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Optimal Extraction and
Trade of Oil under Climate
Policy**

By **Emanuele Massetti**, Fondazione Eni
Enrico Mattei, Euro-Mediterranean
Center for Climate Change

Fabio Sferra, Fondazione Eni Enrico
Mattei

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Address for correspondence:

Emanuele Massetti
Fondazione Eni Enrico Mattei
Corso Magenta 63
20123 Milano
Italy
E-mail: emanuele.massetti@feem.it

**A NUMERICAL ANALYSIS OF OPTIMAL
EXTRACTION AND TRADE OF OIL
UNDER CLIMATE POLICY**

Emanuele Massetti*
*Fondazione Eni Enrico Mattei
Euro-Mediterranean Center for Climate Change*

Fabio Sferra
Fondazione Eni Enrico Mattei

July 2010

Abstract

We introduce endogenous investments for increasing conventional and non-conventional oil extraction capacity in the integrated assessment model WITCH. The international price of oil emerges as the Nash equilibrium of a non-cooperative game. When carbon emissions are not constrained, oil is used throughout the century, with unconventional oil taking over conventional oil from mid-century onward. When carbon emissions are constrained, oil consumption drops dramatically and the oil price is lower than in the BaU. Unconventional oil is not extracted. Regional imbalances in the distribution of stabilisation costs are magnified and the oil-exporting countries bear, on average, costs three times larger than in previous estimates.

* Corresponding author: Corso Magenta, 63, 20123 Milano – Italy. Email: emanuele.masseti@feem.it. The authors wish to thank Carlo Carraro, Shoibal Chakravarty, Alessandro Lanza, Manfred Hafner, Massimo Tavoni and participants at seminars at FEEM, at IEFÉ, at the International Energy Workshop and at the World Congress of Energy and Resource Economists for valuable comments and suggestions. The usual disclaimers apply.

Introduction

Ambitious climate policies that aim at stabilising Greenhouse Gases concentrations in the atmosphere at low levels ask for a dramatic contraction of fossil fuels use during the entire century. The shift from fossil fuel-based to zero-carbon energy systems will be gradual, but after two and a half centuries of supremacy, coal, oil and natural gas will only be used marginally. It is not necessary to employ sophisticated Integrated Assessment Models (IAMs) to depict this scenario.¹ A simple back-of-the-envelope exercise would show only a minimal amount of Greenhouse Gases (GHG) emissions that will be tolerated in the long-run equilibrium to keep concentrations stable at safe levels. In a future world in which GHG emissions must virtually disappear, it will be more valuable to keep carbon underground than releasing it into the atmosphere.

While it might still be convenient to use coal and natural gas in power plants equipped with carbon capture and sequestration (CCS) devices, the impossibility to capture diffused emissions from transport dooms oil to a fast decline.² Volumes of crude oil traded in the international market will become almost irrelevant and financially modest, and oil rich countries have to restructure their economies deeply to avoid major economic and welfare losses. The emergence of a low-carbon world will mark the end of an “oil age”, with still widely unexplored economic, technological and geopolitical implications.

It is straightforward to predict that oil demand will shrink dramatically in a scenario in which climate policy is severe and is implemented successfully worldwide. It is instead harder to imagine an optimal transition to this long-run equilibrium and to assess the economic consequences and the distributional impacts of the oil market collapse. These issues are addressed in this paper.

The main questions are the following: how will investment decisions in oil extraction capacity be affected when a cap on emissions is imposed throughout the century? How will these decisions shape oil supply and how will they affect international trade of oil and oil price? Economies that are heavily dependent on oil export will likely lose from a terms of trade effect and from the contraction of demand. To what degree will they be able to restructure their production activities to answer the threat that a low-carbon world poses to their economies? And what will eventually be the long-term macroeconomic impact of the mitigation policy, at the global and regional level when we describe the oil sector with greater accuracy ?

