Energy, Environmental and Economic Impact Assessment of Hydrogen Scenarios in the Portuguese Road Transportation Sector (2010-2050)

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Abbreviations and acronyms

BEV – Battery Electric Vehicles

CCS - Carbon Capture and Storage

CES - Constant Elasticity of Substitution

CGE, Computable General Equilibrium

CO_2 – Carbon Dioxide

CTG – Cradle-To-Grave

EJ – Exajoule, 1 EJ = 10^{18} J

FCV/FCEV - Fuel Cell Vehicles

FCHEV – Fuel Cell Hybrid Electric Vehicle

FCH-JU – Fuel Cell and Hydrogen Joint Undertaking

FCPHEV - Fuel Cell Plug-in Hybrid Electric Vehicle

GAMS, General Algebraic Modelling System

GDP, Gross Domestic Product

GHG - Greenhouse Gases

Gt – Gigatonne, 1 Gt = 10^9 tonne

HEV - Hybrid Electric Vehicle

H_2 HEV – Hydrogen Hybrid Electric Vehicle

ICE-Internal Combustion Engine

IGCC –Integrated Gasification Combined Cycle

LCA – Life Cycle Assessment

LDV – Light-Duty Vehicle

LWP – Lower Warming Potential

MAIP – Multi-Annual Implementation Plan (2008-2013) from Fuel Cell and Hydrogen Joint Undertaking

Mtoe - Million tons of oil equivalent

NLP - Non Linear Problem

PJ – Pentajoule, 1 PJ = 10^{15} J

PHEV - Plug-in Hybrid Electric Vehicles

R&D – Research and Development

RD&D – Research, Development and Demonstration

RNBC 2050 – Roteiro Nacional Baixo Carbono

SET – Plan - Strategic Energy Technology Plan

SMR – Steam Methane Reforming

SWOT - Strength, Weaknesses, Opportunities and Threats

TTW – Tank-to-Wheel

TOC – Total Ownership Cost

Water Electrolysis - WE

WTT – Well-to-Tank

WTW – Well-to-Wheel

Document organization

Following the executive summary in the first section, we have the introduction of the subject in the second section. The third section presents the main conclusions of the reviewed studies concerning hydrogen deployment in transportation. Section four presents the energy model denoted PATTS. The fifth section consists of the macroeconomic model. The major results and conclusions are in the last section of this report.

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Tables & Figures

1. EXECUTIVE SUMMARY

This report refers to the the AP2H2 subcontracted study “*Elaboração de cenários de penetração de H2 como vector energético para a mobilidade em 2020/30/50*”. We would like to thank Patricia Baptista for the very useful input data. We would also like to thank Professor Joaquim Borges Gouveia at the University of Aveiro for his encouragement. We are very grateful to Professor Christoph Böhringer for his always very helpful comments provided in the computer lab session on GAMS programming that took place at the University of Oslo in Norway during the Integrated Assessment Modelling intensive course on 9-12 September 2014. All errors are the authors’ sole responsibility.

The report presents an analysis of the potential economic-wide energy and CO_2 emissions implications of hydrogen vehicle penetration into the Portuguese road transport over the time-horizon 2010-2050. The energy and emissions implications are obtained using PATTS (Projections for Alternative Transportation Technologies Simulation), an excel spreadsheet model based on forecast scenarios. Historical data and trends of gasoline versus diesel share, fleet scrappadge, representative light-duty vehicle technologies life cycle energy and emission factors, are used to estimate, on a yearly basis, the total fleet life cycle energy consumption, CO_2 emissions and air quality related impact. The macroeconomic effects are assessed with a Computable General Equilibrium model that is solved as a non-linear optimization problem formulated in GAMS software capable of dealing with substitution between labour, capital stock, electric energy and non-electric energy factors of production. It integrates parameter inputs obtained from PATTS tool where the transportation sector becomes hydrogen driven and a wide hydrogen refuelling infrastructure is deployed.

The simulation experiments show that "*hydrogen technologies*" are likely to become economically viable. Household consumption, real GDP and investment increase from baseline. The positive impact upon the economic variables is supplemented by energy costs reductions, of just -0.1 to -0.3 percent per annum, in both high-price and low-price cases. The economy grows faster in the low-price case where the reductions in energy costs are also more pronounced. CO_2 avoided emissions due to hydrogen economy reach a maximum of 2 kton/km in 2050, if the natural gas steam reforming production method is adopted.

2. INTRODUCTION

This report refers to the point 2.a)1) of the AP2H2 subcontracted study “Estudo de modelação de penetração do Hidrogénio na mobilidade no quadro da ENE 2020/30/50”. For moving to a low carbon economy in 2050, and respect the 2ºC maximum temperature rise, the developed countries will need to target a cut of 80-95% of greenhouse gas emissions below 1990 levels by 2050. Knowing that the road transport contribution share for this emission is roughly 20%, this sector has been particularly studied as far as forecasting/ backcasting/ scenarization is concerned. Concerning scenarios in existing reports, e.g. [1], [2], [3], [4], [5], [6], [7] it is noted that the variations are not only due to hydrogen penetration but also different assumptions concerning other technologies, demography, oil dependency, feedstock energy cost and economic growth, between others.

Hydrogen as an energy carrier and its use in passenger transportation through the fuel cell technology is widely considered as part of the solution to help meeting the targets. Hydrogen vehicles may include vehicles with internal combustion engines, but for the longer term fuel cell powered vehicles are expected to prevail. Due to being an in-use zero emission technology, the need for a methodology on how to account for GHG intensity of energy carriers and determining appropriate metrics is essential to make sure that post 2020 targets provide the right incentives to manufacturers and energy suppliers. Therefore some studies consider the hydrogen complete chain, i.e., hydrogen production and use to compute an overall GHG benefit comparing with conventional diesel/gasoline fuel use. This approach is called well-to-wheel (WTW), and is composed by fuel production (well-to-tank, WTT) and fuel use when driving the vehicles (tank-to-wheel, TTW). Some other studies consider only the WTT stage. Concerning energy security, hydrogen is one of the fuels that become more secure, due to expected increased contributions from renewables. The following studies mention hydrogen: Global Transports Scenarios [1]; Technology Map of the European SET-Plan [2]; Roteiro Nacional Baixo Carbono [3]; Scenarios for Portugal [4]; HYRREG for SUDOE [5]; HyWays for Europe [6]; McKinsey for

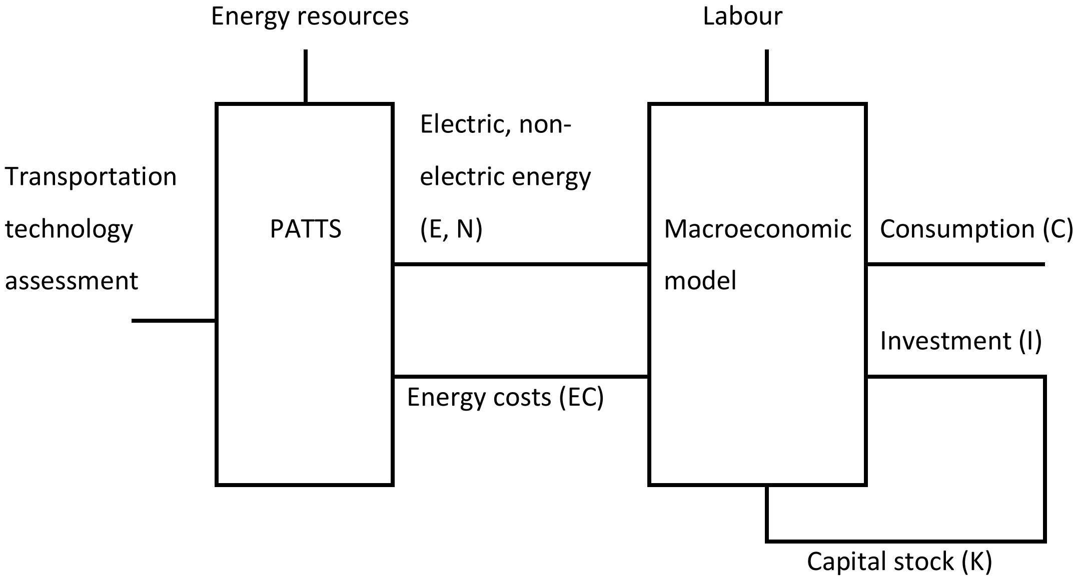
Europe [7]. No GDP impact was predicted within these studies and this is one of the main novelties of the present research along with life cycle impact estimations. The later may be found in some author related research examples [8], [9], [10], [11].

About 450 billion m^3 of hydrogen were produced and consumed worldwide in 2011, but mostly as raw material for the production of chemicals rather than as a fuel itself [12]. Regarding vehicles using hydrogen, several technologies are possible: Fuel Cell Vehicles (FCV), Fuel Cell Hybrid Electric Vehicles (FCHEV), Fuel Cell Plug-in Hybrid Electric Vehicles (FCPHEV) and Internal Combustion Engines (ICE) being this last option possible to combine with hybridization, defined as H_2 HEV. Mainly demonstration projects are related to the public bus sector, such as the Clean Urban Transport for Europe (CUTE), the Global Hydrogen Bus Platform (HyFLEET:CUTE), the Sustainable Transport Energy Programme (STEP) and the Ecological City Transport System (ECTOS). Some original equipment manufacturers (OEM) of light-duty vehicles have already engaged in alternative powertrain using hydrogen. About those prototypes, out of more than 20, there are: Mercedes-Benz F600 Hygenius (hybrid), Honda FCX (hybrid), GM Chevy Volt Hydrogen (hybrid plug-in) and Ford Edge with HySeries Drive (hybrid plug-in) [13]. Despite the promising aspects of hydrogen economy, its realization faces multiple challenges, from economic to technological and institutional barriers that the need arises for a coordinated Roadmap with a strategy to overcome these barriers [5].

In this report three fleet model scenarios are combined with two Brent price possible evolutions, one hydrogen and one electricity price evolution to integrate with one macroeconomic model and to obtain as outputs fossil energy importation impact, CO_2 emission impact, criteria emissions impact, and GDP impact.

This paper main focus is on integrating the energy simulation tool PATTS [14] and the CGE model to assess the macroeconomic effects where the transportation sector becomes hydrogen driven. Figure 1 provides an overview of the principal static linkages between the two blocs.

Fig. 1 - Models interaction scheme.



Source: adapted from [15]

3. LITERATURE REVIEW

Concerning the production of H_2, it is identified a tendency to consider the production in the short-medium term (2020-2030) by SMR and electrolysis, this last one essentially in decentralized mode. The CCS appears as a new technology, which development will play a key role in the chosen feedstock and production process. In the long term there is a trend for more centralized production, gasification of coal and biomass entering in the mix. It is expected that H_2 is produced from a diversity of resources, depending on the endogenous resources available in each region. In Roteiro Nacional de Baixo Carbono, that is specific for Portugal it is presented the H_2 production mainly from biomass gasification [1]. HyWays for Europe [2] and the HYRREG for SUDOE [3], present the electrolysis essentially from renewable sources, being the wind the preferred feedstock, solar photovoltaic also appears in the second study as a potential source after 2030, in Portugal. The endogenous energy resources of each region can determine which one to use for the electrolysis process. The level of population and geographic conditions also influence the most cost-effective (centralized or decentralized) way to produce the H_2 in each area.

The hydrogen distribution is expected to be in the short-medium term by truck (gaseous or liquid), and in the long term it will be mainly by pipelines, remaining the other ways an option for less populated or remote areas. Concerning refueling stations, there is a forecast that they will be in the early stages small (2 dispensers, 0.4 tonnes of hydrogen/day), than medium (4 dispensers, 1 tonne of hydrogen/day) and large stations (10 dispensers, 2.5 tonnes of hydrogen/day) take place.

About the use of H_2 in the transports, it will be made essentially by means of the fuel cell technology in hybrid configurations of passenger cars. For studies that only take into account the midterm, like [4] and [2], the consumption could be respectively between the order of 10 and 10^-4 PJ. The Global Transports Scenarios [5], forecasts a total consumption of H_2 between 0.1 and 1 EJ for cars in 2050, what means, depending on the scenario, 0.62 to 4% of the total energy consumed in that sector. It does not consider the use of hydrogen in other transports. For the specific case of Portugal, in Roteiro Nacional de Baixo Carbono [1], the consumption in 2050 can reach 0.01EJ, corresponding to a percentage between 0 and 16.5% in of the total energy consumption in transports; in the Scenarios for Portugal [6] the percentage of hydrogen consumption in Portugal in 2050 will reach a maximum of 9% in the fleet, corresponding to 10 PJ.

Regarding the fleet penetration, the Global Transports Scenarios [5], preview the penetration of hydrogen vehicles between about 1.6 and 3.3% (FCV+H_2 HEV) in 2030, while in 2050 the percentage can vary among 1.25 and 6.17%. Studies for Europe are more optimistic concerning the penetration of hydrogen vehicles, in the scenarios of HyWays for Europe [2], the percentage reaches 3 to 24% in 2030, while in 2050 it varies from 26 to 74%. The Mckinsey for Europe [7] considers a penetration of 25% of hydrogen vehicles in 2050. The Scenarios for Portugal [6], depending on the scenarios shows an entering that can vary from 0 to 22% in 2050.

