and then acts as a single entity. This assumption appears weak as other sectors may behave more independently and influence the interaction between the energy system and the shipping sector. The interpretations are therefore limited by all other possible representations of the energy and shipping interaction and more generally of the energy and other sectors' interaction. Although, the developed modelling framework gives an alternative option to the pure cost optimisation behaviour of the energy system model and to the pure profit maximisation of the shipping model, it is possible that a different representation may produce entirely different results.

7.2.2 The meaning of the uptake of hydrogen in shipping

Based on the analysis carried out in this thesis, it can be concluded that hydrogen could be one of the options available for decarbonising the shipping industry. From this finding several interpretations can be formulated, which are divided into four topics. The first topic covers what this finding means for the uptake of other low carbon fuels or equivalent fuels that were not modelled in the framework. The second topic covers the implications that can be derived for fuels and infrastructure, while the third topic regards the implications for government and industry. Finally, key learning for the IMO GHG policy debate are derived from the overall findings of the thesis.

7.2.2.1 Low carbon fuels in shipping

One of the findings of this thesis is that shipowners could invest in hydrogen powered ships based on the maximisation of the profit and their compliance with a defined carbon budget. Under the scenario analysed in this thesis, the global fleet gradually switched from conventional marine fuels and LNG to hydrogen in order to decarbonise. The fact that hydrogen was found as a viable option for a drastic reduction of emissions shows that LNG is not a viable long term solution from a decarbonisation point of view, rather the uptake of a low carbon fuel such as hydrogen is necessary for a decarbonisation in line with the target. However, hydrogen is the only low carbon fuel that is used in the model as other possible marine fuels such as biofuels, and other synthetic fuels are excluded from the marine fuels portfolio. Hydrogen becomes economically viable only with a high carbon price meaning that the industry could adopt any type of low

carbon fuel as long as its price in combination with carbon price reaches the economic advantage in comparison with high carbon content fuels. In other words, the carbon price can in theory offset the high price of any low carbon fuel relative to fossil fuels. So in conclusion, the fact that the model responded with a high sensitivity to the carbon budget regulation by switching to hydrogen means that the shipping industry could adopt any other similar low carbon fuel.

The understanding of the future price of low carbon fuels and their availability as well as their upstream emissions appears to be more complex. This is a limitation of the interpretation derived above as the supply of such fuels needs to be represented within the energy model in order to evaluate the net impact of using energy sources for the production and distribution of these types of fuel.

7.2.2.2 Fuels and infrastructure

The analysis of the findings also leads to important interpretations in regards to the fuels and the associated infrastructure. For example, in this section considerations are made from analysing the following key aspects found in this thesis: the use of LNG as a marine fuel, the production of hydrogen from natural gas, the use of CCS technology, and the fuel storage system on board ships.

From a decarbonisation point of view, the fact that LNG and other technical and operational energy efficiency measures did not appear sufficient for the necessary emission reduction and that hydrogen, instead, may be a viable option from 2030, implies that there are some associated implications arising from the use of LNG as a marine fuel. The projected use of hydrogen from 2030 implies that investments would be required soon, in order to ensure a worldwide hydrogen infrastructure for shipping. However, at the same time LNG would compete with hydrogen, as it was found that LNG could significantly get taken up from 2025 (just 5 years before the first use of hydrogen). This situation could have important implications on the supply infrastructure. It might not be completely justifiable to invest in LNG infrastructure as LNG ships could not be competitive after a relatively short period of time (5-10 years). So, today's investments are particularly important in shipping as not only the infrastructure but also the ships have a long average lifetime (approximately 30 years).

The use of hydrogen in shipping produced from natural gas raises other interpretations. It may be possible that the emissions implication of using natural gas as fuel on

board is more significant than the emissions of using natural gas to produce hydrogen. In some scenarios of this thesis was observed that hydrogen produced from natural gas and bio-energy with CCS technology is a possible option. Although, such a mix means that hydrogen cannot be considered completely a green hydrogen, the mix of energy sources used to produce such hydrogen remains in line with the 2 degree target. Essentially, it may be acceptable to pay the price of upstream emissions producing hydrogen from not 100% renewable energy sources as it will still be in line with the broader strategy of the energy system which may see renewable energy be used in a more cost effective way in other sectors. For example, under the scenario of the high cost of biomass production technologies (TG2D_BioC) hydrogen was produced almost entirely from natural gas with CCS. This thesis, however, has not provided robust evidence of the emissions of using natural gas to produce hydrogen for shipping, which means that the interpretation that it can be acceptable to use hydrogen produced from fossil sources is limited by further analysis on this aspect.

Another interpretation can be derived from the scenario with an absence of CCS technology. This thesis found that hydrogen may be produced from electrolysis and biomass and that the global energy system will have to decarbonise with a high rate in order to compensate the emissions that cannot be sequestered with CCS. This finding shows that CCS is an important technology that may enable the hydrogen production of relatively low cost and upstream emission and at the same time ensure that the supply is in line with a global decarbonisation trajectory.

In general the supply infrastructure of any fuel is very complex and the interpretations provided in this section can be limited by the low resolution used to represent them into the global energy model. In reality it is likely that an infrastructure configuration may change based on specific local factors, in particular when factors at port level are taken into account. Another element that may limit the given interpretations above is the representation of hydrogen trade among regions. Hydrogen trade is not enabled as it is assumed that the production of hydrogen should be developed relatively close to the energy demands of users, while the energy sources to produce hydrogen can be traded worldwide. This of course could not be the reality as it is possible that hydrogen will be produced where it is more convenient and traded into the locations where it will be demanded. This may have an effect on the projected supply infrastructure of hydrogen and therefore on the derived interpretations.

The selection of an alternative fuel is also influenced by the infrastructure on board ships. Another finding of this thesis remarks that there are cost implication for the space requirement of liquid hydrogen storage system. Based on the size of the ship such cost implications may play a crucial role, for example, for small ships the space requirement may have a significant impact on the economics of the ship. Such considerations are valid not only for liquid hydrogen but also for any other alternative fuel. The characteristic of the fuels and the associated storage systems are very important as they may lead to different technical design solutions which may change the cost implication.

As mentioned in section 4.8.1, to store hydrogen in a liquid state, an active cooling is required, and there will inevitably be some boil-off, however, these were not accounted as it was assumed that they would mean minimised and therefore negligible. As a consequence the sfc could be higher than the one used in this thesis. This is a limitation of the interpretation derived above because in addition to the cost implication, there is also a performance implication.

A final consideration on hydrogen infrastructure is that the results of this thesis are based on global trend, more likely not all routes would shift to hydrogen. Perhaps the development of an infrastructure would start just a few major routes where hydrogen would have the lowest cost and upstream emissions associated.

7.2.2.3 Government and industry implications

Under a carbon budget constraint this thesis found that hydrogen is taken up from 2030, however this projected evolution was only possible under two important premises, which may have important implications for the industry and the government.