¹ For recent work on climate policy and energy scenarios with IAMs see Clarke *et al* (2009).

² While it is technically possible to use oil in power plants with CCS, this option is not economically convenient.

In order to provide an answer to these questions we introduce endogenous investments in oil extraction capacity and international trade of oil in the hybrid integrated assessment model WITCH (Bosetti *et al*, 2006; Bosetti, Massetti and Tavoni, 2007; Bosetti *et al*, 2009). We design long-term world and regional scenarios of optimal demand and supply of oil when GHG emissions are capped in order to reach a concentration level of 550ppm CO₂-eq at the end of the century. We compare them to oil sector dynamics when carbon emissions are not constrained. The mutual interactions of the oil sector with the demand of other fossil fuels, with investments in the power sector, the incentives to develop a carbon-free substitute for oil in transport and an international carbon market are all taken into account.

For the twelve macro-regions of WITCH, we model an oil sector that evolves endogenously. Production of oil is a function of extraction capacity built by means of endogenously determined investments. The Oil sector is modelled considering eight categories of oil, reflecting minimal extraction costs and emissions related to oil extraction for each category. The cost of additional oil extraction stocks is also endogenous and depends both on a short-term component, which mimics cost spikes when expansion capacity grows too fast, and on a long-term component, which reflects oil scarcity. Thus, the total expenditure in the oil sector is also endogenous. Once extracted, oil can be used for domestic consumption and can be traded internationally. The price of oil emerges endogenously as an outcome of a Nash game among the twelve regions.

In Table 1 and in Table 2 we summarise the main characteristics of a sub-set of all IAMs that have endogenous trade of oil: MERGE (Manne and Richels 2004), REMIND-R (Leimbach et al 2008), IMACLIM (Hourcade et al 2006), IMAGE (Bouwman, Kram and Goldewijk 2006), MiniCAM (Brenkert et al 2003), MESSAGE (Nakicenovic and Riahi 2003), EPPA (Paltsev et al 2005; Babiker et al 2008).³

³ MERGE also models trade of natural gas. IMAGE and TIAM model trade of oil, gas and coal; TIAM models trade of uranium. TIAM, however, is a bottom-up engineering-type model that does not describe the macro-economy or the impact of emissions on global climate.

FOSSIL FUELS				
Models	Cost Function	Trade	Transportation Costs	Technological Progress
WITCH	Endogenous. Floor cost based on oil categories.	Global trade	Markups reflect constraints and other costs.	No
IMAGE	Step function with multiple grades. 12 categories for oil, gas and nuclear fuels, 14 for coal.	Bilateral trade	Interregional distances. Mark-up to reflect constraints and other costs (taxes, etc.).	Yes Endogenous
MINICAM	Supply curve. Short term capacity constraint.	Global trade	Regional mark-up.	Yes
EPPA	Step function with multiple grades. Convex aggregation of different fuel resources allows multiple resource grades to be produced at the same time.	Bilateral trade	Interregional distances. Mark-up to reflect constraints and other costs (taxes, etc.).	Yes
MESSAGE	Step functions with multiple grades.	Global trade	Markups that mimic transportation costs.	Yes Endogenous
IMACLIM	Step function exogenous.	Global trade	Yes	No
MERGE	Step function - 10 Cost Categories.	Global trade	Yes	No
REMIND	Specific fuel costs are a function of previous cumulative extraction (extraction cost curve - see Rogner, 1997).	Global trade	REMIND-R: import and export of tradable primary energy types is added, taking specific trade costs into account.	No