Analyzing the cost of the H_2 for the midterm 2020-2030, the range of values from the different studies goes from a minimum of 2.5€/kg [6] to 6.6€/kg [8]. In 2050 the value varies between 3.09 $/kg [5] and 4€/kg [7]. Concerning the Fuel Cell cost, it is forecasted for the midterm the cost between 148 and 250$/kW [5], while the European studies for the same timeframe consider the cost in the order of dozens. For 2050, only in [5] it is expected a value, that can vary among 84 and 250 $/kW. The FCV acquisition cost in the midterm (2020-2030) is among $18200 [5] and 31000€ [7]. In the long term (2050) the cost can vary between 21900 [5] and 22802 € [6].

The level of CO_2 emissions from the H_2 production depend on the process and the feedstocks used. Anyway, according to the assumptions assumed (variations also in the demography, economic, other technologies used, energy cost, between others), the scenarios considering the introduction of hydrogen in the energy used in transports result in a considerable decrease in the CO_2 emissions. According to [7] , FCV can achieve in 2050 zero CO_2 WTW emissions. There is a univocal opinion between the revised studies that technological developments are necessary for the envisaged hydrogen economies to be low-carbon: abundant and competitive renewable electricity or carbon sequestration. While fossil fuels are seen by most studies as transitional, some envisage a long-term role for fossil fuels based on CCS. In cases of CCS technology failure, a high percentage of renewables is the option for low-carbon H_2 production.

The studies reviewed identify the H_2 as an energy vector that will play an important role in the in the transport sector. Nevertheless, the introduction of hydrogen into the energy system does not happen autonomously. Substantial barriers have to be overcome, ranging from economic, technological, institutional, social and infrastructural barriers. An interchange between national and local policy makers, manufacturers, consumers and producers will be essential if we are to meet the introduction of H_2 in the transportation system.

Regarding the social part, it is necessary to inform consumers about the benefits of the hydrogen over other vehicles. Subsidies and public support are necessary to encourage both: private and public sector to invest in this technology. It is indispensable a diligent planning and government support in parallel with build infrastructure/ stations and vehicle fleets. It is also necessary to develop legislation and certification standards for material, hydrogen storage and distribution systems. As FCV are very innovative energy technology it is necessary to improve the system efficiency. The infrastructure net needs to be built, with a big investment necessary, the partnerships between the public and private institutions are indicated as a solution. To build the distribution infrastructure there is a high risk and therefore greatly reduced if many companies commit on the investment.

Amidst a range of factors that can define the future of hydrogen, the policy drivers evident in the literature are climate change (international commitments assumed), energy security and reducing fossil fuels dependence.

H_2 and FC implementation in the transportation sector in Portugal has the potential to decrease foreign energy dependency, being an energy storage system and reducing pollutant and CO_2 emissions. It is also a way of store the excess energy from renewable energies, allowing for an easier management of these resources.

The following tables summarize the main findings for the studies, on hydrogen production, supply, use, cost and potentially CO_2 reduction for the time periods

2020/2030 and 2050. No GDP impact was predicted within these studies and this is one of the main novelties of the research along with life cycle impact estimations.

Table 1 - Hydrogen use in road transportation.

Study	H_2 use	H_2 vehicles share in fleet
Global Transports Scenarios	Light-duty vehicles	(car fleet) Scenarios 2030 2050 Tollway FCV 2.3% 5.2 % H_2HEV 1.0% 1.0% Freeway FCV 0.5% 0.4% H_2HEV 1.2% 0.9%
Technology Map of the European SET-Plan	Light-duty vehicles Buses Auxiliary Power Unit (APU) for: Aircraft, heavy-duty and board cruise ships	Number of vehicles in 2020: 0.39 million
Roteiro Nacional Baixo Carbono	Light-duty vehicles Heavy-duty vehicles (more representative)	NA
Scenarios for Portugal	Light-duty vehicles Heavy-duty vehicles	(FCHEV+FCPHEV) Scenarios 2050 BAU 0.0% S5 1.3% M4 22%
HYRREG for SUDOE	Light-duty vehicles	NA
HyWays for Europe	Light-duty vehicles Buses	Scenarios 2030 2050 modest policy + modest learning 3% 26% high policy + modest learning 8% 40% high policy + fast learning 12% 59% very high policy + fast learning 24% 74%
Mckinsey for Europe	Light-duty vehicles (particularly segment C/D)	FCV 2050 25%

Table 2 - Studies specifications and CO_2 reduction potential.

Study	Region	Time-frame	Methodology	CO_2 reduction (-) or increase (+) 2050 vs 1990
Global Transports Scenarios	World	2005-2050	Scenarios forecast	TTW Tollway +72% Freeway +144%
Technology Map of the European SET-Plan	Europe (32 nations)	2010-2020/2030	Plan of the Energy Policy	NA
Roteiro Nacional Baixo Carbono	Portugal	2005-2050	Scenarios backcast	GHG - TTW CASM, CBSM 0% CA60, CB60 -60% CA70, CB70 -70%
Scenarios for Portugal	Portugal	2010-2050	Scenarios forecast	LCA from energy consumed in Portugal BAU +19.50% S5 +6.40% M4 -2.40%
HYRREG for SUDOE	30 regions and cities of Spain, France, Portugal and Gibraltar: 18.2% area of EU-27	2020-2030-2050	Forecast and SWOT analysis	NA
HyWays for Europe	Finland, France, Germany, Greece, Italy, the Netherlands, Norway, Poland, Spain, United Kingdom	2010-2050	Scenarios backcast (starting point: penetration rate of H_2)	WTW baseline scenario: -10% modest policy + modest

Mckinsey for Europe	Europe (29 nations)	2010 - 2050	Forecast and backcast	learning: -37% high policy + fast learning: -60% very high policy + fast learning: -64% WTW -100% (emissions close to zero in 2050)

Table 3 - Hydrogen production pathways.

Study	H_2 production		H_2 distribution	H_2 share in energy
Global Transports Scenarios	NA		NA	(in car fleet) Scenarios 2030 2050 Tollway 1.00% 4.00% Freeway 0.54% 0.62%
Technology Map of the European SET-Plan	(Ton/day) capacity in 2020 centralized (SMR and gasification) + CCS decentralized reforming of biogas electrolysis	 200 3 50	NA	H_2 consumption in transports in 2020 0.4 Mt/year
Roteiro Nacional Baixo Carbono	Biomass gasification		NA	(in transports) Scenarios 2050 CASM, CBSM 0.00% CA60 10.71% CB60 0.00% CA70 16.50% CB70 0.07%
Scenarios for Portugal	40% decentralized electrolysis 60% centralized SMR		NA	2050 BAU 0.00% S5 0.45% M4 9.00%

HYRREG for SUDOE	Estimated timeframe			Estimated timeframe		NA
		2020	2030	2020	2030	
	feedstock	wind NG electricity	solar PV	CGH$_2$ truck pipeline	LH$_2$ truck liquid vector	
	process	onsite electrolysis onsite SMR	central electrolysis central SMR + CCS			
HyWays for Europe	Scenarios		Main pathways in 2050		2030	NA
	Stakeholders (-35% CO$_2$)		NG, coal nuclear, renewable	low populated + remote areas: onsite supply, LH$_2$ transport too low demand + centralized areas: onsite supply large stations in city boarders: gaseous from pipeline (pipeline dominates the gaseous transport)		
	-80% CO$_2$		Wind, NG, coal			
	CCS failure (-35% CO$_2$)		wind, biomass			
	Least cost (-35% CO$_2$)		NG, coal, biomass			
Mckinsey for Europe		Until 2020	2020-2050	2020 Gaseous truck 2030 Gaseous truck + liquid trucks + pipeline 2050 Gaseous truck + pipeline		NA
	Central SMR	40%	30%			
	Distributed SMR	30%	-			
	Central WE	-	15%			
	Distributed WE	30%	15%			
	IGCC	-	30%			
	Coal Gasification	-	10%			

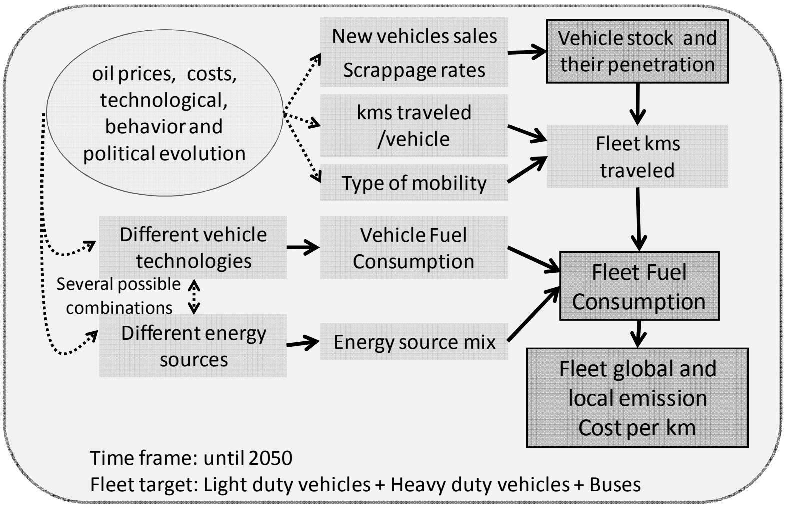
Table 4 - Hydrogen cost.

Study	H_2 cost			FC cost			FCV cost		
Global Transports Scenarios	($\$_{2000}$/kg)			($\$_{2000}$/kW)			($\$_{2000}$/car)		
	Scenarios	2030	2050	Scenarios	2030	2050	Scenarios	2030	2050
	Tollway	3.32	3.21	Tollway	148.02	84.13	Tollway	18200	21900
	Freeway	2.95	3.09	Freeway	250.00	250.00	Freeway	18200	21900
Technology Map of the European SET-Plan	2020		6.6	2020		50 (€/kW)	2020		
	2030		5.0 (€/kg)				<30000 (€/car)		
Roteiro Nacional Baixo Carbono	NA			NA			NA		
Scenarios for Portugal	2020		2.5	NA			(€/car)	2030	2050
	2050		3.6 (€/kg)				FCHEV	21656.9	22802.3
							FCPHEV	30737.7	32745.8
HYRREG for SUDOE	NA			NA			NA		
HyWays for Europe	2020		4.0	2030		50 (€/kW)	2030		20000-23000 (€/car)
	2030		3.0 (€/kg)						
Mckinsey for Europe	2030		5.0	2020		43 (€/kW)	2020		31000
	2050		4.4 (€/kg)				2030		26000 (€/car)

4. ENERGY MODEL

A model for the energy consumption, local emissions (HC, CO, NOx, PM) and global CO_2 equivalent emissions of the road transportation sector was developed and is fully documented in references [4][14]. The Projections for Alternative Transportation Technologies Simulation tool (PATTS) allows the estimation of the behavior of the road transportation sector. In order to model the fleet evolution over time, the vehicle stock (considering not only entries in the market but also vehicle scrappage) and the fleet kilometers travelled are considered. Combining them with the vehicles' fuel consumptions (according to the technology/fuel configuration) and emissions, the total fleet energy consumption and emissions are estimated for the country's in-use fleet over time, as can be seen in Fig. 2.

Fig. 2 - PATTS inputs and outputs overview (adapted from [16]).



The model is based on several linear programming modules using Microsoft Excel that track several variables such as new vehicle sales, market shares of different propulsion systems and vehicle stock, their fuel consumption, annual kilometers travelled and fuel mixes. In the case of Portugal, the historic data starting in 1973 was used to calibrate the model.

The population evolution influences directly the car fleet stock over time. Several approaches can be used to assess the evolution of car fleets. Car ownership relates to the standard of living in a country but economic parameters may sometimes be insufficient to explain the fleet's evolution. Car ownership is expressed in a normalized way, expressing the number of vehicles per 1000 inhabitants in a country (vehicle density - VD), as a sigmoid function. This curve fits the fleet evolution from the "virgin" market status, to the booming car market until the nearly saturated markets. The vehicle density can be expressed mathematically through a Logistic function [17]:

$$VD(t) = \frac{number\ of\ vehicle}{1000\ inhabitants} = \beta + \frac{\alpha - \beta}{1 + e^{-k(\log(t) - \varphi)}} \qquad \text{Equation 1}$$

where α is the final size achieved, k is a scale parameter, φ is the x-ordinate of the inflection point of the curve and t is time in years (e.g. 0 for 1973 and 34 for 2007). More specifically, for Portugal, the fitting was performed with the 1973-2007 data and the best fitting results were obtained for a vehicle density value of 618 vehicles per 1000 inhabitants. The same reasoning was applied to the HDV fleet and to the bus fleet, where the historic vehicle stock data was used to create a Logistic function capable of estimating the evolution of the two fleets stabilizing at 15 and 2 vehicles per 1000 inhabitants respectively for HDV and Buses.