The first premise was that during the first period (2020 to 2030) the shipping industry was able to buy CO_2 offsets without competing with other sectors and that the other sectors were able to decarbonise so that CO_2 offsets were available. The decarbonisation of the shipping industry during this period relied on this premise as a relatively large amount of CO_2 offsets was purchased. One possible implication of this condition is that the shipping industry would have to find agreements with other sectors or regions to ensure the access to such an amount of offsetting during this period.

In long term the CO_2 offsets was not found to be so crucial for the decarbonisation but rather the availability of hydrogen worldwide as a marine fuel from 2030 became important. This premise along with the fact that in 2030 shipping was found as the

main consumer of hydrogen (using about 70% of the total production), implies that the shipping and hydrogen production industries would have to work closely to facilitate that a large amount of hydrogen will be available from 2030. In addition, if hydrogen will be chosen the shipping industry would have to collaborate with other stakeholders in particular with ports authorities in order to ensure that hydrogen infrastructure at ports will be facilitated. Moreover, hydrogen supply industry may have an interest in stipulating contracts with shipping company in order to facilitate a competitive price. For example, during the initial period before a worldwide infrastructure will be constructed, hydrogen price can be lined to the conventional marine fuel price, so that the price is not necessarily linked to the balance between supply and demand but on the expectation that such a fuel will be taken up in shipping. Finally, shipping may be in competition with other transportation mode for the use of hydrogen after 2030 in particular with buses and trucks. This implies that integration and collaboration with these modes may help with the access of shipping to hydrogen in the future.

Other important implications for the industry can be derived from the finding regarding the ship propulsion system. Hydrogen was found a viable option in combination with fuel cells system as a propulsion engine. A key assumptions is, therefore, that fuel cells with a high power output will be available for marine applications, which means that a dramatic acceleration on the development of this technology should be undertaken. If hydrogen will be chosen with fuel cells, the shipping industry would have to collaborate with fuel cell producers in order to facilitate that this technology will be available in a relatively short time (5-10 years) for marine applications. As highlighted in the sensitivity cases, the uptake of hydrogen was found sensitive to the cost of fuel cells systems.

A similar argument used for fuel cell technology can be used for the hydrogen storage system. Hydrogen was found as a viable option in combination with liquid hydrogen storage systems on board ships. This has two implications in terms of cost and space requirements due to the low volumetric energy density of hydrogen. The robustness analysis undertaken in this thesis has already demonstrated that a change in these assumptions can affect the uptake of hydrogen significantly. Hydrogen storage is, therefore, considered an important aspect and if hydrogen will be chosen the shipping industry may have an interest in collaborating with hydrogen storage producers in order to facilitate that such technology will be available for marine applications.

Without emissions sequestration technology such as CCS the production of hydrogen switched to use clean energy sources and technology. Under this scenario, hydrogen was produced with electrolysis plant and biomass gasification. These technologies are generally more expensive and increase the hydrogen price. As consequence, the introduction of a very high carbon price was required in order to make hydrogen economically viable, which means that there may be significant cost implications for the sector under this case.

This thesis concluded that hydrogen could be one of the few options available for decarbonising the shipping industry. Operational and technical efficiency measurements and the switch to LNG could not be sufficient to keep the global shipping emissions share to the current level. This has implications for governments. The reduction of GHG emissions in the policy debate of governments should not be associated directly to a growing role for LNG in shipping. Financing and/or a facilitation programme for LNG as an alternative fuel for shipping should be carefully assessed as the emissions implications associated with this fuel remains significant and the high investment requirement for the infrastructure remains risky. Port regulation should also take into account these types of considerations.

Hydrogen for shipping may be produced from natural gas in combination with CCS technology. In order to allow the shipping industry to have access to such a fuel, governments should consider this type of production in the development of a guide for the definition of sustainable hydrogen. It may be more cost effective to resolve the problem of emissions at the point of production rather than enable the global shipping fleet to use fossil fuels such as natural gas.

7.2.2.4 Key learning for IMO GHG policy debate

This thesis highlights key learnings for the IMO which has started a debate for future policy that may allow the decarbonisation of the sector and its future CO_2 emissions share as percentage of the global CO_2 emissions. In particular, this thesis found that even with the introduction of the global carbon price, there was no reduction of shipping emissions and therefore the shipping share continued to increase. In contrast, the introduction of a target that allows the carbon price to increase proportionally, made hydrogen a viable option for a drastic emissions reduction, which in turn kept the future shipping emissions share at a value similar to the current share. This means that from

a policy point of view the establishment of a target should have a high priority to avoid being dependent on the fact that all other sectors will succeed doing more than this equal burden sharing.

Essentially, it appears that the key element is the introduction of a regulation that limits the amount of CO_2 emissions from ships. The most important effect would be that the introduction of a carbon pricing system would reduce the gap between the cost-effectiveness of low carbon fuels and conventional fossil-fuel derived fuels. The switch to low carbon fuel would be the key driving force for the decarbonisation of the sector in line with the decarbonisation of the wider energy system and therefore to the pathway to the Paris target.

In addition, the fact that hydrogen has shown the ability to decarbonise the sector means that incentives for low carbon fuels should be a focus of the regulatory framework, while other technical and operational measurements should be of secondary importance. As a switch to LNG would not ensure the decarbonisation of the sector, this fuel should be considered only as a fuel for transition to low carbon fuels or not considered as an alternative for the decarbonisation of the sector.

Finally, it must be recognised that there is a great uncertainty surrounding the form of a future emissions reduction regulation as the hypothetical MBM adopted in this thesis is only one possibility. Different forms of regulation may produce different results, and affect the interpretations provide in this thesis.

7.3 Recommendations for further research

This thesis raises several questions and limitations that deserve further attention, which leads to a number of recommendations for future research. They can be divided in four areas. The first area regards the extra features that could be added to the modelling framework TIAM-GloTraM. The second area regards the exploration of uncertainty associated with the findings and interpretations of this thesis. The third area focuses on the technical challenges of the design of hydrogen powered ships. Finally, the fourth area comprises all other relevant topics of research that can be raised from this research. The following sections examine each of these areas.

7.3.1 Adding features to TIAM-GloTraM

TIAM-GloTraM could be further developed in order to include a number of possible features that may improve the modelling representation of the energy and transport systems' interaction.

7.3.1.1 Soft-linking other transport modes

As already mentioned energy system models are less useful when the focus is on the exploration of technology diffusion, so other transport modes may not decarbonise as projected which may have several implications such as CO_2 offsets may not be available as reported in the short term. To overcome the limitations of having only the shipping industry acting differently from the rest of the energy model, other models that simulate other transport modes could be soft-linked to the energy model. In this way the evolution of other transport modes can be represented with a specific objective function and sectoral emissions target. The energy model would focus on the best way to use the energy sources, while specific sectoral models would focus on the technology selection.