Table 1. Fossil fuel sector: a Model Comparison

Models	OIL				NATURAL GAS				COAL		
	Refined Oil	Resources Conv.	Resources Non Conv.	Price Index at 2050 Base Year 2000 (BaU)	GTL	Resources Conv.	Resources Non Conv.	Price Index at 2050 Base Year 2000 (BaU)	CTL	Resources	Price Index at 2050 Base Year 2000 (BaU)
WITCH	No	20	93	2.2 ^b	No	15 ZJ	No	2.2 ^b	No	433 ZJ	1.25 ^b
IMAGE	Yes	45 ZJ ^c	Yes	1.7	No	117 ZJ ^c	Yes	1.9	No	300 ZJ	1.3
MINICAM	Yes	18 ZJ	Yes	1.6	Yes	19,5 ZJ	16 ZJ	1.2	Yes	> 250 ZJ	1.1 ^d
EPPA	Yes	35 ZJ ^a	637 ZJ	3.0 ^e	No	19 ZJ	Synthetic gas from coal	2.1 - 5.5 ^f	No	179 ZJ	1.1 - 2.0 ^f
MESSAGE	Yes	12 ZJ	98	2.0	No	16.5 ZJ	836 ZJ	1.6	Yes	258 ZJ	n.a.
IMACLIM	Yes	9 ZJ ^h	7 ZJ ^h	3.5 ^g	Yes	n.a.	Yes	2.0	Yes	n.a.	1.5
MERGE	Yes	6 ZJ	Yes	1.5	No	5 ZJ	No	2.2	Yes	300 ZJ	1.1 ^b
REMIND	Yes	< 10 ZJ ^h	Yes	2.1 ^b	No	6 ZJ	Yes	1.2 ^b	Yes	< 30 ZJ	2.0 ^b

^a Including tar sands

^b Base Year 2005

^c includes non-conventional resources

^d at 2100

^e Base year 1997

^f depending on the region

^g Base Year 2001

^h Oil reserves

Table 2. Fossil fuels data: an overview of assumption in Integrates Assessment Models.

In IMACLIM, coal and gas extraction costs are described using reduced forms of cost functions from the energy model POLES (Criqui 2001). Oil price is equal to the production cost plus a mark-up. The available capacity of oil production is assumed to follow a ‘Hubbert’ curve (1962). In IMAGE, the production cost increases endogenously as a consequence of fossil fuels exhaustion. A more detailed description of the oil sector is given in MESSAGE IV, which displays eight categories of conventional and non-conventional oil. In MINICAM, REMIND and EPPA model the oil resources data are taken from Rogner (1997). However, in EPPA the authors make shale oil available only in four regions where the resources are more promising: USA, Former Soviet Union, Africa, and in Australia. In MERGE, oil resources are divided into ten categories; costs increase as oil extraction moves from conventional to unconventional categories.

We calibrate the model in order to reproduce observed oil production and international inter-regional net trade flows of oil in 2005, the base year of the WITCH model. The time paths of the oil price and world oil consumption are calibrated to be almost identical to the dynamics we had in a previous version of the model without investments and trade of oil. As a consequence, the time path of GDP, consumption, investment and emissions are almost identical to what we have in the model without endogenous oil extraction. This allows insightful comparisons between scenarios obtained with the old and the new formulation of WITCH. In particular, we can study how global and regional stabilisation costs change when oil sector dynamics are modelled more appropriately.

Our main conclusion is that with respect to previous estimates, mitigation policy costs are three times higher in oil exporting regions. As for oil importing countries the costs are about two times higher. Globally, we find that costs more than double when oil dynamics are endogenous.

In section 2 we provide a brief overview of the WITCH model. In section 3 we present in detail the equations that describe the oil sector and the international market of oil and section 4 describes calibration issues. In section 5 we compare oil sector dynamics in the reference and in the policy scenarios. The concluding section is used to draw an overall assessment of the findings presented in the paper and to present further modelling development and additional policy analysis that we expect to undertake in the future.

1. The WITCH Model: a Brief Overview

WITCH – World Induced Technical Change Hybrid – is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate policies (Bosetti *et al.* 2006, 2009b; Bosetti, Massetti and Tavoni, 2007).