From crossing the vehicle density curves with population, the general fleet evolution along time is obtained, according to Equation 2.

$$Total\ car\ stock = Vehicle\ density\ \times Population \qquad \text{Equation 2}$$

The fleet composition is determined by the number of vehicles entering each year, expressed by new vehicle sales, and by their survival characteristics in the fleet. This information defines, for each vehicle type, how long the vehicles will circulate and when they will be scrapped. Vehicle scrappage is a function of the technical lifetime of the vehicle. It composes the probability of breakdown before the planned technical lifetime, the probability of car wreckage (for instance, after a car accident) and the probability of a car being replaced by a new or used car.

The annual vehicle scrappage curves may be defined as the number of vehicles that are no longer in circulation after *k* years. A Weibull distribution was used as is presented in Equation 3.

$$\varphi(k) = \exp\left[-\left(\frac{k+b_i}{T}\right)^{b_i}\right] \quad and\ \varphi(0) = 1 \qquad \text{Equation 3}$$

where *k* is the age, $\varphi(k)$ is the presence probability of vehicles of type *i* having age *k*, *b* is the failure steepness for vehicle type *i* (b_i>1, so failure steepness increases with age) and T the characteristic service lifetime for vehicle type *i*. For the Portuguese fleet, the past values obtained through surveys by Moura (Moura, 2009) were assumed. These scrappage curves are applied to all vehicles entering the market. This means that for each year, the number of cars entering in the market will be distributed in the next 30 years into the future, according to its probability of survival. For the HDV and Bus vehicles similar curves are applied.

The combination of new vehicle sales per technology, with scrappage curves, taking into account the exiting total number of vehicles (which results of the population and vehicle density scenarios) results in the yearly fleet composition from 1973 to 2050, with the disaggregation between gasoline and diesel LDV, the two main technologies in the LDV car stock. The same methodology was applied to the HDV and Bus fleets.

An important aspect concerning new vehicle sales of passenger and commercial light duty vehicles in Portugal has been the increasing penetration of diesel vehicles. Over the last several years, the sales of vehicles have shown a considerable shift to diesel light-duty passenger vehicles, adding to the light-duty commercial vehicles. As a result, the historic diesel/gasoline share in new vehicle sales was assumed to divide the new vehicles sales data per technology and a future trend between conventional gasoline and diesel vehicles was defined. It was assumed that this consumer preference towards diesel vs gasoline affects not only conventional technologies but also HEV and PHEV in their gasoline and diesel versions in the same proportion, when both technologies are available in the market.

At this point the fleet's composition is crossed with the VKT curve of each vehicle technology (according to [18]) over time to obtain the yearly fleet's total vehicle kilometers (Equation 4). The fleet's total vehicle kilometers are also matched with energy consumption or emissions factors to obtain the resulting yearly fleet's energy consumption and emissions for each vehicle technology (Equation 5 and Equation 6 respectively).

$$Vehicle.kilometers_{i,j} = Car\ stock_{i,j} \times kilometers\ per\ vehicle\ technology_{i,j}$$ Equation 4

$$Energy\ consumption_{i,j} = Energy\ consumption\ factors_{i,j} \times Vehicle.kilometers_{i,j}$$ Equation 5

$$Emissions_{i,j} = Emission\ factors_{i,j} \times Vehicle.kilometers_{i,j}$$ Equation 6

Accordingly, the energy consumption or emissions are obtained yearly for every technology *i*. Combining all *i* technologies, the total fleet energy consumption/emissions can be obtained (Equation 7 and Equation 8).

$$Fleet's\ Energy\ consumption_i = \sum_{j=1}^{\#techn} Energy\ consumption_i$$ Equation 7

$$Fleet's\ Emissions_i = \sum_{j=1}^{\#techn} Emissions_i$$ Equation 8

The considered vehicle technologies were extensively characterized in all LCA stages for their energy consumption and emissions values. The TTW stage regards the driving stage of the vehicle. The typical energy consumption and emissions values for the Portuguese fleet regarding conventional vehicles were used. The European relative historic vehicle fuel consumption evolution (and respective emissions) was assumed [19] for characterizing the past. For local pollutants the emissions factors presented are based on extrapolation of the EURO standards, hence the emissions values are merely indicative of the magnitude of these emissions and are not intended to represent real-world values. In the case of liquid fuels, since biofuels can be blended with conventional fuels, the energy consumption and emission factors are also corrected according to the emissions factors presented in the MEET methodology [20] for ethanol and to Knöthe for biodiesel [21]. For some of the alternative vehicle technologies, which still use gasoline or diesel, values for their local pollutants emissions were not calculated; it was considered that their local pollutants emissions would be equal to those of conventional gasoline or diesel ICEV. The TTW values considered in 2010 for all vehicle technologies are presented in

Table 5.

Table 5 - TTW Energy consumption and emission factors for the different vehicle technologies.

Vehicle technology	Energy source	TTW					
		Energy MJ/km	CO_2 g/km	HC g/km	CO g/km	PM g/km	NO_x g/km
ICEV Gasoline	Gasoline	2.12	154	0.10	1.12	0.005	0.05
ICEV Diesel	Diesel	1.96	146	0.05	0.50	0.02	0.21
ICEV E100	Ethanol	2.12	0 (a)	(b)			
ICEV B100	Biodiesel	1.86		(c)			
HEV Gasoline	Gasoline	1.67	59	= ICEV gasoline			
HEV Diesel	Diesel	1.54	76	= ICEV diesel			
PHEV Gasoline	Gasoline	1.80	122	= ICEV gasoline			
	Electricity	1.12	0	0	0	0	0
PHEV Diesel	Diesel	1.66	116	= ICEV diesel			
	Electricity	1.04	0	0	0	0	0
EV	Electricity	0.60	0	0	0	0	0
FC-HEV	Hydrogen	1.08	0	0	0	0	0
FC-PHEV	Hydrogen	0.67	0	0	0	0	0
	Electricity	0.42	0	0	0	0	0
NG	natural gas	2.04	116	0.24	0.40	-	0.08
HDV	Diesel	8.89	662	1.12	10.76	0.10	6.18
Bus	Diesel	10.72	798	= HDV			
Bus NG	Natural gas	13.72	1022	= HDV			
Bus H_2	Hydrogen	14.47	0	0	0	0	0

Note: (a) Biofuels CO_2 emissions in the TTW stage are considered zero, since a neutral balance is considered considering CO_2 absorption in the feedstock cultivation stage; (b) The effect of using an increasing ethanol percentage in the emissions of pollutants was estimated according the values presented in the MEET methodology [20]; and (c) The effect of using an increasing 1st generation biodiesel percentage in the emissions pollutants was estimated according the values by Knöthe [21].

Additionally, a web based survey to nearly 1000 respondents was performed to better understand people's expectations towards alternative vehicle technologies: in terms of PHEV utility factor (percentage of time of use in charge depleting or charge sustain mode), and an 80 to 20% ratio between full electric and internal combustion engine was estimated. For the future evolution of LDV vehicle technologies, future technological improvements were considered. Reduction in vehicle weight, reduction in the rolling resistance coefficient and more efficient powertrains were considered and were simulated in ADVISOR. The combination of these factors allowed reduction potentials of up to 40% by 2050, as presented in Table 6.

Table 6 - LDV vehicle technologies total energy consumption reduction potential by 2050 maintaining the power to weight ratio constant.

LDV vehicle technologies	Fuel consumption reduction potential (%)
ICEV gasoline	35.7
ICEV diesel	37.5
HEV	35.0
FCV HEV	28.1
EV	31.6
PHEV	32.3

These energy consumption reduction values were applied linearly over time until reaching these minimum values in 2050. These results are in accordance with those obtained by Bandivadekar *et al.* for similar US based technologies [16] in comparison with the 2005 technologies. For vehicle technologies already in the market, their maximum efficient value is considered to be achieved in 2050, while for the remaining their minimum point is considered to be obtained after (2060). For HDV and Buses a potential 20 and 10% reduction on fuel consumption is considered until 2050 according to literature [22] [23].

The emissions of the local pollutants (CO, HC, NO_x, PM) were calculated individually. However, for assessing their trend they were aggregated into one category, referred further on as local pollutants. The weighting coefficients used are based on the methodology by Dincer [24] and corresponds to 0.017, 1, and 0.64 for CO, NO_x, and VOC respectively.

The selected energy pathways used in PATTS were characterized in terms of their WTT energy consumption and emission factors, which are detailed in Table 7.

Table 7 - WTT Energy consumption and emission factors for the different energy pathways considered.

Energy source	Pathway	WTT					
		Energy MJ_{exp}/MJ	CO_2 g/MJ	HC g/GJ	CO g/GJ	PM g/GJ	NO_x g/GJ
Gasoline	EU mix [25][26]	0.14	13	220	5.1	2.2	43
Diesel	EU mix [25]	0.16	14	100	4.6	1.2	37
Ethanol	Sugar cane etanol [26](Edwards et al., 2008; EU, 2009b)	0.95	24	419	61	54	249
Ethanol	Farmed wood ethanol [26] [27]	0.79	20	220	32	28	131
Biodiesel	Portuguese mix [28]	0.79	55	190	55	27	215
Biodiesel	Hydrotreated vegetable oil from palm oil (process with methane capture at oil mill) [27]	0.33	29	100	29	14	113
Biodiesel	Waste wood Fischer-Tropsch diesel [27]	0.12	4	14	4	2	15
Electricity	2010 mix	1.05	100	-	-	21	218
Hydrogen	From central natural gas reforming plants with steam co-generation [25][9]	0.57	88	251	1	1	11
	Produced in refueling stations via onsite electrolysis generation [25][9]	3.60	207	-	-	15	152
Natural gas	EU mix [25]	0.12	6	251	1	1	11

Future evolution due to efficiency improvements of the energy consumption and emission factors was also considered. Already established processes were assumed to have lower reduction potential (around 5% by 2050) than alternative ones (around 10% by 2050), still in a very early development stage. Additionally, in the case of electricity, its factors were recalculated yearly according to the assumed electricity generation mix and the average efficiency of fossil-fuel power plant increases substantially reaching values of 37-50% to coal power plants and 58-63% for natural gas power plants, according to IEA reports [23]. The same reasoning regarding the electricity generation mix was applied to hydrogen obtained via on-site electrolysis.

All the considered vehicle technologies available in PATTS were characterized in terms of Materials Cradle-to-Grave energy consumption and emission factors, which are presented in Table 8.

Table 8 - Materials Cradle-to-Grave energy consumption and emission factors for the different vehicle technologies.

Vehicle technology	Materials CTG					
	Energy (MJ/km)	CO_2 (g/km)	NO_x (g/km)	PM (g/km)	HC (g/km)	CO (g/km)
ICEG gasoline	0.48	31	0.061	0.082	0.255	0.200
ICEV diesel	0.50	32	0.063	0.085	0.255	0.213
HEV gasoline	0.58	38	0.074	0.096	0.254	0.251
HEV diesel	0.60	39	0.076	0.100	0.254	0.267
PHEV gasoline	0.70	44	0.075	0.097	0.257	0.254
PHEV diesel	0.73	46	0.092	0.121	0.308	0.323
EV	0.77	48	0.103	0.122	0.254	0.264
FC-HEV	0.73	48	0.087	0.104	0.255	0.229
FC-PHEV	0.88	56	0.088	0.106	0.258	0.232
HDV	2.52	161	0.315	0.427	1.283	1.071
Bus	3.03	194	0.379	0.513	1.543	1.288
Bus NG	3.03	194	0.417	0.565	1.697	1.417
Bus H_2	4.39	280	0.524	0.632	1.543	1.385

In this case, future evolution was assumed in parallel by considering the European average electricity mix (converging to a renewable energy resources incorporation of 55% in 2050 according to [23], since this has a considerable important in the CTG factors. This influence is presented in detail in Table 9.

Table 9 - Reduction potential by 2050 for each technology compared to the present situation by evolution of the electricity generation mix.

Vehicle technology	Materials CTG					
	Energy (MJ/km)	CO_2 (g/km)	NO_x (g/km)	PM (g/km)	HC (g/km)	CO (g/km)
ICEG gasoline	11%	17%	12%	11%	0%	1%
ICEV diesel	11%	16%	12%	11%	0%	1%
HEV gasoline	14%	21%	17%	17%	0%	2%
HEV diesel						
PHEV gasoline						
PHEV diesel						
EV	19%	33%	29%	32%	1%	4%
FC-HEV	11%	16%	13%	13%	0%	2%
FC-PHEV						
HDV	11%	16%	12%	11%	0%	1%
Bus						
Bus NG						
Bus H_2						

Three scenarios were adopted for Portugal:

- BAU corresponding to continuing the current trends in terms of fleet, based on a liquid fuel infrastructure, and considering a low incorporation of alternative vehicle technologies and biofuels;
- M2 Diversified: a diversity of alternative vehicle technology/energy sources will penetrate in the road transportation sector; initially the consumer will choose more fuel efficient vehicles such as HEV, but as the electricity recharging infrastructure is available the consumer will choose EV and increasingly more PHEV due to autonomy issues; acceptance of the electricity recharging infrastructure enables a later introduction of a hydrogen refuelling infrastructure and consequently of fuel cell vehicles;
- M4 Hydrogen powered: a dispersed hydrogen refuelling infrastructure is deployed allowing the consumer to rapidly adopt fuel cell vehicles on a large scale (similarly to the FC IEA scenario [23]. Hydrogen storage and cost issues are overcome.