7.3.1.2 The estimate of the carbon price

The estimate of the global carbon price is based on the assumption that in a global market all information is available across all industries, and industries will decarbonise where it is most cost effective first. So it is possible that the global carbon price is relatively low compared to what is actually necessary in the real world in which perfect information may not exist. In contrast, the estimate of the shipping carbon price is based on the assumption that the shipping industry sets its own target, and sends a signal to the rest of the economy which decarbonises where it is most cost effective. The shipping carbon price is higher than the global carbon price as it takes into account factors and barriers that are embedded in a specific sector. The fact that global and shipping carbon price are estimated in two different ways raises questions around the effect of different carbon pricing systems across different sectors and regions. Therefore, a different representation of the estimate of the carbon price that take into account this difference may improve the modelling representation of the energy and transport sector interaction.

7.3.1.3 Other fuels

This thesis highlights the potential of any low carbon fuel to uptake in shipping. Fuels such as biofuels and other synthetic fuels could, therefore, be included in the portfolio of marine fuels and their supply could be represented within the energy model. The inclusion of such fuels could also help understand the difference on upstream emissions among fuels and the competitiveness of hydrogen in comparison with these types of fuels.

7.3.1.4 Including the changes of transport cost

This thesis found that under the scenario in which shipping is constrained to decarbonise, the sector might be subjected to a carbon pricing system which can lead to changes in the fleet specification. Both elements, the carbon prices and the specifications of the future shipping fleet influence the transport costs which in turn may influence the transport demand. The model TIAM-GLoTraM captures this interaction only in part through its ability to capture the dynamic between the transport demand and the fuel mix evolution of the global fleet. However, it is assumed that transport demand would not be affected by any transport cost consequences of technical and operational energy efficiency measurement and MBM regulation. Further effort could, therefore, be dedicated to represent in the model how these elements may change and how they may effect the transport demand.

7.3.1.5 The bunkering infrastructure and the trade of hydrogen

The supply infrastructure of hydrogen appears to be of relevance in relation to the derived hydrogen price, however, there are two important limitations in the modelling representation of the supply in TIAM-GLoTraM: the level of aggregation used to represent the infrastructure and the representation of hydrogen trade among regions. On the one hand, more effort could be dedicated for a more accurate modelling representation of bunkering infrastructure at ports and on the other hand the international trade of hydrogen could be introduced into the energy system model.

7.3.2 Exploring uncertainty

More effort could be dedicated to exploring the uncertainty of the results provided in this thesis. An extended robustness analysis is the first example, a larger number of

parameters could be included in the robustness analysis, as well as a larger number of reasonable values of the input factors. There are many uncertain parameters that are inputs to each of the scenarios. Systematically varying those parameters can help to test the robustness of the outputs of the modelling and therefore provide greater insight into the viability, constraints and likelihood of different future pathways for the sector. This could be useful not only to test the robustness of the results but also to reveal thresholds at which the energy and shipping interaction may have dramatic changes.

This thesis has provided two main global decarbonisation pathways. One is achieved with the shipping sector decarbonising predominantly using a switch to hydrogen, in the other, instead the decarbonisation is carried out by other sectors and shipping switches to LNG without decarbonise (at least before 2050). The key driver of such different pathways is the introduction of a specific carbon budget in shipping which forces shipping to decarbonise at the same rate as the global economy overall rate. This justifies the need for deeper inspection and exploration of different regulatory measures that may reduce shipping emissions. One example could be the run of a number of sensitivity scenarios with different carbon budgets or a different modelling representation of an emissions reduction regulation.

Hydrogen does not seem to be competitive as marine fuel under the scenario without the specific carbon budget, therefore, further research questions could be explored such as how uncompetitive hydrogen actually is in this particular scenario? How far away is it from being competitive? Why is it less competitive in shipping compared to the other transport modes? Different sensitivity scenarios built around the scenario without a carbon budget (TG2D) could, therefore, be useful to answer these questions.

The transport demand used in this thesis changes based on different scenarios, however, it is only the trade of energy commodities that differs among scenarios. Different transport demands of non-energy commodities could, therefore, be explored in order to explore the sensitivity of the results to this input parameter.

In this modelling work, hydrogen price is derived as a global average of the cost of production, however, in the practice during the first period of development, the hydrogen price may not be directly linked to the supply and demand balance and the hydrogen supplier may stipulate a contract with a shipping company in order to ensure a competitive price and market share. A modelling representation of this dynamic could be included in the model for any alternative fuels in order to explore the effect on the

findings of such behavior.

7.3.3 Ship design

In this thesis only the liquid hydrogen storage system has been considered, even though other different hydrogen storage options exist that could be used in maritime applications. The fuel cell system is another technology that is assumed to be available for shipping, however, a fuel cell system with sufficient power that can be used as propulsion system for large ships, currently does not exist. More research should be dedicated to those technologies in relation to their applicability and future capital costs in the maritime context. Such research should also consider the technical challenges involved with the installation on board ships and the associated safety aspects.

Liquid hydrogen system on board ship as well as other hydrogen storage system would need energy for storage and there will inevitably be some boil-off. The magnitude of these would depend from on the tank insulation and the effectiveness of the active cooling system, as well as the design solution adopted (e.g. heat recover). More research effort should be dedicated on this in order to estimate more accurate figures and to analyses the implication on the potential uptake of hydrogen.

Fuel cells and hydrogen storage systems will have most likely a lower volumetric density in comparison with the current marine engine and oil tank system. In this thesis the potential loss of cargo capacity was estimated without considering a possible reduction in range and power in comparison with the reference ship. The method used takes into account only the extra space that it might be required in comparison with a reference HFO tank and it analyses the theoretical loss of cargo capacity. This assumption implies that more research effort could be dedicated around the design and sizing requirements of alternative fuel storage systems and fuel cells systems on board ships.

7.3.4 Other relevant topics of research

The evaluation of the risks that the shipping industry could face in a decarbonised energy system is another important topic that can be raised from this thesis. The development of a systematic method that takes into account the specifications of a fleet of ships, and the associated transport costs could support the investment decisions of shipping companies.

The recent focus on LNG as alternative marine fuel and the findings of this thesis which do not see LNG as an option for the decarbonisation of the sector raises questions regarding the LNG bunkering infrastructure investment that is currently being deployed. Moreover, the possible use of natural gas to produce hydrogen raises questions on the upstream emissions implication; It would be useful to investigate what are the net emissions implication of using natural gas as a fuel for shipping or of using it to produce hydrogen. Upstream emissions are obviously very important; in this thesis they are accounted in the energy model and in its climate module which include all upstream emissions and makes sure that the mix of technologies is in line with the climate target. However, they are not easily quantifiable because it is not possible to extract in a clear way this information from TIAM-UCL. On the other hand, the shipping model does not need to account for the upstream emissions as in this thesis it is assumed that the shipowner will take his decision only based on operational emissions. Further analysis is required in order to answer questions on net emissions implication (upstream plus operational).

Finally, as mentioned above, long-term contracts can generate prices that are not necessarily linked with the balance of the supply and demand, but on the expectation that a particular fuel will be taken up in shipping, therefore, more effort could be dedicated to the exploration of the acceptability and expectation of the use of hydrogen in shipping and the associated commercial and financial dynamics that might arise. A road-map exercise could also create awareness on the potential of the fuel to be used in the sector.