It is a hybrid model because it combines features of both top-down and bottom-up modelling. The top-down component consists of an inter-temporal optimal growth model in which the energy input of the aggregate production function has been integrated into a bottom-up like description of the energy sector. WITCH's top-down framework guarantees a coherent, fully intertemporal allocation of investments, including those in the energy sector.

World countries are aggregated in twelve regions on the basis of geographic, economic and technological vicinity. The regions interact strategically on global externalities: GHGs, technological spillovers, and a common pool of exhaustible natural resources.⁴

WITCH contains a detailed representation of the energy sector, which allows the model to produce a reasonable characterisation of future energy and technological scenarios and an assessment of their compatibility with the goal of stabilising greenhouse gases concentrations. In addition, by endogenously modelling fuel prices (oil, coal, natural gas, uranium), as well as the cost of storing the CO₂ captured, the model can be used to evaluate the implication of mitigation policies on the energy system in all its components.

In WITCH, emissions arise from fossil fuels used in the energy sector and from land use changes that release carbon sequestered in biomasses and soils. Emissions of CH₄, N₂O, SLF (short-lived fluorinated gases), LLF (long-lived fluorinated) and SO₂ aerosols, which have a cooling effect on temperature, are also identified. Since most of these gases arise from agricultural practices, the modelling relies on estimates for reference emissions, and a top-down approach for mitigation supply curves.⁵

⁴ The regions are USA, WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (South Korea, South Africa and Australia), CAJANZ (Canada, Japan and New Zealand), TE (Transition Economies), MENA (Middle East and South Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), SEASIA (South-East Asia), CHINA, LACA (Latin America and the Caribbean).

⁵ Reducing emissions from deforestation and degradation (REDD) is estimated to offer sizeable low-cost abatement potential. WITCH includes a baseline projection of land use CO₂ emissions, as well as estimates of the global potential and costs for reducing emissions from deforestation, assuming that all tropical forest nations can join an emission trading system and have the capacity to implement REDD programs. However, avoided deforestation is not a source of emissions reductions in the version of the model that we used for this study.

A climate module governs the accumulation of emissions in the atmosphere and the temperature response to growing GHGs concentrations. WITCH is also equipped with a damage function that provides the feedback on the economy of global warming. However, in this study we exclude the damage function and we take the “cost-minimisation” approach: given a target in terms of GHGs concentrations in the atmosphere, we produce scenarios that minimise the cost of achieving this target.

Endogenous technological dynamics are a key feature of WITCH. Dedicated R&D investments increase the knowledge stock that governs energy efficiency. Learning-by-doing curves are used to model cost dynamics for wind and solar power capital costs. Both energy-efficiency R&D and learning exhibit international spillovers. There are two backstop technologies in the electricity sector and the non-electricity sector that necessitate dedicated innovation investments to become competitive. In line with the most recent literature, the costs of these backstop technologies are modelled through a so-called two-factor learning curve, in which their price declines both with investments in dedicated R&D and with technology diffusion.

The base year for calibration is 2005; all monetary values are in constant 2005 USD. The WITCH model uses market exchange rates for international income comparisons.

2. The Oil Sector and the Oil Market in the WITCH Model

In this section we describe the equations that govern the oil sector and the international oil market in the present enhanced version of the WITCH model.

2.1. Oil Demand and Oil Supply

Crude oil is used both in the electric and in the non-electric sector in WITCH. In country n at time t total oil demand (OIL) is given by the sum of oil used in the electric sector (OIL_{el}) and non-electric sector (OIL_{nel}):

$$OIL(t, n) = OIL_{el}(t, n) + OIL_{nel}(t, n). \quad (1)$$

Oil demand is covered by means of domestic production (OIL_{prod}) of each category g of oil and/or by means of net oil imports (NIP_{oil}) from the international oil market:

$$OIL(t, n) = \sum_g (OIL_{prod}(t, n, g)) + NIP_{oil}(t, n). \quad (2)$$

In oil-exporting regions, domestic production of oil is greater than domestic consumption and net imports are negative. We model eight distinct extraction sectors for oil but we assume that oil traded internationally is a homogenous good.