Hydrogen is assumed to be produced by 40% decentralized electrolysis and 60% centralized SMR. The vehicles percentage in the fleet is shown in the Table 10. Demography considered was a population of roughly 10.7 million inhabitants according to national statistics and a vehicle density of 618 vehicle/1000 inhabitants.

Table 10 Fleet market share shifted (%) for the 2012-2050 period. Portugal.

Scenario \ Years	2012	2020	2030	2050
BAU	0	2	6	11
M2 Diversified	2	7	18	38
M4 Hydrogen powered	1	3	6	29

Table 11 Accumulated investment in million € for

Scenario \ Years	2020	2030	2050
BAU	0	0	0
M2 Diversified	12.1	24.2	48.4
M4 Hydrogen Powered	150	300	600

The electric infrastructure is already deployed and a total of 1300 normal chargers and 50 fast chargers are already in use. For the hydrogen no infrastructure exists and has to be created from scratch. Therefore the investment related was extrapolated having as base the investment estimated in the report McKinsey for Europe [7] and adapt it for the scale of vehicles to serve, see Table 2. The energy prices may be different, but the following assumptions were made. For the crude oil, two scenarios were assumed, fast growth (C) and slower growth (B), based on IEA scenarios [29] and EIA scenarios [30], see Fig. 3. The relations between the crude oil price (x in USD/bbl) and gasoline and diesel prices in Portugal were historically found to be correlated as follows: gasoline 0.0088x + 0.6385 €/l; diesel 0.0096x + 0.3868 €/l.

Electricity was assumed to be growing in the average domestic consumer by assuming a constant Annual change based on historical data, and natural gas (NG) follows the projection of the Smart energy for Europe Platform (*http://wupperinst.org/uploads/tx_wupperinst/Metastudy_Info_PolMakers1.pdf*). Hydrogen prices can be highly correlated to NG prices [31] if steam reforming is the production technology. In this work hydrogen prices are based on European Commission WETO 2050 [32] and have an opposite tendency than those observed in Balat work [31], expecting more contribution from renewables for electrolysis and/or fiscal incentives. See Table 3 below for the final prices per MJ of energy.

Table 12 Energy prices in €/MJ up to 2050.

	Gasoline		Diesel		Electricity	H_2	Natural Gas
Years	C	B	C	B			
2020	0.059893	0.050474	0.050829	0.04148	0.06	0.032683	0.012
2030	0.073349	0.054511	0.064185	0.045487	0.08	0.026704	0.016
2050	0.094878	0.059893	0.085554	0.050829	0.11	0.017828	0.022

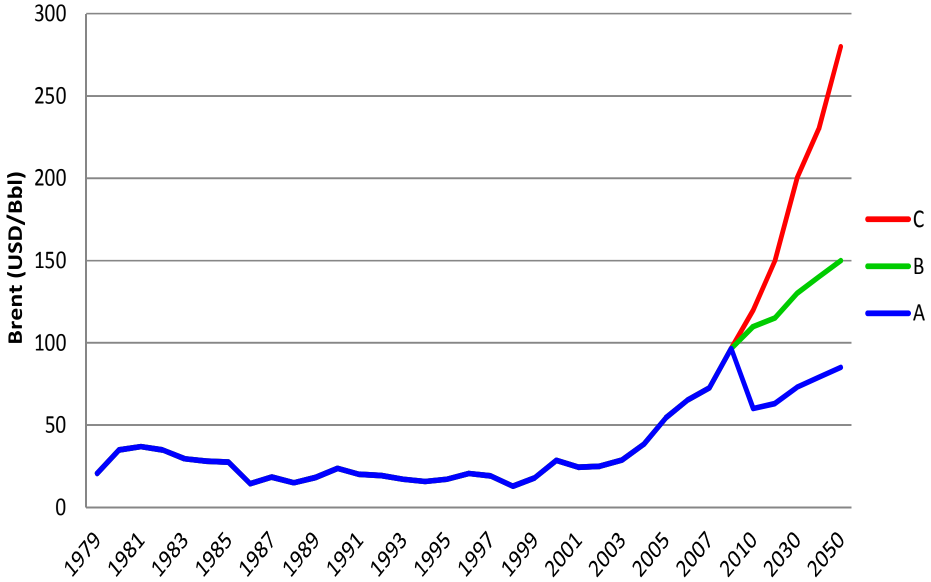


Fig. 3- Crude oil scenarios, own data based on IEA scenarios.

5. MACROECONOMIC MODEL

5.1. Introduction[1]

The application of computable general equilibrium (CGE) models to energy economics is gaining popularity. A CGE model of energy-economy interactions is a standard and widely used tool to investigate the impacts of economic events, or to measure the contribution of sectors to the wider economy. The key advantage or strengths of the general equilibrium framework are transparency, logical coherence and consistent accounting of both direct and indirect effects. The model, which is a simplification of reality, is either calibrated or estimated and formulated to match both current economic statistics on both the supply and demand sides. Therefore, the model is only as good as information is available to model the relationships between inputs and outputs. CGE models belong to a class of price endogenous models that are based on actual transactions and that simulate the working of market economics. The distinguish feature of such models is that optimizers respond to relative prices, hence changes in relative energy prices signal to agents the need for altering their production and consumption patterns.

The algebraic formulation of the CGE model adopts the Arrow-Debreu model of general-equilibrium framework [33], and follows standard neoclassical assumptions, where the economy is viewed as a competitive market and its competitive economic equilibrium is determined by optimization decisions of producers and consumers, consisting of a system of three groups of equilibrium conditions:

a) Profit-maximizing firms;
b) Market clearing condition with supply and demand mediated through prices;
c) Budget-constrained utility-maximizing household condition.

We build a top-down, partial-sector, static CGE model for Portugal, which is designed to analyse the medium-run economic effects of the penetration of alternative vehicle technologies into the Portuguese transportation sector in 40 years' time (2010-2050). The heart of the model is the assumed aggregate production function relating gross output (Y) to the inputs of energy demand (E and N) and all other factors (K and L). It is assumed that *F(.)* is positive, differentiable, and convex function exhibiting constant returns to scale. The model captures the inter-relationships between the wider economy and the transportation sector as well as their combined resource requirements. The CGE model allows us to perform computer simulations to investigate the consequences of alternative energy technologies in the transport sector on the economy.

5.2. Computable general equilibrium model

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[1] The model is originally based on a model developed by Manne, A.S. (1977), ETA-MACRO: A Model of Energy-Economy Interactions. In Hitch, C J, Ed, Modelling Energy-Economy Interactions: Five Approaches, Resources for the Future, Washington, DC. See also: Manne, A.S. (1976), [41].

5.2.1. Energy-economy interactions

The economy sub-model is a model of energy-economy interactions and simulates a market economy through dynamic optimization. It is part of the two sub-models of the production relationships within this economy, namely the transportation technology assessment analysis simulation tool (Projections for Alternative Transportation Technologies Simulation – hereafter PATTS [14]), which examines the effects of technological change in transportation and energy, and the macroeconomic growth model dealing with substitution between labour, capital and energy inputs. The macro-economic model is a non-linear optimization model with a parameterization formulation from the inputs of the transportation sub-model. Additionally, in technical terms, the macro-economic sub-model parameters have been estimated by using informal econometric techniques and parameter definition has also been supported based on observed data.

The economic model is of the type which is called a general equilibrium model, in that it envisages at the same time the effects which the macro-economy has on the energy system and vice versa the impacts of the energy system on the economy. It is a general equilibrium model that consists of a profit maximizing firms, markets, typically with supply and demand mediated through prices and budget-constrained utility-maximizing households (Arrow Debreu framework). Numerated calibrated versions of these models are referred as Computable or Applied General Equilibrium Models (CGE). The economy sub-model is a top-down CGE model in a mathematical framework implemented in the General Algebraic Modelling System (GAMS) software and solved with the NLP solver CONOPT3 Version 3.14U. The GAMS program code of the macroeconomic model can be provided upon request by the coordinator of the macroeconomic model.

In this case, the CGE model is a simple model for organizing concepts and parameters. The aggregate model provides insights and a perspective on energy policy impacts within the transportation sector on the remainder of the economy. The macro-economic model simulates a market economy through a dynamic non-linear optimization process, but there are “look-ahead” features to allow for interactions between periods. Savings and investment decisions are modelled so that consumers will receive equal benefits from an additional monetary unit worth of current consumption and a monetary unit worth of investment. The production relationships within this economy are modelled through a macroeconomic growth model providing for substitution between capital, labour and energy inputs. We are working with the concepts and terminology of the macroeconomic production function from the neoclassical growth model.

The convergence of the two sets of results from the energy sub-model and the economic sub-model are achieved through an iteration process, rather than by having to solve the optimization problems of the two sub-models simultaneously[2]. The main feedback of information between the two parts is through parameters specifying the amount to which energy separated

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[2] A comparative overview of existing energy system models is provided by Bhattacharyya, S.C., Timilsina, G.R. (2010), [42].

for electric and non-electric form is required as an input for the production of a unit GDP (Gross Domestic Product), and the energy expenditures that the economy is willing to pay. The model determines for each point in time the equilibrium between supply and demand, whereby substitution between labour, capital and energy inputs take place according to the availability of the production factors and their cost of production. The prices for energy will affect the future level of energy demand, the energy-mix and the production structure of the economy. Inter-energy substitution will have macroeconomic implications and the entire economy will adjust to a new equilibrium according to the time lags built into the model.

To distinguish between short-run and medium-run responses to higher energy prices, we employ the so-called "putty-clay" model of energy use [34]. In this model, large varieties of capital goods are combined with energy in fixed proportions. The "putty-clay" model delivers a low elasticity of energy use in the short-run, because existing capital uses energy in fixed proportions. As time goes by, in response to permanent differences in energy prices, agents invest in different capital goods with different fixed energy intensities. As a result, energy use becomes responsive to differences in energy prices.

5.2.2. Economy-wide aggregate production function

In order to focus upon the medium run issues of energy-economy interactions, and the introduction of new technologies in the transport sector, the economy is described in highly aggregative terms. Outside the energy sector, all economic quantities are combined in terms of a numeraire (unit of account) based upon dollars of constant real purchasing power. This is a broad classification system. One can argue that more details would be needed to analyse specific proposals related to energy policy, but it is impractical, however, to use a single model to answer all questions related to the transportation technology assessment analysis and its effects upon the economy. Instead, it appears more reliable to depend upon informal information flows back and forth between individual analyses; each designed to handle specific issues at an appropriate level of detail with respect to time.

Fig. 1 provides an overview of the principal static linkages between the two sub-models, namely the sectoral energy model (a process analysis for energy technology assessment) and the rest of the economy (the macroeconomic growth model). Electric and non-electric energy (denoted, respectively by the symbols E and N) are supplied by the energy sector to the rest of the economy. Like the material balance equations of an input-output model, aggregate economic output (Y) is allocated between inter-sectoral payments for energy costs (EC) and final demands for current consumption (C) and investment (I). We obtain the following equation:

$$Y = C + I + EC \qquad \text{Equation 9}$$

Each component of equation (9) is measured as an annual flow in billions of constant 2005 dollars. For the economy-wide production function, we assume that gross output (Y) depends upon four inputs: K, L, E, N – respectively capital, labour, electric and non-electric energy. The production function is a nested non-linear function (see Fig. 4) based upon the following assumptions:

a) There are constant returns to scale in terms of the four inputs;

b) There is a unit elasticity of substitution between one pair of inputs (capital and labour) σ_{KL} with α being the optimal value share of capital within this pair;

c) There is a unit elasticity of substitution between the other pair of inputs – electric and non-electric energy σ_{EN}, with β being the optimal value share of electricity within this pair;

d) There is a constant elasticity of substitution between these two pairs of inputs the constant being denoted by $\sigma_{KL\text{-}EN}$.