References

- [ABB 2013] ABB: *Optimized cost of ownership. See all the hidden costs without paying any.* 2013
- [Agnolucci et. al. 2013] AGNOLUCCI, Paolo ; AKGUL, Ozlem ; McDOWALL, William ; PAPAGEORGIOU, Lazaros G.: The importance of economies of scale, transport costs and demand patterns in optimising hydrogen fuelling infrastructure. An exploration with SHIPMod (Spatial hydrogen infrastructure planning model). In: *International Journal of Hydrogen Energy* 38 (2013), Nr. 26, S. 11189–11201
- [Agnolucci and McDowall 2013] AGNOLUCCI, Paolo ; McDOWALL, William: Designing future hydrogen infrastructure. Insights from analysis at different spatial scales. In: *International Journal of Hydrogen Energy* 38 (2013), Nr. 13, S. 5181–5191
- [Alkaner and Zhou 2006] ALKANER, Selim ; ZHOU, Peilin: A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application. In: *Journal of Power Sources* 158 (2006), Nr. 1, S. 188–199
- [Anandarajah et. al. 2011] ANANDARAJAH, G ; PYE, S ; USHER, W ; KESICKI, F ; MCGLADE, Ch: TIAM-UCL Global model documentation. (2011)
- [Anandarajah et. al. 2013] ANANDARAJAH, Gabriel ; McDOWALL, Will ; EKINS, Paul: Decarbonising road transport with hydrogen and electricity. long term global technology learning scenarios. In: *International Journal of Hydrogen Energy* 38 (2013), Nr. 8, S. 3419–3432
- [Andersen et. al. 2011] ANDERSEN, Mads Lyder ; CLAUSEN, Niels B. ; SAMES, Pierre C.: *Costs and benefits of LNG as ship fuel for container vessels.* Germanischer Lloyd and MAN, 2011

- [Andrews and Shabani 2012] ANDREWS, John ; SHABANI, Bahman: Re-envisioning the role of hydrogen in a sustainable energy economy. In: *International journal of hydrogen energy* 37 (2012), Nr. 2, S. 1184–1203
- [Anon 2009] ANON: A portfolio of power-trains for Europe.a fact-based analysis. The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles. (2009)
- [Argyros et. al. 2014] ARGYROS, D ; SMITH, T ; RAUCCI, C ; SABIO, N: *Global marine fuel trends 2030*. 2014
- [Barreto et. al. 2003] BARRETO, Leonardo ; MAKIHIRA, Atsutoshi ; RIAHI, Keywan: The hydrogen economy in the 21st century: a sustainable development scenario. In: *International Journal of Hydrogen Energy* 28 (2003), Nr. 3, S. 267–284
- [Bauer et. al. 2008] BAUER, Nico ; EDENHOFER, Ottmar ; KYPREOS, Socrates: Linking energy system and macroeconomic growth models. In: *Computational Management Science* 5 (2008), Nr. 1-2, S. 95–117
- [Bengtsson 2011] BENGTSSON, Selma: *Life cycle assessment of present and future marine fuels*. Chalmers University of Technology, 2011
- [Bevan et. al. 2011] BEVAN, AI ; ZÜTTEL, A ; BOOK, D ; HARRIS, IR: Performance of a metal hydride store on the “Ross Barlow” hydrogen powered canal boat. In: *Faraday discussions* 151 (2011), S. 353–367
- [Böhringer 1998] BÖHRINGER, Christoph: The synthesis of bottom-up and top-down in energy policy modeling. In: *Energy economics* 20 (1998), Nr. 3, S. 233–248
- [Böhringer and Rutherford 2008] BÖHRINGER, Christoph ; RUTHERFORD, Thomas F.: Combining bottom-up and top-down. In: *Energy Economics* 30 (2008), Nr. 2, S. 574–596
- [Böhringer and Rutherford 2009] BÖHRINGER, Christoph ; RUTHERFORD, Thomas F.: Integrated assessment of energy policies. Decomposing top-down and bottom-up. In: *Journal of Economic Dynamics and Control* 33 (2009), Nr. 9, S. 1648–1661
- [Bosetti et. al. 2006] BOSETTI, Valentina ; CARRARO, Carlo ; GALEOTTI, Marzio ; MASSETTI, Emanuele ; TAVONI, Massimo: WITCH-A world induced technical change

- hybrid model. In: *University Ca'Foscari of Venice Economic Research Paper* (2006), Nr. 46/06
- [Boudries 2014] BOUDRIES, R: Hydrogen as a fuel in the transport sector in Algeria. In: *International Journal of Hydrogen Energy* 39 (2014), Nr. 27, S. 15215–15223
- [Bows-Larkin et.al. 2015] BOWS-LARKIN, Alice ; ANDERSON, Kevin ; MANDER, Sarah ; TRAUT, Michael ; WALSH, Conor: Shipping charts a high carbon course. In: *Nature Climate Change* 5 (2015), Nr. 4, S. 293–295
- [Brynolf et.al. 2014] BRYNOLF, Selma ; FRIDELL, Erik ; ANDERSSON, Karin: Environmental assessment of marine fuels. liquefied natural gas, liquefied biogas, methanol and bio-methanol. In: *Journal of Cleaner Production* 74 (2014), S. 86–95
- [Buhaug et.al. 2009] BUHAUG, Øyvind ; CORBETT, JJ ; ENDRESEN, Ø ; EYRING, V ; FABER, J ; HANAYAMA, S ; LEE, DS ; LEE, D ; LINDSTAD, H ; MARKOWSKA, AZ et.al.: Second imo ghg study 2009. In: *International Maritime Organization (IMO), London, UK* 24 (2009)
- [Bulletin 2013] BULLETIN, Fuel C.: First hydrogen fuel cell powered ferry in UK. In: *Fuel Cells Bulletin* 2013 (2013), Nr. 7, S. 4. – URL <http://www.sciencedirect.com/science/article/pii/S1464285913702499>. – ISSN 1464-2859
- [Campolongo et.al. 2011] CAMPOLONGO, Francesca ; SALTELLI, Andrea ; CARIBONI, Jessica: From screening to quantitative sensitivity analysis. A unified approach. In: *Computer Physics Communications* 182 (2011), Nr. 4, S. 978–988
- [CCC 2013] CCC: *Fourth Carbon Budget Review – part 2. The cost-effective path to the 2050 target*. Committee on Climate Change, 2013
- [Cohen et.al. 2011] COHEN, L. ; TATE, A. ; WEINHOLD, N.: Investigation into the implications of fuel cell shipboard integration into the T-AGOS 19 class. In: *Naval Surface Warfare Center Carderock Division Center for Innovation in Ship Design (NSWCCD CISD)* (2011)
- [Copeland et.al. 2005] COPELAND, Thomas E. ; WESTON, John F. ; SHASTRI, Kuldeep ; EDUCATION, Pearson: Financial theory and corporate policy. (2005)