Oil production in a given year cannot exceed the extraction capacity (OIL_{cap}) cumulatively built in the country. Extraction capacity depreciates at the rate δ . Therefore there is space for spare capacity in the model:

$$OIL_{prod}(t, n, g) \leq OIL_{cap}(t, n, g), \quad (3)$$

$$OIL_{cap}(t+1, n, g) = OIL_{cap}(t, n, g)(1 - \delta) + \Delta(t, n, g). \quad (4)$$

2.2. Equilibrium in the International Oil Market

Equilibrium in the international oil market requires that excess demand of oil is equal to zero at any given time period:

$$\sum_n NIP_{oil}(t, n) = 0 \quad \forall t. \quad (5)$$

2.3. Oil and Non-Oil Gross Domestic Product

National Net Gross Domestic Product (GDP) Y can be decomposed in oil and non-oil GDP:

$$Y(t, n) = Y_{NONOIL}(t, n) + Y_{OIL}(t, n). \quad (6)$$

Net non-oil GDP is equal to gross non-oil output (GY_{NONOIL}) net of the climate feedback (Ω), of the expenditure for oil and of the expenditure for other fuels:⁶

$$Y_{NONOIL}(t, n) = \frac{GY_{NONOIL}(t, n)}{\Omega(t, n)} - OIL(t, n)[P_{OIL}(t) + MKUP_{OIL}(t, n)] - \sum_z P_z(t)X_z(t, n). \quad (7)$$

Oil is valued at international market prices also for regions that are net exporters. A mark-up ($MKUP_{OIL}$) is added to the international price of oil (P_{OIL}) to account for local factors that affect the cost of oil for final users; the mark-up can be greater or lower than zero. X_Z is a vector of production inputs that are assumed to be a net loss for the economy, including other fuels and the amount of carbon captured and stored; P_Z is a vector of prices.

⁶ In our analysis we switch climate feedback off and we examine climate policy in a “costminimisation” framework.

Net oil GDP is equal to the value of conventional and non-conventional oil production, valued at the international price of oil:

$$Y_{OIL}(t,n) = \frac{1}{\Omega(t,n)} \sum_g OIL_{prod}(n,t,g) P_{OIL}(t). \quad (8)$$

Consumption is equal to what remains of the economy net output Y , after subtracting investment in all technologies I_j , other expenditures W_k , investments in additional oil capacity extraction I_{OILCAP} (for a more detailed description of the budget constraint see the Appendix). We also account for O&M costs associated with oil extraction:

$$C(t,n) = Y(t,n) - \sum_j I_j(t,n) - \sum_g I_{OILCAP}(t,n,g) - \sum_g OILCAP(t,n,g) O \& M - \sum_k W_k(t,n). \quad (9)$$

Investments for conventional and non-conventional oil extraction are equal to the expenditure for financing the expansion of oil capacity $\Delta(t,n,g)$, region and time specific:

$$I_{OILCAP}(t,n,g) = OIL_{cap\ cost}(t,n,g) \Delta(t,n,g). \quad (10)$$

We assume that labour is not necessary to extract oil. This is a simplification that does not bear relevant implications since the oil-extraction sector is highly capital intensive.⁷

2.4. Oil Extraction Capacity Costs

The cost of each barrel of oil is not explicit in WITCH. It emerges in the model as a shadow cost of the resources invested in the oil sector. This modelling approach allows a full description of capital accumulation for oil extraction, but it complicates the description of oil cost dynamics. In fact, instead of modelling the evolution of the cost to extract a barrel of oil, we describe how the investment cost in extracting capacity changes when oil of a given category becomes scarcer or when different categories are exploited.