The economy sub-model uses a constant elasticity of substitution (CES) production function to build a coherent, self-consistent model of energy-economy interactions[3]. The structure of industry production function employed in the economy sub-model takes into consideration that the economy-wide gross output (Y) depends upon four inputs (K, L, E, N). Capital and labour are combined via a Cobb-Douglas production function and so are electric and non-electric energy inputs. The elasticity of substitution among the input of factors is separated in three fractions: substitution between capital and labour (denoted by α and $1\text{-}\alpha$), substitution between electric and non-electric energy (denoted by β and $1\text{-}\beta$), and substitution between capital/labour and electric/non-electric energy (denoted by σ). The overall aggregation of composite factors, energy inputs and non-energy inputs is a Constant Elasticity of Substitution (CES) production function that takes the following parametric structure form:

$$Y = [a(K^{\alpha}L^{1-\alpha})^{\rho} + b(E^{\beta}N^{1-\beta})^{\rho}]^{1/\rho} \qquad \text{Equation 10}$$

where $\rho = (\sigma - 1) / \sigma$ for $\sigma \neq 0, 1, \infty$). Here $0 < \alpha < 1$, and $0 < \beta < 1$ are the share parameters and ρ determines the degree of substitutability of the inputs. Output elasticities (α and β) measure the responsiveness of output to a change in levels, in this example, of either capital or electric energy in production *centribus paribus*. These values are constants or parameters determined by available technology. The parameters a and b are two empirical positive constants that are determined through a first-order optimality condition for a year in which each of the four inputs (K, L, E and N) has been optimally adjusted to the prevailing prices. The model is calibrated for the base-year 2010, the latest year for which all data is available. To allow for time lags in the economy's response to energy prices, we can no longer work with a static model but must introduce a time index t. A 40-year planning horizon is employed, starting with 2010 and extending through 2050.

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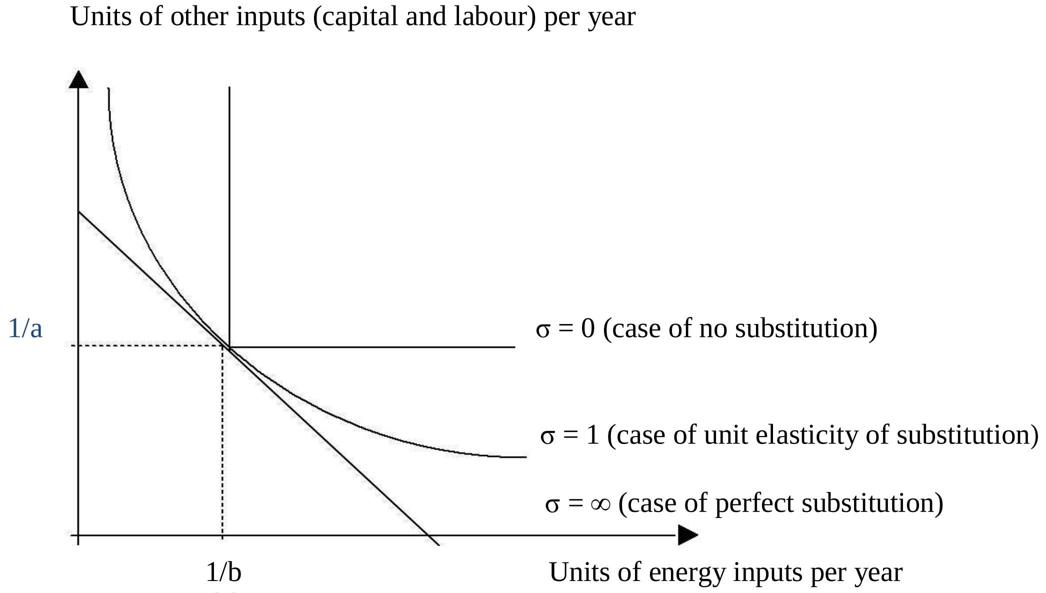
[3] A review of the variants of the CES function used in the old and new theory of growth (theoretical and econometric foundation) and on the economic forces behind the formal concept of the elasticity of substitution can be found in Klump, R., Preissler, H. (2000), CES production functions and economic growth, Scandinavian Journal of Economics, 102(1):41-56.

There are 8 individual time periods, each 5 years in length, and each centred around a "representative" year: 2015, 2020, … , 2050. With 2010 as year 0, therefore the time index t = 0, 5, … , 50.

Figure 3 depicts the isoquants, defined as a curve showing all the various combinations of two factors that can produce a given level of output, for three different CES production functions, each corresponding to a different value of the elasticity of substitution σ. At $\sigma = 0$, the isoquants is that of a fixed-proportion production function and inputs are perfect complements. At $\sigma = 1$, the isoquants are curves. At $\sigma = \infty$ the isoquants is that of a linear production function and inputs are perfect substitutes. The value of the degree of substitutability of the inputs ρ is less than or equal to 1 and can be -∞. The two extreme cases are when ρ = 1 (the case of perfect substitution when isoquants are straight lines for this production function) or ρ = -∞ (the case of no substitution when isoquants are at right angles or L-shaped meaning that the factors of production are used in fixed proportions). In the case of unit elasticity of substitution, $\rho = 0$ and we obtain a Cobb-Douglas production function.

Fig. 4 - Isoquants for the constant elasticity of substitution production function.



Source: own elaboration.

Each of the three production functions discussed above is a special case of the CES production function, which is given by equation (2). The shape of the isoquants varies and the elasticity of substitution lies between $0 \leq \sigma \leq \infty$. The elasticity of substitution varies between zero and infinite and the shape of the isoquants of the CES production function changes from the L-shape of the fixed-proportions function to the curve of the Cobb-Douglas production function to the straight line of the linear production function. We assume constant returns to scale meaning that a proportionate increase in all input quantities results in the same percentage increase in output.

In models with putty-clay capital, the speed of adjustment depends upon a parameter to which we shall refer as speed of adjustment, given the depreciation rate, which governs how many new units are put in place each period[4]. This constant is assumed to remain constant over the projection period and it defines the fraction of the initial capital stock that survives after one year of use. In general, we have supposed that capital stocks are replaced at the rate of 4% per year, hence the yearly capital stock depreciation rate is δ = 0.04[5]. The annual survival factor denoted *spda* is therefore 0.96. The surviving quantities of the input factors are obtained by multiplying the initial known values of real output, household consumption, capital stock, investment, and the energy composite inputs by the yearly surviving factor[6].

If we let the unknowns YN_t , KN_t , IN_t , ES_t , and NS_t denote respectively the new gross output, capital stocks, new investment, new electric-energy consumption, new non-electric energy consumption, by definition, we then obtain the following functions: $YN_t = Y_t - YS_t$, $KN_t = K_t - KS_t$, $IN_t = I_t - IS_t$, $EN_t = E_t - ES_t$ and $NN_t = N_t - NS_t$. Then, the new production function associated with the new investments made since 2010 includes new inputs of capital, labour and energy as follows:

$$YN_t = \left[aKN_t^{\rho\alpha}LN_t^{\rho(1-\alpha)} + bEN_t^{\rho\beta}NN_t^{\rho(1-\beta)}\right]^{\frac{1}{\rho}}$$ Equation 11

Hence, total output may be calculated by the following expression:

$Y_t = YS_t + YN_t$ = gross output at time t =

$$YS_t + \left[aKN_t^{\rho\alpha}LN_t^{\rho(1-\alpha)} + bEN_t^{\rho\beta}NN_t^{\rho(1-\beta)}\right]^{\frac{1}{\rho}}$$ Equation 12

The labour force growth rate is a key parameter, and has an influence upon the economy wide potential growth rate (denoted *g*). All the compute runs are based upon the following annual rates for the labour force:

2010-2015: 0.18 %

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[4] The initial value of capital stocks at constant 2005 US$ prices for Portugal is taken from the Penn World Table 8.0 (available online at Federal Reserve Bank of St. Louis - FRED Economic Data) and compared with the estimates reported in Appendix Table A1 by Gomes, E., Lains, P. (2013), Capital formation and long-run growth: evidence from Portuguese data, 1910-2011, Paper presented at Iberometrics IV, Universidad de Zaragoza.

[5] The annual depreciation rate is taken from D'Auria et al. (2010), [43]. The production function methodology for calculating potential growth rates and output gaps, Economic Papers 420, European Commission, Table 4.2, p. 44.

[6] The capital survival factor describes the share of the capital or investment in period *t* that still exists in period *t+1*. See e.g. Remme, U., Blesl, M. (2006), Documentation of TIMES-MACRO model, Energy Technology Systems Analysis Programme (*www.etsap.org*).

2015-2020: 0.14 %

2020-2025: 0.08 %

2025-2030: 0.04 %

2030-2035: 0.01 %

2035-2040: -0.05 %

2040-2045: -0.13 %

2045-2050: -0.21 %

To compute the annual growth rates, we use the equation for annual growth rate percentage over multiple years $P = [(f/s)^{(1/y)}] - 1$, where f is the final value, s the starting value or population and y the number of years. The population of Portugal is projected to have an inverted-U shape curve across time [35]. These population estimates and projections of population growth show the rate of increase in population to be slowing during the period from 2010 to 2050. The following values have been adopted for the remaining parameters in the production functions (2) and (3):

The capital's value share $\alpha = 0.5$[7].

The electricity's value share parameter $\beta = 0.01$.

It is apparent that the adopted electricity value share is low, implying that a 1 percent change in electric energy would lead to a less than proportionate change in output *centribus paribus*. CES substitution elasticities are specified outside the model by taking econometric estimates from the literature. The substitution elasticities are, as it is common in CGE modelling, exogenously determined. The value of the substitution elasticity between energy inputs (i.e. the transportation fuel price elasticity of factor demand estimate) is based upon the results of various transportation fuel price elasticity studies, reflecting various analysis scopes and perspectives [36]. As a matter of comparison, in a recent study [37], the final demand elasticity of fossil fuel versus electricity (in final consumption demand of the representative household specified in the CES production function which combines consumption of an energy composite and a non-energy composite good) is set to equal the value of 0.4. In the same study, production substitution elasticities of electricity versus fossil fuel aggregate in non-energy production or manufacturing industry sectors is set to equal 0.5.

The CGE modelling literature identifies the elasticity of substitution between inputs in the production function and the structure in which these inputs interact among these assumptions as a key issue, as does the wider energy economics literature. The production function combines a composite of capital (K) and labour (L) inputs first, and then combines with electric energy (E) and non-electric energy (N) in a nested CES production function (with Cobb-Douglas and Leontief adopted at nests where substitutability between inputs is unitary). This case is illustrated in Fig. 5.

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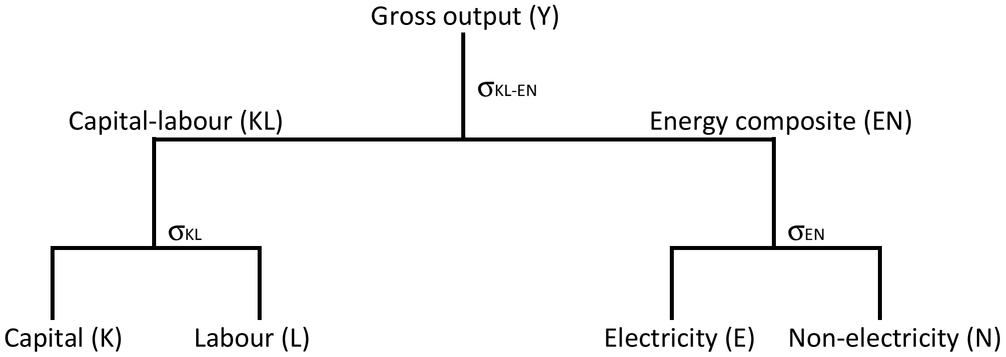
[7] We use the aggregate labour income share for Portugal calculated in [44], Table 1, p.10.

Fig. 5 - The constant elasticity of substitution hierarchical/nested production structure.



Source: adapted from Turner, K., Lange, I., Lecca, P., Jung Ha, S. (2012), Econometric estimation of nested production functions and testing in a computable general equilibrium analysis of economy-wide rebound effects, Economics Discussion Paper 2012-08, University of Stirling.

The imposed structure of the production function and elasticity values therein may impact on model results [38]. A nested production structure requires the imposition of separability among the inputs. Where there are more than two inputs to production, such a structure only allows substitutions between pairs of inputs at any level in the hierarchy. Where one of the input nests involves a composite input resulting from substitution between another pair of inputs at a lower level (for example the capital-labour, or value-added composite) this has the implication that both of the inputs incorporated in the composite must substitute equally well for the third input (i.e., energy inputs).