- [Dagdougui 2012] DAGDOUGUI, Hanane: Models, methods and approaches for the planning and design of the future hydrogen supply chain. In: *International Journal of Hydrogen Energy* 37 (2012), Nr. 6, S. 5318–5327
- [Deane et.al. 2012] DEANE, JP ; CHIODI, Alessandro ; GARGIULO, Maurizio ; GALLACHÓIR, Brian P .: Soft-linking of a power systems model to an energy systems model. In: *Energy* 42 (2012), Nr. 1, S. 303–312
- [DECC 2012] DECC: *DECC Fossil fuel price projections*. Department of Energy and Climate Change, 2012. – URL https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65698/6658-decc-fossil-fuel-price-projections.pdf
- [Decourt et.al. 2014] DECOURT, Benoit ; LAJOIE, Bruno ; DEBARRE, Romain ; OLIVIER, Soupa: *Hydrogen based energy conversion, more than storage. system flexibility*. SBC Energy Institute, 2014
- [DNV 2010] DNV: *The age of LNG is here. Most cost efficient solution for ECAs*. International Maritime Statistic Forum Conference, Oslo, May 2010, 2010
- [DNV 2012] DNV: *Shipping 2020*. Det Norske Veritas Strategic Reserach and Innovation, 2012
- [DNV GL 2014] DNV GL: *Alternative fuels for shipping*. Position paper 1-2014, Det Norske Veritas Strategic Reserach and Innovation and Germanischer Lloyd, 2014
- [Docter and Lamm 1999] DOCTER, A ; LAMM, A: Gasoline fuel cell systems. In: *Journal of Power Sources* 84 (1999), Nr. 2, S. 194–200
- [Dodds and McDowall 2012] DODDS, Paul E. ; MCDOWALL, Will: *A review of hydrogen production technologies for energy system models*. UKSHEC working paper, 2012
- [Dodds et.al. 2015] DODDS, Paul E. ; STAFFELL, Iain ; HAWKES, Adam D. ; LI, Francis ; GRÜNEWALD, Philipp ; MCDOWALL, Will ; EKINS, Paul: Hydrogen and fuel cell technologies for heating. A review. In: *International Journal of Hydrogen Energy* 40 (2015), Nr. 5, S. 2065–2083
- [Dodds and Hawkes 2014] DODDS, PE ; HAWKES, A: The role of hydrogen and fuel cells in providing affordable, secure low-carbon heat. (2014)

- [DOE 2014] DOE: *Early Markets. Fuel Cells for Backup Power*. 2014. – URL http://californiahydrogen.org/sites/default/files/ftco_early_mkts_fc_backup_power_fact_sheet.pdf
- [Ehteshami and Chan 2014] EHTESHAMI, Seyyed Mohsen M. ; CHAN, SH: The role of hydrogen and fuel cells to store renewable energy in the future energy network–potentials and challenges. In: *Energy Policy* 73 (2014), S. 103–109
- [Ekins 2010] EKINS, Paul: *Hydrogen energy: economic and social challenges*. Earthscan, 2010
- [Endresen et. al. 2008] ENDRESEN, Øyvind ; EIDE, M ; VERITAS, DN ; DALSRØREN, HS ; ISAKSEN, IV ; SØRGÅRD, E: The environmental impacts of increased international maritime shipping, past trends and future perspectives. In: *Proceedings of the Global Forum on Transport and Environment in a Globalising World, Guadalajara, Mexico, November, 2008*, S. 10–12
- [EPA 2008a] EPA: Global Trade and Fuels Assessment -Future Trends and Effects of Requiring Clean Fuels in the Marine Sector. In: *Assessment and Standards Division Office of Transportation and Air Quality U.S.* EPA420-R-08-021 (2008)
- [EPA 2008b] EPA: *Technology Characterization. Fuel Cells*. Environmental Protection Agency, 2008
- [Erkko 2011] ERKKO, Fontell: Wärtsilä Fuel Cell Development Program. In: *The 8th annual Green Ship Technology Conference, Oslo, March 21-22, 2011*, 2011
- [EU 2013] EU: *Communication from the Commission to the European Parliament and the Council, The European Economic and Social Committee and the Committee of the regions. Clean Power for Transport. A European alternative fuels strategy*. European Union. European Commission, 2013
- [Farrell et. al. 2003] FARRELL, AE ; KEITH, DW ; CORBETT, JJ: A STRATEGY FOR INTRODUCING HYDROGEN INTO TRANSPORTATION. In: *Transportation, Energy, and Environmental Policy. Managing Transitions*, 2003
- [FCH 2015] FCH: *Advanced multi -fuel reformer for CHP- fuel cell system*. The Fuel Cells and Hydrogen Joint Undertaking (FCH JU), 2015. – URL <http://www.fch.>

- europa.eu/project/advanced-multi-fuel-reformer-chp-fuel-cell-systems. – Zugriffsdatum: 2015-17-11
- [Fernández Soto et.al. 2010] FERNÁNDEZ SOTO, JL ; GARAY SEIJO, R ; FRAGUELA FORMOSO, JA ; GREGORIO IGLESIAS, G ; CARRAL COUCE, L: Alternative sources of energy in shipping. In: *Journal of Navigation* 63 (2010), Nr. 03, S. 435–448
- [Geels 2002] GEELS, Frank W.: Technological transitions as evolutionary reconfiguration processes. A multi-level perspective and a case-study. In: *Research policy* 31 (2002), Nr. 8, S. 1257–1274
- [Gerd 2009] GERD, Wursig: *Shipping - A Market for Fuel Cell Systems? Challenges and Opportunities for Fuel Cell Technology*. 2009
- [GL 2011] GL: *Costs and benefits of LNG as ship fuel for container vessels*. Lloyd Germanischer Research and Rule, 2011
- [GL 2012] GL: *LNG powering the future of shipping*. Germanischer Lloyd, 2012
- [Godfrey-Smith 2006] GODFREY-SMITH, Peter: The strategy of model-based science. In: *Biology and Philosophy* 21 (2006), Nr. 5, S. 725–740
- [Hammerschmidt 2016] HAMMERSCHMIDT, A.: *Fuel Cell Propulsion of Submarines*. Advanced Naval Propulsion Symposium 2006, October 30- 31, 2006, Arlington, VA, USA, 2016
- [Han et.al. 2012] HAN, Jingang ; CHARPENTIER, JF ; TANG, Tianhao: State of the art of fuel cells for ship applications. In: *Industrial Electronics (ISIE), 2012 IEEE International Symposium on IEEE* (Veranst.), 2012, S. 1456–1461
- [Hourcade et.al. 2006] HOURCADE, Jean-Charles ; JACCARD, Mark ; BATAILLE, Chris ; GHERSI, Frédéric: Hybrid Modeling. New Answers to Old Challenges Introduction to the Special Issue of "The Energy Journal". In: *The Energy Journal* (2006), S. 1–11
- [HYTEC 2015] HYTEC: *Project Summary*. URL <http://hy-tec.eu/2012/project-summary/>. – Zugriffsdatum: 2015-09-04, 2015