The cost of oil extraction capacity is equal to the sum of three components: (1) a fixed factor, (2) an element that mimics short-term frictions that arise in the market when demand increases too fast, and (3) a module that reflects the exhaustibility of oil. In the next section we discuss calibration details for easier reference and we introduce the equations that govern the dynamics of oil extraction capacity costs.

⁷ Share of labour force in the oil sector for selected countries in 2002: United States, 0.4%; Saudi Arabia 1.6%; China, 0.8%; Venezuela, 0.5%; Canada, 1.1%; Russian Federation, 1.8% (ILO 2010)

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
Resources (Bln. Barrels)												
Conventional (Cat I-IV)	347	120	13	15	59	538	1341	130	20	186	76	445
Non Conventional (Cat. V-VIII)	1749	416	39	989	1823	1336	3007	331	32	1737	269	3848
Production (Bln. Barrels)												
Conventional (Cat I-IV)	2.1	1.8	0.0	0.2	1.0	4.1	10.1	1.9	0.3	1.3	0.9	3.9
Non Conventional (Cat. V-VIII)	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Net Exports (Bln. Barrels)	-4.8	-2.8	-0.5	-1.0	-1.5	2.4	7.6	1.6	-0.8	-1.4	-0.6	1.7
Consumption (Bln. Barrels)	7.0	4.6	0.5	1.2	2.6	1.7	2.5	0.3	1.1	2.7	1.5	2.3

Table 3. Oil Overview in 2005.

3. Calibration

3.1. Oil Market Dynamics in the Base Year

We calibrate the model to replicate base year oil production, import and export. We assume that oil traded internationally is homogeneous. Therefore we have a unique international oil price.

Oil resources are derived from Rogner (1997) and they are assumed not to grow over time. Oil resources are distinguished in eight categories. In Table 3 we aggregate them in two categories: conventional oil (categories I-IV) and non-conventional oil (categories V-VIII).

In 2005, non-conventional oil production is negligible and concentrated only in a few regions: Canada (CAJANZ aggregation) Brazil and Venezuela (LACA aggregation) and USA, in decreasing order.⁸

Oil imports and exports in the base year are calibrated using data provided by Enerdata (World Energy Database).⁹ In 2005, USA is the largest oil importer (4.83 Billion Barrels per year), followed by WEURO, CAJAZ and CHINA. The largest oil exporter is MENA (7.6 Billion Barrels per year) followed by TE, LACA and SSA in decreasing order. An overview of the oil sector is given in Table 3.

3.2. Cost of Oil Extraction Capacity

A correct description of the oil market is problematic for all large-scale economic models because they are typically unable to replicate the functioning of non-competitive markets. WITCH is not an exception. The players of the non-cooperative game that all regions play, in

⁸ Source of data: UNESD database (Production of Tar Sands and Oil Shales).

⁹ Enerdata compiles more than 150 specialised information sources in the energy sector. All data are expertised with a tested statistical methodology, to provide an extensive, reliable and timely updated global energy market database on a single online interface.

WITCH behave as price-takers, not able to recognise that they can influence other players choices.¹⁰

It is then clear why a simple step cost function, as in Rogner (2007) cannot guide investment decisions: if the market price of oil is higher than the (implicit) cost of extracting a barrel of oil, there is a tendency for large resource owners to flood the market with oil supply.

One option to circumvent this problem is to impose a complex set of rules that restricts the quantity of oil that can be extracted, in each region, at each point in time. Another option is to introduce a cost curve that has short-term increasing marginal extraction costs. We opted for the second option to allow greater flexibility to the investment decisions of oil producing countries.

The cost of additional oil capacity is governed by three elements. First, each oil category has a specific investment cost that represents a cost floor. This represents the flat part of a step function. Second, we reduce the incentive to over-invest in oil extraction capacity by introducing a short-term cost component that inflicts severe cost increments when capacity additions are above a given threshold. Third, we smooth the transition from a lower (cheaper) to a higher (more expensive) category of oil by introducing a cost component that is inversely related to remaining oil resources for each category. The second and third components of the cost function allow having more resource categories in use at the same time, which is not possible with a simple step cost function.