5.2.3. Estimating the elasticity of substitution between factor inputs

The elasticity of substitution between capital-labour and energy, non-energy inputs is of the order of σ = 0.05. As a matter of fact, the energy value share of GDP is typically on the order of 4-5% in industrial countries. The empirical basis for this estimate is a multiple regression model derived from an adaptation of the basic Nerlove's partial adjustment model [39] to estimate the elasticity of demand for crude oil. The approach used to model crude oil demand consists in specifying a partial adjustment equation to account for the difficulty and cost of changing technology in the short run. We specify the equation to be estimated in the following log-linear form[8]:

$$lnD_t = ln \propto + \beta lnP_t + \gamma lnY_t + \delta lnD_{t-1} + \varepsilon_t \qquad \text{Equation 13}$$

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[8] The theoretical underpinning for this procedure can be found in Cooper, J. (2003), Price elasticity of demand for crude oil: estimates for 23 countries, OPEC Review, 27(1):1-8.

where D_t is the per capita consumption of crude oil in year t, P_t is the real price of crude oil in year t, Y_t is the real GDP per capita in year t, and ε_t is the assumed random error term. Coefficient β can be interpreted as the price elasticity of demand. The coefficients are estimated by the Cochrane-Orcutt iterative procedure instead of the usual OLS to overcome serial correlation due to the introduction of the lagged dependent variable in the set of explanatory variables. A time trend that captures technological (energy efficiency) changes is included in the estimations and annual data is used for the period 1980-2010. Oil consumption and price data are supplied by *British Petroleum Statistical Review of World Energy 2013*, while real GDP per capita is taken from the *World Development Indicators (WDI)* database (*http://data.worldbank.org/*). Here, we parameterise the elasticity of substitution σKL-EN from the econometric estimated equation reported below:

$$\underset{}{lnD_t = -6.19 - \underset{(-3.90)}{0.05\, lnP_t} + \underset{(3.68)}{0.65\, lnY_t} + \underset{(5.81)}{0.66\, lnD_{t-1}} + \varepsilon_t} \qquad \text{Equation 14}$$

The t-statistics are shown in parentheses. The adjusted R^2 = 0.95 and the overall F-statistic = 95.43 indicate that the model fits the data well. The estimated coefficients have the expected a priori signs and the associated t-statistics indicate that these coefficients are all statistically significant at the five per cent level. The time trend that captures technological change is statistically significant at the 1% level and has a negative sign indicating that Portugal has made significant improvements to reduce oil intensity over time. The estimated price elasticity of demand is -0.05 meaning that if oil prices increase by 1% crude oil demand will be decreasing by 0.05%. The adoption of low elasticities follows from both the theoretical argument and empirical evidence, implying a presumption that electric energy and non-electric energy composite are found to be relatively price inelastic. This is because the costs associated with shifting to a different technology are generally perceived to be high. These high transfer costs constrain producers upon their short-run and medium-run decisions and thereby limit the scope of factor substitution[9]. The estimates so obtained show that the demand for crude oil is insensitive to changes in prices. Crude oil demand is price-inelastic indicating that consumers respond with a time lag to price changes implying that they have difficulty in finding alternative energy sources.

5.2.4. Macroeconomic relations between investment and consumption

The economy sub-model contains equations for capital accumulation and for terminal investment requirements. Capital stocks are expanded by gross investment I_t, including the investment period multiplier, and are reduced by the survival fraction. The evolution of the capital stock is given by:

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[9] Koschel, H. (2000), Substitution elasticity between capital, labour, material, electricity and fossil fuels in German producing and service sectors, Center for European Economic Research, Discussion Paper No. 00-31.

$$K_{t+1} = spda^{t+5}\, K_t + I_t$$ Equation 15

Gross investment during the terminal year (horizon 2050 = year 40) must provide for subsequent expansion of the annual economy growth rate *g*, and must also provide for replacement at the rate (*1-spda*). We add an additional 40-years accumulated infrastructure investment to the next equation. Additional investment is measured according to the number of vehicles employed in the McKinsey study [7] based on 25 per cent of the light vehicle fleet corresponding to 62.5 million hydrogen-powered vehicles with a total investment of 27 billion euros (approximately 37 billion US dollars) in 2050. The average investment per year in Portugal is computed with the rule of three based on 11200 projected hydrogen-powered vehicles to the planning horizon up to 2050. There is no infrastructure investment in the business-as-usual scenario. The estimated average investment per year is larger in the hydrogen-powered case then in the diversified scenario, respectively 20.1 million US dollars and 1.6 million US dollars. The constraint equation of the terminal investment at *t = 40* can be expressed as follows:

$$I_t = (g + 1 - spda)\, K_t$$ Equation 16

It follows that aggregate consumption in period *t* is then:

$$C_t = Y_t - I_t - EC_t$$ Equation 17

For optimizing the pattern of investment and consumption over successive time periods, we shall take the discounted utility of consumption. The utility function *U(C)* is a function which maps the amount of consumption into the amount of utility. Utility is how much “satisfaction” households derive from consumption. The one-period discount rate is denoted δ, and the utility function is expressed in the logarithm of consumption in the following form:

$$U(C_t) = \log(C_t)$$ Equation 18

The logarithm implies that marginal utility is positive, but it is a diminishing function of the aggregate level of consumption. Marginal utility determines how much of a good a consumer will buy and in this case more is better. The utility function is concave, meaning that the function is increasing at a decreasing rate.

5.2.5. Utility function and discount rate

Individuals may have different utility functions for consumption in different time periods. Usually they value future experiences, but to a lesser degree than present ones. The factor by which the consumer discounts next period's utility is a fixed and positive constant that lies between $0 \leq \delta < 1$. The parameter δ is called the individual's discount rate and is capturing the idea that if the individual is rational he may attach less weight to future consumption than to present consumption. If δ is equal to zero then the individual attaches the same weight, if δ is greater than zero the individual attaches less weight to future consumption. The utility of the future period consumption is discounted by the factor $1/(1+\delta)$. Here the parameter δ is a parameter of the individual's preferences and it represents that rate at which the individual discounts the future. A present-oriented individual discounts the future heavily and so has a low discount factor. A decrease in δ denotes that households have become less impatient and value future consumption higher. In this case, households are willing to sacrifice present consumption. The δ parameter is related to the optimal savings rate in the economy and affects consumption, but has no implications for capital accumulation, whereas capital accumulation is driven by the production function and by exogenous parameters, such as the depreciation rate and population growth.

To determine a numerical value for the key savings parameter, the utility discount factor $1 / (1 + \delta)$, for our base case and diversified versus hydrogen-powered scenarios calculations, we shall adopt a value of δ = 10% per year, but also measure the implications of two other factors: 13% and 17%. For the discount rate δ = 10.1% (0.101), the discount factor is calculated as 1/(1+0.101) = 0.90. This value is similar to the one adopted in a recent study [40]. For the remaining discount rates we obtain current discount factors of 0.88 and 0.85 respectively.

No other constraints are imposed upon the propensities to save and to consume. This means that the economy sub-model is mainly driven by the following key parameters:

a) The savings-investment accumulation process, primarily determined by δ. The initial values of investment;
b) The labour force growth;
c) And the elasticity of substitution, the principal factor governing the economy's ability to cope with higher energy prices.

Time is required for life-styles and for capital stocks to adjust to energy costs (i.e. higher energy prices), etc. The economy sub-model model allows for time-lags in the economy's response to higher energy prices. These lags are built into the production function which is non-linear in type. All other equations used in the economy sub-model are linear combinations of variables. The principal equations of the economy sub-model describe the growth of the capital stock, the allocation between consumption, investments and energy expenditures and the savings process. The initial values of the macro variables are expressed in constant 2005 US dollars. All data is taken from the World Bank's World Development Indicators database on the Internet (*http://data.worldbank.org/).*

5.2.6. PATTS energy model inputs and scenarios

We have seen so far that the general equilibrium model consists of profit-maximizing firms and a market typically with supply and demand mediated through prices, and includes a budget-constrained utility-maximizing household's function. In its broad outline, the economy sub-model is linked to the energy sub-sector by specifying the supply functions of electric and non-electric energy and other inputs such as energy costs. Electric energy is produced by a combination of hydro-electricity, natural gas, oil, etc. Non-electric energy can be produced either from conventional (petroleum and natural gas) or by non-conventional technologies (such as renewable energy sources, electrolytic production of hydrogen, etc.).

The numerical parameters values have been those adopted by the transportation technology assessment analysis Projections for Alternative Transportation Technologies Simulation (PATTS) simulation tool that is capable to develop scenarios of evolution from 2010 to 2050 for energy consumption of the road transportation sector (light-duty and heavy-duty vehicles). The methodology is applied to Portugal and results are analyzed in a life-cycle perspective. A business-as-usual trend and two additional scenarios are explored: diversified (introduction of a wide diversity of alternative vehicle technology/energy sources); hydrogen pathway (a broad hydrogen refueling infrastructure is deployed allowing the consumer to rapidly adopt fuel cell vehicles at a large scale) [4].

In the ”base case” or business-as-usual scenario we have a continuation of the current trends in terms of fleet, based on a liquid fuel infrastructure, and a very low incorporation of alternative vehicle technologies and biofuels. The second scenario is the so-called diversified scenario where a wide variety of alternative vehicle technology/energy sources will eventually penetrate in the road transportation sector. Initially the consumer will choose more fuel efficient vehicles HEV (Hybrid Electric Vehicle) but as the electricity recharging infrastructure is available the consumer will choose EV (Full Electric Vehicle Battery Vehicle) and increasingly more PHEV (Plug-in Hybrid Electric Vehicle) due to autonomy issues. The acceptance of the electricity recharging infrastructure enables a later introduction of a hydrogen refuelling infrastructure and consequently of fuel cell vehicles. The third scenario of evolution is the hydrogen-powered scenario, where the transportation sector becomes hydrogen driven and a wide hydrogen refuelling infrastructure is deployed allowing the consumer to rapidly adopt fuel cell vehicles at a large scale (similarly to the fuel cell vehicles International Energy Agency scenario). Storage and cost issues are overcome.

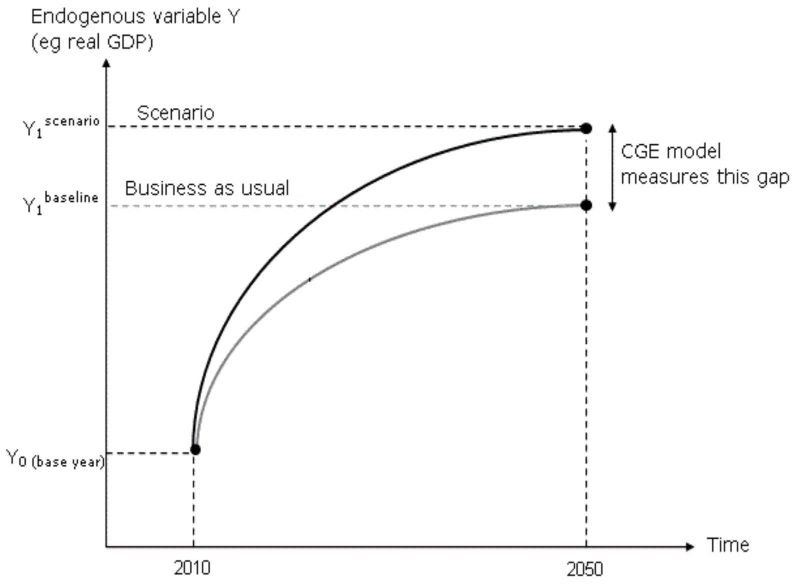
The energy sub-model parameters that are included in the economy sub-model are related to energy price costs (electricity and fuel costs), yearly growth rates of electric energy and non-electric energy prices (low and high scenarios) and the exogenously determined activity levels of electric and non-electric energy consumption provided by PATTS simulation tool projections in 2050 compared to 2010 for the considered scenarios. Total life cycle energy consumption for road transportation is reduced in the considered scenarios. Thus, in terms of energy consumption profile, this study has revealed a disappointing business-as-usual profile, a pattern that can be improved by developing and implementing significant improvement in vehicle efficiency and alternative vehicle technologies with the hydrogen and the electricity powered visions producing the best results. Regarding the demand for fossil fuels and energy dependency, the proportion of liquid oil-based fuels will remain dominant in the scenarios studied. Alternative vehicle technologies can help to lower the baseline scenario impacts.

The influence of oil prices is based on IEA predictions. All data are taken from World Energy Outlook 2010 published by the International Energy Agency. Following the IEA scenarios, we consider the high scenario, that starts at 120 US dollars per barrel in 2010 and stabilizes at 280 US$ per barrel in 2050, and a low scenario, that begins with 110 US dollars per barrel and stabilizes at 150 US dollars per barrel. In the high-price scenario, we see that oil prices more than double between 2010 and 2050. Electricity price evolution is considered according to ERSE, the Portuguese Energy Services Regulatory Authority, and is presented together with oil price scenarios in Table 12.

5.3. Modelling approach

We need first to establish a base case to which the results of the various aforementioned scenarios can be compared. This means there is a constant point of analysis between various scenarios. The base case (or baseline) is referred to as a business-as-usual scenario and is essentially what would happen in the absence of any significant change in the macro-economy. In this study, the model's base year (or starting point) is 2010 and the terminal year is 2050.

Fig. 6 - The computable general equilibrium model simulation.



Source: adapted from "Scenarios using a computable general equilibrium model of the New Zealand economy" October 2009, Economic Impacts of Immigration Working Paper Series, Ministry of Business, Innovation & Employment, *http://www.dol.govt.nz/publications/research/cge/index.asp*, Figure 2.2.