- [ICS 2009] ICS: *Shipping World Trade and the Reduction of CO₂ Emissions*. United Nations Framework Convention on Climate Change (UNFCCC). International Chamber of Shipping, 2009
- [IEA 2006] IEA: *Hydrogen production and storage - R&D Priorities and Gaps*. International Energy Agency, 2006
- [IEA 2011] IEA: *Technology roadmap. Biofuels for Transport*. International Energy Agency, 2011
- [IEA 2015] IEA: *Technology roadmap. Hydrogen and Fuel Cells*. International Energy Agency, 2015
- [IMO 2015] IMO: *Air Pollution Energy Efficiency and Greenhouse Gas Emissions*. URL <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Default.aspx>. – Zugriffsdatum: 2015-09-04, 2015
- [INTERTANKO 2012] INTERTANKO: *Emission Control Area (ECA) SO_x Requirements - Guidance to INTERTANKO Members for the Selection of Compliance Alternatives*. 2012
- [IPCC 2013a] IPCC: SCENARIOSEMISSION SSPECIAL REPORT. In: *Working Group III of the Intergovernmental Panel on Climate Change. Emissions Scenarios. Washington, DC, USA. UNT Digital Library* (2013)
- [IPCC 2013b] IPCC ; STOCKER, T.F. (Hrsg.) ; QIN, D. (Hrsg.) ; PLATTNER, G.-K. (Hrsg.) ; TIGNOR, M. (Hrsg.) ; ALLEN, S.K. (Hrsg.) ; BOSCHUNG, J. (Hrsg.) ; NAUELS, A. (Hrsg.) ; XIA, Y. (Hrsg.) ; BEX, V. (Hrsg.) ; MIDGLEY, P.M. (Hrsg.): *Summary for Policymakers*. Cambridge, United Kingdom and New York, NY, USA : Cambridge University Press, 2013. – 1–30 S. – URL www.climatechange2013.org. – ISBN ISBN 978-1-107-66182-0
- [Jacobsen 1998] JACOBSEN, Henrik K.: Integrating the bottom-up and top-down approach to energy–economy modelling. The case of Denmark. In: *Energy Economics* 20 (1998), Nr. 4, S. 443–461
- [James et.al. 2010] JAMES, Brian D. ; KALINOSKI, Jeffrey A. ; BAUM, Kevin N.: Mass production cost estimation for direct H₂ PEM fuel cell systems for automotive applications. 2010 update. In: *Directed Technologies inc. report* (2010)

- [James et. al.] JAMES, Brian D. ; MOTON, Jennie M. ; COLELLA, Whitney G.: Hydrogen Storage Cost Analysis.
- [James et. al. 2012] JAMES, Brian D. ; SPISAK, Andrew B. ; COLELLA, Whitney G.: *Stationary Fuel Cell System Cost Analysis*. URL https://www.hydrogen.energy.gov/pdfs/progress12/v_a_3_james_2012.pdf, 2012
- [Jens Oluf Jensen and Bjerrum 2010] JENS OLUF JENSEN, Qingfeng L. ; BJERRUM, Niels J.: *The Energy Efficiency of Different Hydrogen Storage Techniques, Energy Efficiency*. Jenny Palm (Ed.) InTech, 2010
- [Joffe and Strachan 2007] JOFFE, David ; STRACHAN, Neil: Review of modelling approaches to the development of a ‘hydrogen economy’. (2007)
- [JRC 2007] JRC: *Report on the Workshop on the contribution of hydrogen to reach European renewable energy targets*. European Commission Joint Research Center (JRC), 2007
- [Koeftman 2012] KOEFMAN, Mike: *Hydrogen as the dominant fuel for shipping. Justification, technology, cost, implications*. 2012
- [Konda et. al. 2011] KONDA, NVSN M. ; SHAH, Nilay ; BRANDON, Nigel P.: Optimal transition towards a large-scale hydrogen infrastructure for the transport sector. The case for the Netherlands. In: *international journal of hydrogen energy* 36 (2011), Nr. 8, S. 4619–4635
- [Krčum et. al. 2004] KRČUM, Maja ; GUDELJ, Anita ; JURIĆ, Zdeslav: Fuel Cells for Marine Application. In: *46th International Symposium Electronics in Marine, ELMAR 2004*, Hrvatska znanstvena bibliografija i MZOS-Svibor (Veranst.), 2004
- [Kumbaroğlu and Madlener 2003] KUMBAROĞLU, Gürkan ; MADLENER, Reinhard: Energy and climate policy analysis with the hybrid bottom-up computable general equilibrium model SCREEN. The case of the Swiss CO₂ act. In: *Annals of Operations Research* 121 (2003), Nr. 1-4, S. 181–203
- [Kunze and Kircher 2012] KUNZE ; KIRCHER: *Cryo-Compressed hydrogen storage*. 2012
- [Lloyds Register 2012] LLOYDS REGISTER: *LNG-fuelled deep sea shipping*. Technical report. Lloyds Register, 2012

- [Loulou and Labriet 2008] LOULOU, Richard ; LABRIET, Maryse: ETSAP-TIAM. the TIMES integrated assessment model Part I. Model structure. In: *Computational Management Science* 5 (2008), Nr. 1-2, S. 7–40
- [Ludvigsen and Ovrum 2012] LUDVIGSEN, KB ; OVRUM, E: Fuel cells for ships. In: *Research and Innovation, Position Paper* (2012)
- [Manne and Wene 1992] MANNE, Alan S. ; WENE, Clas-Otto: MARKAL-MACRO. A linked model for energy-economy analysis. (1992)
- [Mansilla et. al. 2012] MANSILLA, C ; AVRIL, S ; IMBACH, J ; LE DUIGOU, A: CO 2-free hydrogen as a substitute to fossil fuels. What are the targets? Prospective assessment of the hydrogen market attractiveness. In: *International Journal of Hydrogen Energy* 37 (2012), Nr. 12, S. 9451–9458
- [Mazloomi and Gomes 2012] MAZLOOMI, Kaveh ; GOMES, Chandima: Hydrogen as an energy carrier, prospects and challenges. In: *Renewable and Sustainable Energy Reviews* 16 (2012), Nr. 5, S. 3024–3033
- [McConnell 2010] MCCONNELL, Vicki P.: Now, voyager? The increasing marine use of fuel cells. In: *Fuel Cells Bulletin* 2010 (2010), Nr. 5, S. 12–17
- [McDowall 2012] MCDOWALL, Will: *Endogenous technology learning for hydrogen and fuel cell technology in UKSHEC II. Literature review, research questions and data*. UKSHEC working paper, 2012
- [McDowall and Eames 2007] MCDOWALL, William ; EAMES, Malcolm: Towards a sustainable hydrogen economy: A multi-criteria sustainability appraisal of competing hydrogen futures. In: *International Journal of Hydrogen Energy* 32 (2007), Nr. 18, S. 4611–4626
- [McGlade and Ekins 2014] MCGLADE, Christophe ; EKINS, Paul: Un-burnable oil. An examination of oil resource utilisation in a decarbonised energy system. In: *Energy Policy* 64 (2014), S. 102–112
- [McGlade and Ekins 2015] MCGLADE, Christophe ; EKINS, Paul: The geographical distribution of fossil fuels unused when limiting global warming to 2 [deg] C. In: *Nature* 517 (2015), Nr. 7533, S. 187–190