With more precision, we model the cost of additional oil extraction capacity, at time t , in region n , for grade g , as detailed in Equation 11:

$$\begin{aligned}
 OIL_{capcost}(t, n, g) = & \lambda(g) + \varphi(g)\Delta(t, n, g)^{1/\psi} + \varphi(g) \left\{ \left[\frac{\Delta(t, n, g)}{\zeta(n, g)} \right]^\psi - 1 \right\} \\
 & + \mu(g) \left(\frac{\sum_{s=1}^{t-1} OIL_{prod}(t, n, g)}{\theta OIL_{res}(t, n, g)} \right)^\chi
 \end{aligned} \tag{11}$$

$\lambda(g)$ represents the first component – the price floor – calibrated using the upper bound of the cost range provided by Rogner (1997) for each category of oil.¹¹ The second and third terms are

¹⁰ In the previous version of the WITCH model without investments in the oil sector and without an explicit formulation of the international market for oil, the oil price was still endogenous and it was governed by a global cost function that was based on cumulative consumption of oil.

¹¹ In particular, if we denote with $\Gamma(g)$ the extraction cost of one barrel of oil as in Rogner (1997), the cost of the extraction capacity that will supply one barrel of oil per year is equal to $\alpha(g) = \Gamma(g)/(r + \delta)$.

the two power functions, which model the short-term cost component as a function of additional capacity $\Delta(t, n, g)$. Their weight is limited since $\varphi(g)$ is set equal to 4% of $\lambda(g)$. The parameter ψ is set equal to 3. For categories II-VIII of oil, the parameter $\zeta(g)$, is calibrated so that the cost starts increasing at fast pace when additional capacity is higher than 0.16 billion barrels per year. For category I, this threshold is equal to ten percent of extraction capacity in the base year. Finally, the last term is a power function of the depletion rate that allows a smooth transition from one oil category to the other. Also χ is set equal to 3. $\mu(g)$ is equal to the difference between extraction capacity costs of category g and category $g+1$; the calibration is based again on Rogner (1997). λ is equal to 0.5.¹²

Parameters have been chosen to replicate realistic short- and medium-term expansion paths of oil supply and to obtain a path of oil price that is very close to the version of WITCH that does not include an explicit description of the oil sector. By pinning the oil price down to the old time path, investments in other technologies are largely unaffected, allowing interesting comparison exercises between the two versions of the model. The sensitivity analysis in Section 7 tests different assumptions on the value of $\varphi(g)$ and on the amount of oil resources for each category.

The existing oil capacity is subject to depreciation, with $\partial = 0.1$ per year (see Equation 4). An upper bound to cumulative oil production constrains extraction below feasible levels at any point in time:

$$\sum_{s=1}^{t-1} OIL_{prod}(t, n, g) \leq OIL_{res}(t, n, g). \quad (12)$$

Operation and maintenance (O&M) costs – including lifting costs – that appear in Equation (9) are set equal to 10 USD per barrel for all categories of oil, in all regions.¹³

We do not model regional extraction cost curves for coal, whose price grows following a power law as world resources are depleted. The price of natural gas is fixed at 70% of the international price of oil.

¹² This implies that when fifty percent of resources of a given oil category are depleted, if we abstract from the short-term cost component, the cost of additional extraction capacity of category g becomes almost equivalent to the extraction cost of category $g+1$.

¹³ All monetary values are expressed in constant 2005 USD. According to EIA lifting costs for the FRS companies were 9.98 USD per barrel of oil equivalent of production. Source: Performance Profiles of Major Energy Producers 2007 – EIA December 2008. See Table 10.