Fig. 6 shows how the CGE model results should be interpreted. The example of real GDP is used. First, the level of real output in the snapshot year 2050, noted as $Y_1^{baseline}$, consistent with a baseline scenario is generated. Thereafter, the CGE model experiment proceeds by changing one (or more) of the assumptions that have been adopted to determine the baseline or control level of gross output or the real gross domestic product ($Y_1^{baseline}$). It is best to change only one assumption at a time so the impact of that change can be understood. If multiple assumptions are changed, it becomes more difficult to understand the individual impact of each change or the impact as a result of the interaction between the changed assumptions. The result of our model's simulation would be a measure of the difference between $Y_1^{scenario}$ and $Y_1^{baseline}$; that is, the difference between real gross output resulting from alternative transportation technologies simulation scenarios envisaged above and real gross output without any change in the baseline case. The analysis should be taken as giving a short and medium term perspective of the impact of alternative transportation technologies experiments.

6. RESULTS AND DISCUSSION

The final electric and non-electric energy consumption, including hydrogen, by the light-duty transportation sector is in Fig. 7. Fossil energy consumption is reduced by roughly 50% in 2050 due to alternative technologies using electricity and hydrogen. This is important due to the necessity of reducing foreign energy dependency and is mainly possible by using more electricity with renewables incorporation. Local pollutant emissions are reduced by 90%, which is a major contribution for air quality improvement. The hydrogen isolated effect in terms of CO2 reduction potential in 2050 is 2 kton/km if 100% natural gas steam reforming is adopted. Fig. 8 shows the CO_2 evolution scenarios.

Fig. 7 - Final energy consumption (TTW energy consumption).

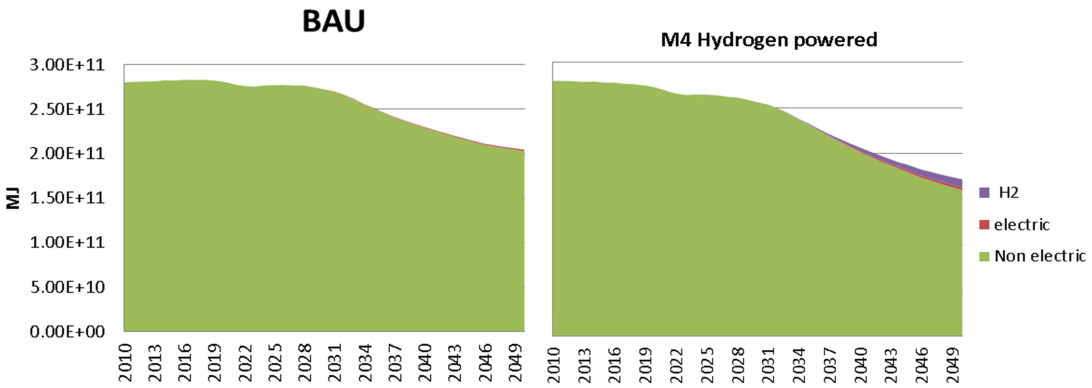
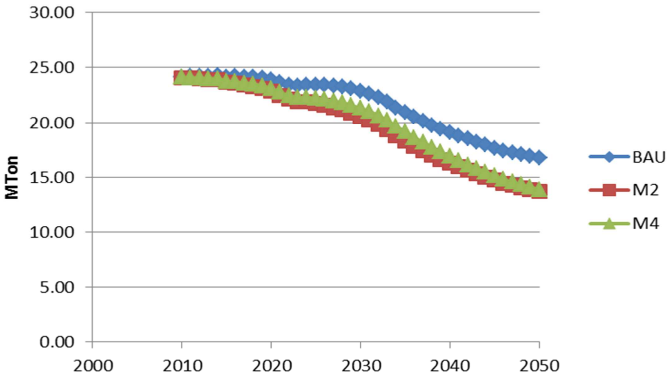


Fig. 8 - CO_2 equivalent emissions (WTW).



Let's now present and discuss detailed numerical results based upon our model experiments. All simulations begin in the year 2010. We first run the reference case simulation that assumes business as usual conditions where we let the economy grow and do not introduce the new technologies into the model. The base case is characterized by modest growth. Household consumption grows a little more than gross domestic product. Investment remains practically unchanged in the baseline case. Energy costs begin an upward march, but then grow at nearly half pace. Regarding the implications of high oil prices on the macro-economy, these seem to affect more the aggregate outcomes, forcing the macro variables to slow down over time. The macro variables have lower growth rates in the high-price cases than in the low-price ones. Table 13 reports the annual growth rates for the principal macroeconomic variables in the baseline case between 2010 and 2050.

Table 13 - Economic simulation results in the baseline case.

Macro variable	Household consumption		GDP		Investment		Energy costs	
Brent crude oil price	C	B	C	B	C	B	C	B
Years	Annual growth rate (unit:%/year)							
2010-2015	1.741	1.810	1.350	1.407	0.000	0.000	0.046	0.037
2015-2020	1.210	1.328	0.950	1.047	0.001	0.001	0.015	0.021
2020-2025	0.889	1.045	0.704	0.832	0.002	0.002	0.011	0.023
2025-2030	0.567	0.838	0.452	0.673	0.002	0.002	0.007	0.028
2030-2035	0.622	0.666	0.499	0.539	0.001	0.001	0.030	0.028
2035-2040	0.354	0.294	0.285	0.238	0.001	0.001	0.008	0.000
2040-2045	-0.016	0.152	-0.013	0.123	0.001	0.001	0.005	0.001
2045-2050	-0.173	-0.001	-0.139	-0.001	0.001	0.001	0.006	0.003

Source: own elaboration with the results from the CGE model experiments.

We then report the estimated percent change of model versions relative to the base case or reference model. To recall, we mean to assess the impact that alternative vehicle transportation technologies have on model results. To that end, we simulate two alternative versions of the reference model. This yields results that are reported in Table 3 and Table 4 which show the two time profiles on which we focus and compare the macro variables within each oil price assumption in terms of their impacts on the economy over the interval 2015-2050.

The results in both tables reflect common patterns that appear to be related to aggregate effects of both transportation technologies scenarios. An examination of the results of our several model runs ascertained that the pattern of changes to the economy is consistent in that there are no discontinuities in the results. In general, the introduction of transportation technologies, compared to the base case, yields positive outcomes in the macro variables. Compared to the baseline scenario, in both the diversified and hydrogen-powered scenarios, household consumption, gross output and investment levels go in the same direction.

There are higher levels of growth for economic variables under each alternative compared with the baseline scenario. The annual growth rates of macro variables projected in the two sets of scenarios from 2010 onwards are almost comparable. One of the most noticeable results is related to investment that indicates a larger and continued increase from its baseline values. Moreover, annual savings in energy costs are achieved in relation to the baseline. In both the high and low oil price cases, assuming stronger demand growth, costs savings are attained until 2050. Simulation results show that the extent of energy costs reductions is not slightly higher under the assumption of low crude oil prices. In both the high-price case and low-price path, the biggest energy costs reductions are achieved in the diversified case. In comparison with the baseline case, the hydrogen-powered case accomplishes lower reductions in energy costs. Nevertheless, in the low-price case, the economy registers losses in household consumption and gross output in the projection, given the negative estimated percent change in the years 2030 and 2035, when compared with the high oil case but recovers as production expands.

Table 14 - Economic simulation results in the diversified case.

Macro variable	Household consumption		GDP		Investment		Energy costs	
Brent crude oil price	C	B	C	B	C	B	C	B
Years	Estimated change from baseline (unit: %/year)							
2015	0.027	0.100	0.014	0.072	0.000	0.000	-0.210	-0.199
2020	0.263	0.165	0.205	0.134	0.015	0.049	-0.136	-0.167
2025	0.376	0.022	0.311	0.032	0.101	0.121	-0.137	-0.188
2030	0.814	-0.264	0.675	-0.190	0.172	0.184	-0.132	-0.251
2035	0.347	-0.580	0.310	-0.440	0.234	0.241	-0.217	-0.324
2040	0.299	0.255	0.283	0.246	0.301	0.295	-0.222	-0.267
2045	1.613	1.197	1.349	1.021	0.345	0.347	-0.178	-0.228
2050	2.975	2.425	2.452	2.027	0.398	0.399	-0.171	-0.199
Annual growth rate (unit: %/year)								
2010-2015	1.748	1.835	1.356	1.428	0.000	0.000	0.057	0.050
2015-2020	1.270	1.344	0.998	1.063	0.004	0.012	0.033	0.029
2020-2025	0.917	1.009	0.731	0.807	0.022	0.018	0.011	0.018
2025-2030	0.677	0.766	0.543	0.617	0.018	0.016	0.008	0.012
2030-2035	0.505	0.587	0.407	0.475	0.015	0.014	0.009	0.009
2035-2040	0.342	0.504	0.278	0.411	0.017	0.014	0.006	0.014
2040-2045	0.310	0.387	0.252	0.316	0.011	0.013	0.016	0.011
2045-2050	0.160	0.301	0.132	0.247	0.013	0.013	0.008	0.011

Source: own elaboration with the results from the CGE model experiments.

The results of Table 14 indicate that household consumption and gross output increase from baseline. The economic effects are dependent on the oil price assumptions. The aforementioned macroeconomic effects vary in the high-price scenario between 0.2 percent in 2020, 0.8 percent in 2030 to almost 2-3 percent in 2050. In the low-price case, the estimated change from baseline in macro variables is lower at most by 0.1, -0.2, and 2.4 percent in 2020, 2030 and 2050 respectively. Investment increases to approximately 0.2 percent in 2030 and 0.4 percent in the terminal year. One of the more striking results is that energy costs decrease in each scenario and vary roughly between -0.1 and -0.2 percent over the reference case when taking into account high-price assumptions, and between -0.1 and -0.3 percent when considering low-price suppositions. The economy grows faster in the low-price case where the reductions in energy costs are also more pronounced.

Table 15 - Economic simulation results in the hydrogen-powered case.

Macro variable	Household consumption		GDP		Investment		Energy costs	
Brent crude oil price	C	B	C	B	C	B	C	B
Years	Estimated change from baseline (unit: %/year)							
2015	0.024	0.097	0.014	0.072	0.000	0.000	-0.143	-0.132
2020	0.258	0.161	0.204	0.133	0.015	0.049	-0.070	-0.100
2025	0.369	0.017	0.309	0.031	0.101	0.121	-0.071	-0.121
2030	0.807	-0.269	0.672	-0.192	0.172	0.184	-0.065	-0.184
2035	0.338	-0.586	0.306	-0.443	0.234	0.241	-0.150	-0.257
2040	0.290	0.248	0.278	0.243	0.301	0.295	-0.155	-0.201
2045	1.602	1.190	1.343	1.017	0.345	0.347	-0.111	-0.162
2050	2.963	2.416	2.444	2.023	0.398	0.402	-0.105	-0.133
Annual growth rate (unit: %/year)								
2010-2015	1.748	1.835	1.355	1.427	0.000	0.000	0.057	0.051
2015-2020	1.269	1.344	0.998	1.062	0.004	0.012	0.033	0.029
2020-2025	0.917	1.009	0.730	0.807	0.022	0.018	0.011	0.018
2025-2030	0.676	0.766	0.543	0.617	0.018	0.016	0.008	0.012
2030-2035	0.505	0.586	0.407	0.475	0.015	0.014	0.009	0.009
2035-2040	0.342	0.504	0.278	0.411	0.017	0.014	0.006	0.014
2040-2045	0.310	0.386	0.252	0.316	0.011	0.013	0.016	0.011
2045-2050	0.160	0.300	0.132	0.247	0.013	0.014	0.008	0.011

Source: own elaboration with the results from the CGE model experiments.

The results of Table 15 show that the main economic variables increase from baseline. In this case, the macroeconomic effects vary in the high-price scenario between 0.2 percent in 2020, 0.8 percent in 2030 to almost 2-3 percent in the terminal year. In the low-price case, the estimated change from baseline in macro variables is lower at most by 0.1, -0.2, and 2.4 percent in 2020, 2030 and 2050 respectively. Investment levels increase to approximately 0.2 percent in 2030 and 0.4 percent in the terminal year. Energy costs decrease in each scenario and vary roughly between -0.06 and -0.16 percent over the reference case with high-price assumptions, and between -0.1 and -0.26 percent with low-price suppositions. The macroeconomic effects are also more pronounced in the high-price case, but larger energy costs reductions are achieved in the low-price hypothesis scenario.

Table 16 - Sensitivity analysis in the diversified case.