- [MEPC.1/Circ.61/INF2 2010] MEPC.1/CIRC.61/INF2: *Reduction of GHG emissions from ships. Full report of the work undertaken by the Expert Group on Feasibility Study and Impact Assessment of possible Market-based Measures*. IMO Note by the Secretariat, 2010
- [MEPC.1/Circ.6851 2015] MEPC.1/CIRC.6851: *Reduction of GHG emissions from ships. Setting a reduction target and agreeing associated measures for international shipping*. IMO Submitted by the Marshall Islands, 2015
- [Messner and Schrattenholzer 2000] MESSNER, Sabine ; SCHRATTENHOLZER, Leo: MESSAGE-MACRO. Linking an energy supply model with a macroeconomic module and solving it iteratively. In: *Energy* 25 (2000), Nr. 3, S. 267–282
- [Michalski and Bünger 2016] MICHALSKI, Jan ; BÜNGER, Ulrich: *Green Hydrogen Supply For the Power and Mobility Sectors*. LBST presentation at World Hydrogen Energy Conference (WHEC) 2016, June 13-16, Zaragoza, Spain, 2016
- [Monique and Vermeire 2012] MONIQUE ; VERMEIRE: *Everything You Need to Know About Marine Fuels*. Published by Chevron Global Marine Products, 2012. – URL http://www.chevronmarineproducts.com/content/dam/chevron-marine/Brochures/Chevron_EverythingYouNeedToKnowAboutFuels_v3_1a_DESKTOP.pdf
- [Moyo et. al. 2012] MOYO, Alfred ; WINKLER, Harald ; WILLIAM, Wills: *Challenges of linking sectoral and economy-wide models*. MAPS, 2012
- [Mueller-Langer et. al. 2007] MUELLER-LANGER, F ; TZIMAS, E ; KALTSCHMITT, M ; PETEVES, S: Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term. In: *International Journal of Hydrogen Energy* 32 (2007), Nr. 16, S. 3797–3810
- [Mulder and Mulligan 2010] MULDER, Chris ; MULLIGAN, Mark: Project to build a prototype hydrogen-powered hybrid electric tug. In: *Paper No G4 at ITS - International Tug and Salvage Convention and Exhibition* ITS (Veranst.), 2010
- [Oh and Karimi 2010] OH ; KARIMI, IA: Operation planning of multiparcel tankers under fuel price uncertainty. In: *Industrial & Engineering Chemistry Research* 49 (2010), Nr. 13, S. 6104–6114

- [Ohira 2016] OHIRA, Eiji: *Current Policy and Research and Development Activity on Hydrogen Energy in Japan*. NEDO presentation at World Hydrogen Energy Conference (WHEC) 2016, June 13-16, Zaragoza, Spain, 2016
- [Pannell 1997] PANNELL, David J.: Sensitivity analysis of normative economic models: theoretical framework and practical strategies. In: *Agricultural Economics* 16 (1997), Nr. 2, S. 139 – 152. – URL <http://www.sciencedirect.com/science/article/pii/S0169515096012170>. – ISSN 0169-5150
- [Pincock 2012] PINCOCK, Christopher: *Mathematics and scientific representation*. Oxford University Press, 2012
- [Psoma and Sattler 2002] PSOMA, Angela ; SATTLER, Gunter: Fuel cell systems for submarines. From the first idea to serial production. In: *Journal of Power Sources* 106 (2002), Nr. 1, S. 381–383
- [Riekkola et. al. 2013] RIEKKOLA, Anna K. ; BERG, Charlotte ; AHLGREN, Erik O. ; SÖDERHOLM, Patrik: Challenges in Soft-Linking. The Case of EMEC and TIMES-Sweden. (2013)
- [Rodrigue et. al. 2013] RODRIGUE, Jean-Paul ; COMTOIS, Claude ; SLACK, Brian: *The geography of transport systems*. Routledge, 2013
- [Rohde and Nikolajsen 2013] ROHDE ; NIKOLAJSSEN: *Zero-Emission Ferry Concept for Scandlines*. URL <http://www.ship-efficiency.org/onTEAM/pdf/07%20Fridtjof%20Rohde.pdf>, 2013
- [Rojon 2013] ROJON, INM: Blowin’ in the wind? Possibilities of the International Maritime Organization to promote the uptake of wind propulsion in international shipping. (2013)
- [Rosenberg et. al. 2010] ROSENBERG, Eva ; FIDJE, Audun ; ESPEGREN, Kari A. ; STILLER, Christoph ; SVENSSON, Ann M. ; MØLLER-HOLST, Steffen: Market penetration analysis of hydrogen vehicles in Norwegian passenger transport towards 2050. In: *international journal of hydrogen energy* 35 (2010), Nr. 14, S. 7267–7279
- [Ruud Verbeek 2011] RUUD VERBEEK, Herman den U.: *Alternative fuels for sea shipping*. 2011

- [Saltelli and Annoni 2010] SALTELLI, Andrea ; ANNONI, Paola: How to avoid a perfunctory sensitivity analysis. In: *Environmental Modelling & Software* 25 (2010), Nr. 12, S. 1508–1517
- [Sattler 1998] SATTLER, Gunter: PEFCs for naval ships and submarines. Many tasks, one solution. In: *Journal of power sources* 71 (1998), Nr. 1, S. 144–149
- [Sattler 2000] SATTLER, Gunter: Fuel cells going on-board. In: *Journal of power sources* 86 (2000), Nr. 1, S. 61–67
- [SBA 2014] SBA: *Hydrogen-based energy conversion. More than storage. System flexibility*. 2014
- [Schaefer and Jacoby 2006] SCHAEFER, Andreas ; JACOBY, Henry D.: Vehicle technology under CO₂ constraint. A general equilibrium analysis. In: *Energy Policy* 34 (2006), Nr. 9, S. 975–985
- [Schafer 2012] SCHAFER, Andreas: Introducing behavioral change in transportation into energy/economy/environment models. In: *World Bank Policy Research Working Paper* (2012), Nr. 6234
- [Schoots et.al. 2010] SCHOOTS, K ; KRAMER, GJ ; VAN DER ZWAAN, BCC: Technology learning for fuel cells. An assessment of past and potential cost reductions. In: *Energy Policy* 38 (2010), Nr. 6, S. 2887–2897
- [Semolinos 2013] SEMOLINOS, Olsen G. Giacosa A.: *LNG as marine fuel Challenges to be overcome*. 17th International Conference and Exhibition on Liquefied Natural Gas, April 16-19, Houston, Texas, 2013
- [Shukla 2013] SHUKLA, PR: Review of linked modelling of low-carbon development, mitigation and its full costs and benefits. (2013)
- [Shukla et.al. 2010] SHUKLA, PR ; DHAR, Subash ; FUJINO, Junichi: Renewable energy and low carbon economy transition in India. In: *Journal of Renewable and Sustainable Energy* 2 (2010), Nr. 3, S. 031005
- [Smith and Wrobel 2015] SMITH, Traut Bows-Larkin Anderson K.2 M. ; WROBEL: CO₂ Targets, Trajectories and Trends for International Shipping. In: *Shipping in Changing Climates (SCC)* University College London, University of Manchester (Veranst.), 2015