Utility discount rate δ		10%		12%		15%	
Brent crude oil price		C	B	C	B	C	B
Macro variable	Years	Estimated change from the baseline					
Investment (unit:%/year)	2015	0.000	0.000	0.000	0.000	0,000	0.000
	2020	0.015	0.049	0.016	0.000	0.000	0.000
	2025	0.101	0.121	0.107	0.051	0.021	0.132
	2030	0.172	0.184	0.178	0.125	0.116	0.192
	2035	0.234	0.241	0.239	0.187	0.185	0.247
	2040	0.301	0.295	0.295	0.244	0.244	0.299
	2045	0.345	0.347	0.348	0.297	0.298	0.350
	2050	0.398	0.399	0.399	0.349	0.349	0.400
Household consumption (unit:%/year)	2015	0.027	0.100	0.546	0.117	0.460	0,175
	2020	0.263	0.165	0.829	0.206	0.643	0,378
	2025	0.376	0.022	1.128	-0.034	0.756	-0.088
	2030	0.814	-0.264	1.341	-0.411	0.756	0.969
	2035	0,347	-0.580	0.680	0.476	0.112	2.120
	2040	0.299	0.255	1.523	1.392	1.185	3.374
	2045	1.613	1.197	2.004	2.537	1.734	4.454
	2050	2.975	2.425	2.140	3.847	1.820	5.638
Estimated macroeconomic impact							
Consumption to GDP ratio[1] (unit:%)	2010	79.946	79.946	79.946	79.946	79.946	79.946
	2015	81.035	81.087	81.035	81.,087	81.035	81.087
	2020	81.796	81.886	81.781	81.881	81.777	81.883
	2025	82.321	82.463	82.304	82.452	82.293	82.436
	2030	82.700	82.892	82.680	82.874	82.662	82.901
	2035	82.977	83.213	82.951	83.224	82.922	83.232
	2040	83.160	83.484	83.192	83.479	83.154	83.467
	2045	83.327	83.689	83.338	83.667	83.289	83.632
	2050	83.408	83.845	83.403	83.807	83.341	83.800
Annual growth rate of household consumption (unit:%/year)	2010-15	1.748	1.835	1.748	1.835	1.748	1.835
	2015-20	1.270	1.344	1.245	1.337	1.239	1.328
	2020-25	0.917	1.009	0.914	0.998	0.903	0.980
	2025-30	0.677	0.766	0.671	0.755	0.659	0.830
	2030-35	0.505	0.587	0.492	0.637	0.471	0.605
	2035-40	0.342	0.504	0.443	0.475	0.427	0.436
	2040-45	0.310	0.387	0.277	0.355	0.255	0.313
	2045-50	0.160	0.301	0.130	0.271	0.106	0.321

Source: own elaboration with the results from the CGE model experiments. [1] The ratio is computed as a percentage of household consumption divided by the sum of household consumption and investment.

Table 17 - Sensitivity analysis in the hydrogen-powered case.

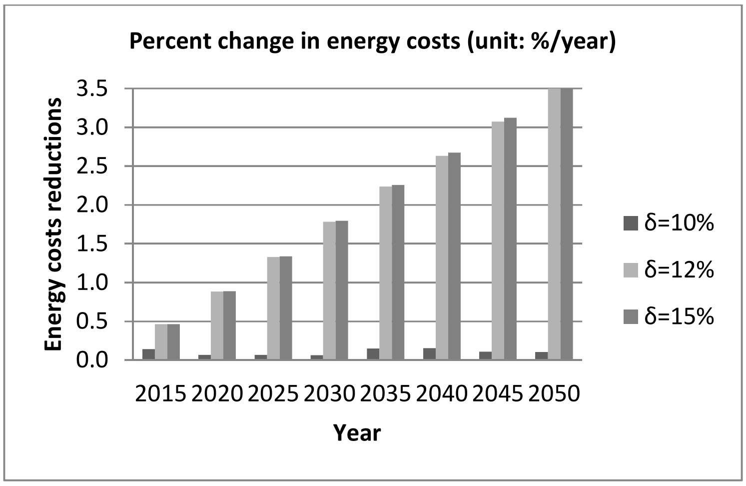
Utility discount rate δ	10%		12%		15%	
Brent crude oil price	C	B	C	B	C	B

Macro variable	Years	Estimated change from the baseline					
Investment (unit:%/year)	2015	0.000	0.000	0.000	0.000	0.000	0.000
	2020	0.015	0.049	0.016	0.051	0.021	0.050
	2025	0.101	0.121	0.107	0.125	0.116	0.124
	2030	0.172	0.184	0.178	0.187	0.185	0.192
	2035	0.234	0.241	0.240	0.244	0.244	0.247
	2040	0.301	0.295	0.294	0.297	0.298	0.299
	2045	0.345	0.347	0.347	0.376	0.349	0.350
	2050	0.398	0.402	0.399	0.400	0.400	0.400
Household consumption (unit:%/year)	2015	0.024	0.097	0.543	0.114	0.456	0.172
	2020	0.258	0.161	0.824	0.202	0.638	0.363
	2025	0.369	0.017	1.121	-0.039	0.749	-0.091
	2030	0.807	-0.269	1.333	-0.416	0.749	0.963
	2035	0.338	-0.586	0.672	0.470	0.105	2.113
	2040	0.290	0.248	1.513	1.385	1.176	3.366
	2045	1.602	1.190	1.993	2.525	1.724	4.447
	2050	2.963	2.416	2.128	3.840	1.808	5.630
Estimated macroeconomic impact							
Consumption to GDP ratio[1] (unit:%)	2010	79.946	79.946	79.946	79.946	79.946	79.946
	2015	81.034	81.087	81.034	81.087	81.034	81.087
	2020	81.795	81.885	81.781	81.880	81.776	81.874
	2025	82.320	82.462	82.303	82.451	82.292	82.436
	2030	82.699	82.891	82.679	82.873	82.661	82.900
	2035	82.976	83.212	82.950	83.223	82.921	83.231
	2040	83.159	83.484	83.190	83.478	83.153	83.466
	2045	83.325	83.688	83.337	83.662	83.288	83.631
	2050	83.407	83.844	83.402	83.806	83.340	83.799
Annual growth rate of household consumption (unit:%/year)	2010-15	1.748	1.835	1.748	1.835	1.748	1.835
	2015-20	1.269	1.344	1.245	1.336	1.238	1.325
	2020-25	0.917	1.009	0.914	0.998	0.903	0.982
	2025-30	0.676	0.766	0.671	0.755	0.658	0.829
	2030-35	0.505	0.586	0.491	0.637	0.471	0.605
	2035-40	0.342	0.504	0.442	0.475	0.426	0.436
	2040-45	0.310	0.386	0.277	0.354	0.255	0.313
	2045-50	0.160	0.300	0.130	0.272	0.105	0.321

Source: own elaboration with the results from the CGE model experiments. [1]The ratio is computed as a percentage of household consumption divided by the sum of household consumption and investment.

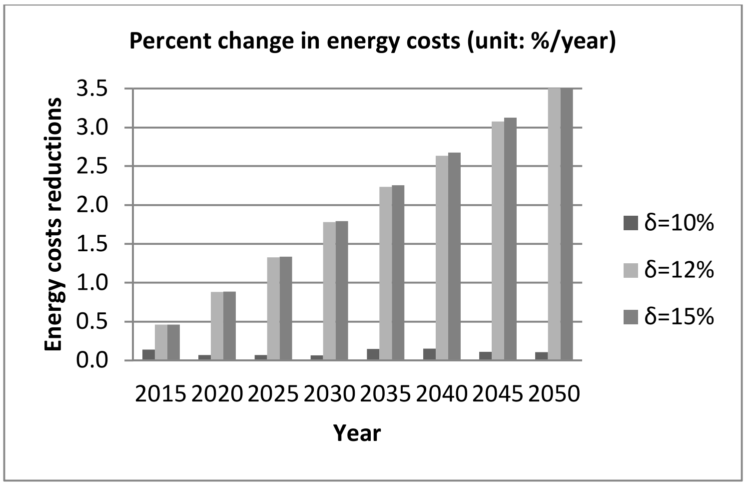
A robustness analysis is conducted to examine the effects of alternative utility discount rates on our model experiments. The results for the diversified and for the hydrogen-based scenarios are respectively reported in the tables above. It does not appear that a major impact upon the calculation of the economic effects associated with different transportation technologies as δ varies from 10% to 15% per year. We can infer from the additional model experiments that the choice of different utility discount rates in the consumer's utility function can impact particularly upon the calculations of the energy costs variable. Because of the greater rate at which the consumer discounts the future consumption and the weight attached to the present consumption in the utility function, higher energy costs reductions are paired with higher Brent crude oil prices regardless of the envisaged PATTS scenarios. These results are observable in Fig. 9 and Fig. 10 which compare the impact upon the reduction of energy costs under the two road transportation scenarios in which we have altered the assumptions of pre-existing utility discount rates. The sensitivity analysis further reveals that the choice of the discount rate does not have the same impact when the Brent crude oil price is low. The graphical inspection of Figure 10 and Figure 11 reveals that the changes in energy costs relative to the baseline are reduced. Symmetrically, lower Brent crude oil prices will pull down the overall costs savings for energy. The energy cost reduction effect remains higher in the high-price scenario.

Fig. 9 - Impact of different utility discount rates in the percent change of energy costs from baseline in the high-price diversified case



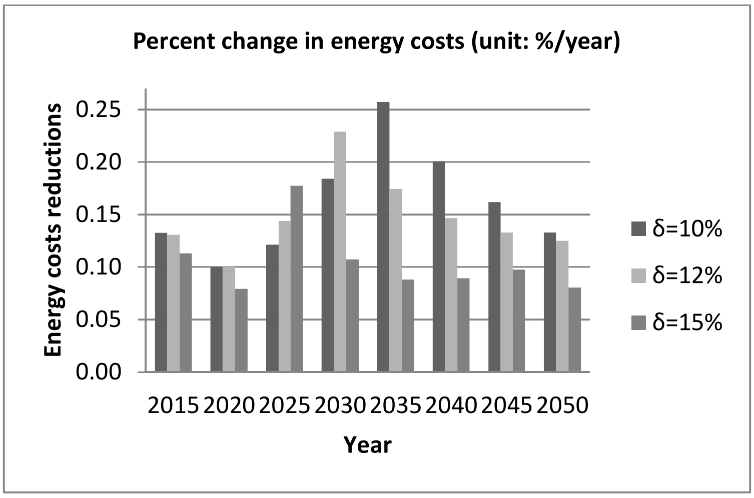
Source: own elaboration with the results from the CGE model experiments.

Fig. 10 - Impact of different utility discount rates in the percent change of energy costs from baseline in the high-price hydrogen-powered case



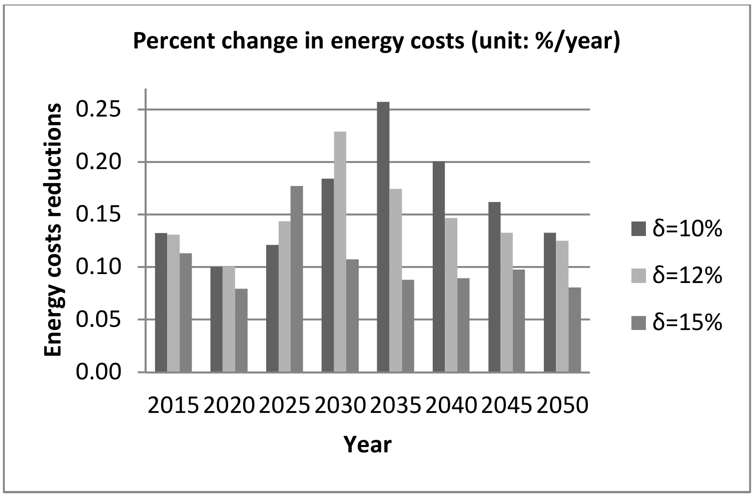
Source: own elaboration with the results from the CGE model experiments.

Fig. 11 - Impact of different utility discount rates in the percent change of energy costs from baseline in the low-price diversified case



Source: own elaboration with the results from the CGE model experiments.

Fig. 12 - Impact of different utility discount rates in the percent change of energy costs from baseline in the low-price hydrogen-powered case



Source: own elaboration with the results from the CGE model experiments.

7. CONCLUSIONS

A strong hydrogen penetration in the road transportation, maximum 22% of hydrogen based road vehicles in 2050, for the *hydrogen powered* scenario, may be responsible for a decrease of CO_2 and fossil energy consumption compared with the BAU of 29 % and 20%. A reduction of life cycle (WTW) CO_2 emissions of 3% in 2050 face to 1990 values is achievable, 60% if only TTW is considered. Moreover, this study has employed analytical and numerical general equilibrium models to assess the economic impact of hydrogen scenarios in the Portuguese road transportation sector. We can infer from the economic experiments that the PATTS scenarios lead to positive impacts upon the main macro variables. The simulations results show a significant household response to energy prices by 2050. We have conducted a robustness analysis to examine the effects of alternative utility discount rates on our model experiments, which have shown no noticeable impact upon the calculation of the main macro variables. The economy grows faster in the low-price scenario where the reductions in energy costs are also more pronounced. Thus, the projected energy costs savings are sensitive to consumer preferences. The sensitivity analysis further reveals that in the presence of higher energy price levels, and if we augment the utility discount rate, then the higher is likely to be the expected reduction in energy costs, and hence the lower the energy bill for the aggregate economy. This study is not without any limitations. Therefore, future developments of this research should look at extending the CGE model, namely to set up a nested CES production function that is more appropriate for modelling energy in production activities, in order to make the model more consistent with reality.

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