- [Smith 2012] SMITH, T.W.P.: Technical energy efficiency, its interaction with optimal operating speeds and the implications for the management of shipping's carbon emissions. In: *Carbon Management* 3 (2012), Nr. 6, S. 589–600
- [Smith et. al. 2015] SMITH, T.W.P. ; JALKANEN, J.P. ; ANDERSON, B.A. ; CORBETT, J.J. ; FABER, J. ; HANAYAMA, S. ; O'KEEFFE, E. ; PARKER, S. ; JOHANSSON, L. ; ALDOUS, L. ; RAUCCI, C. ; TRAUT, M. ; ETTINGER, S. ; NELISSEN, D. ; LEE, D. S. ; NG, S. ; AGRAWAL, A. ; WINEBRAKE, J. J. ; HOEN, M. ; CHESWORTH, A.: Third IMO GHG Study 2014. In: *International Maritime Organization (IMO), London* (2015)
- [Smith et. al. 2013a] SMITH, T.W.P. ; O'KEEFFE, E. ; HAJI, S. ; AGNOLUCCI, P.: GloTraM external factors. (2013)
- [Smith et. al. 2013b] SMITH, T.W.P. ; O'KEEFFE, E. ; HAJI, S. ; AGNOLUCCI, P.: Maritime Sector Model Report. (2013)
- [Sødal 2003] SØDAL, Sigbjørn: Fuel cells in shipping. higher capital costs and reduced flexibility. (2003)
- [Solano and Drummond 2014] SOLANO, B. ; DRUMMOND, P.: *Techno-Economic Scenarios for Reaching Europe's Long-Term Climate Targets. Using the European TIMES Model (ETM-UCL) to Model Energy System Development in the EU*. CECILIA 2050 Optimal EU Climate Policy, 2014
- [Song et. al. 2013] SONG, Xiao-meng ; KONG, Fan-zhe ; ZHAN, Che-sheng ; HAN, Ji-wei ; ZHANG, Xin-hua: Parameter identification and global sensitivity analysis of Xin'anjiang model using meta-modeling approach. In: *Water Science and Engineering* 6 (2013), Nr. 1, S. 1–17
- [Strachan et. al. 2009] STRACHAN, Neil ; BALTA-OZKAN, Nazmiye ; JOFFE, David ; MCGEEVOR, Kate ; HUGHES, Nick: Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. In: *International Journal of Hydrogen Energy* 34 (2009), Nr. 2, S. 642–657
- [Taljegard et. al. 2014] TALJEGARD, Maria ; BRYNOLF, Selma ; GRAHN, Maria ; ANDERSSON, Karin ; JOHNSON, Hannes: Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World. Results from a Global Energy Model. In: *Environmental science & technology* 48 (2014), Nr. 21, S. 12986–12993

- [TENconnect 2009] TENCONNECT: TRANS-TOOLS version 2: Model and Data Improvements. In: *DK: Centre for Traffic and Transport, Technical University of Denmark and Kiel: Institute for Regional Research, Christian Albrechts University* (2009). – URL http://energy.jrc.ec.europa.eu/transtools/docs/TenC408_001_ver20090721.pdf
- [UNCTAD 2012] UNCTAD, Secretariat: *Review of Maritime Transport 2012*. United Nations Publications, 2012
- [Upadhyay et. al. 2011] UPADHYAY, P ; AMANI, Y ; BURKE, R: 17. Integrating Modular Hydrogen Fuel Cell Drives for Ship Propulsion. Prospectus and Challenges. In: *Miscellaneous Problems in Maritime Navigation, Transport and Shipping. Marine Navigation and Safety of Sea Transportation* (2011), S. 133
- [Veldhuis et. al. 2007] VELDHUIS, IJS ; RICHARDSON, RN ; STONE, HBJ: Hydrogen fuel in a marine environment. In: *International Journal of Hydrogen Energy* 32 (2007), Nr. 13, S. 2553–2566
- [Verbeek et. al. 2011] VERBEEK, Ruud ; KADIJK, Gerrit ; MENSCH, Pim van ; WULFERS, Chris ; BEEMT, Bas van den ; FRAGA, Filipe ; AALBERS, Assignor Drs A.: Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands. In: *Delft, TNO* 48 (2011)
- [Vilhelmsen et. al. 2014] VILHELMSSEN, Charlotte ; LUSBY, Richard ; LARSEN, Jesper: Tramp ship routing and scheduling with integrated bunker optimization. In: *EURO Journal on Transportation and Logistics* 3 (2014), Nr. 2, S. 143–175
- [Vogler 2010] VOGLER, Finn: *Fuel cell systems in maritime applications*. Germanisher Lloyd AG, 2010
- [Wartsila 2012] WARTSILA: *LNG as a bunker fuel*. International Maritime Statistic Forum Conference, Oslo, May 2012, 2012
- [Weisberg 2012] WEISBERG, Michael: *Simulation and similarity. Using models to understand the world*. Oxford University Press, 2012
- [Wene 1996] WENE, C-O: Energy-economy analysis. linking the macroeconomic and systems engineering approaches. In: *Energy* 21 (1996), Nr. 9, S. 809–824

- [Winebrake et.al. 2007] WINEBRAKE, James J. ; CORBETT, James J. ; MEYER, Patrick E.: Energy use and emissions from marine vessels. A total fuel life cycle approach. In: *Journal of the Air & Waste Management Association* 57 (2007), Nr. 1, S. 102–110
- [Winsberg 2013] WINSBERG, Eric: *Computer simulations in science*. Stanford Encyclopedia of Philosophy, 2013. – URL <https://stanford.library.sydney.edu.au/entries/simulations-science/>
- [Winter and Nitsch 2012] WINTER, Carl-Jochen ; NITSCH, Joachim: *Hydrogen as an energy carrier: technologies, systems, economy*. Springer Science & Business Media, 2012
- [Zaetta and Madden 2011] ZAETTA, R ; MADDEN, B: Hydrogen fuel cell bus technology state of the art review. In: *Element Energy report for the NextHyLights project, Cambridge* 278 (2011)
- [Zemships 2008] ZEMSHIPS: *One hundred passengers and zero emissions. The first ever passenger vessel to sail propelled by fuel cells*. Zemships, 2008
- [Züttel et.al. 2010] ZÜTTEL, Andreas ; REMHOF, Arndt ; BORGSCHULTE, Andreas ; FRIEDRICHS, Oliver: Hydrogen. the future energy carrier. In: *Philosophical Transactions of the Royal Society of London A Mathematical, Physical and Engineering Sciences* 368 (2010), Nr. 1923, S. 3329–3342