3.3. Carbon Emissions

In WITCH emissions are derived from fossil fuels consumption using the average carbon content of each fuel. Non-conventional oil extraction is an extremely energy intensive process and requires a special treatment. We assume that the emissions associated to the oil traded internationally are the same for all categories. However, the extraction of non-conventional categories of oil requires higher energy use and higher emissions.¹⁴ These emissions are attributed to the country in which extraction occurs.

4. Oil Sector Dynamics in the BaU and in the Stabilisation Scenarios

This section presents major dynamics in the oil sector in the Business-as-Usual Scenario (BaU).¹⁵ We examine how oil sector investment decisions are changed by a stabilisation policy aiming at stabilising world concentrations of GHGs at 550ppmv CO₂-eq. We simulate the climate policy in an ideal environment in which all world regions agree on the stabilisation target and credibly commit to achieve it at the end of the century. Regions receive emission allowances that can be traded in an international carbon market. The distribution of carbon allowances follows a contraction-and-convergence scheme at 2050, progressively shifting from an allocation that gives full weight to present levels of emissions to an allocation that distributes emissions rights proportionally to each region's population.

4.1. A Global Outlook

In the BaU Scenario, oil consumption increases at a constant pace until mid-century, when the growth rate slows down but remains positive throughout the century (Figure 1). As we see with more detail in the Regional Outlook, which follows this sub-section, the model expects that additional oil consumption comes from emerging economies, especially in Asia. There is no shortage of oil in our BaU Scenario, thanks to a wide availability of non-conventional oil resources. Lower growth of oil consumption is explained by a saturation of demand in emerging economies and by energy efficiency improvements induced by a five-fold growth in the price of oil. (Figure 2).

¹⁴ We assume that emissions associated with the extraction of oil are a fraction t_g of the carbon content of a barrel of oil, with $t = [0.00 \ 0.050 \ 0.075 \ 0.100 \ 0.150 \ 0.600 \ 0.700 \ 0.700]$ for the eight oil categories.

¹⁵ In the BaU we assume that no policy is implemented to constrain GHGs emissions.

The concerns about the imminent exhaustion of fossil fuels that have fuelled a dense debate in the 70's (Meadows et al 1972) were unmotivated and the great abundance of oil, natural gas and coal reserves is now motivating environmental pessimism. The major constraints to fossil fuels extractions will probably come from voluntary policies that restrict carbon emissions in the atmosphere. The economics of resource extraction may have to soon convert into an economics of waste accumulation (Sinn 2008).

From 58 USD per barrel in 2005, the oil price reaches, at a rather constant pace, 255 USD per barrel in 2105 (Figure 2). As explained in detail above, the price of oil is formed in the international market to equate demand and supply, at every point in time. It is the outcome of demand and supply forces which are endogenously determined in the model. In the previous version of WITCH, as well as in many other IAMs, the price was formed using a reduced form cost function based on cumulative extraction. Here we obtain the positive relationship between scarcity and oil price endogenously which fits well with historical observations, without the need to use a reduced cost function (Figure 3 and Figure 4).

Regional social planners are forward looking agents who optimally plan the expansion path of the oil sector, assessing future oil prices and the future cost of oil extraction capacity (which evolves according to Equation 11). As they move from easily accessible oil resources to heavy non-conventional oils, the cost of extraction capacity increases and the supply function tilts upward. Figure 5 shows how the weighted average cost of extraction capacity increases over time. Figure 6 relates the cost to cumulative oil production. The large availability of non-conventional oil resources allows an almost linear relationship between cumulative production and costs, with the slope roughly equal to one.

Decisions on the optimal capacity of oil in place at each point in time drive investments in new oil fields. Figure 7 gives information on how additional oil extraction capacity evolves over time. In the BaU Scenario, extraction capacity expands at a regular pace until mid-century when new additions peak at 4.7 billion barrels per year. After 2050, new extraction capacity is used to replace old oil wells, leaving an overall supply of oil almost unchanged.

World Oil Consumption

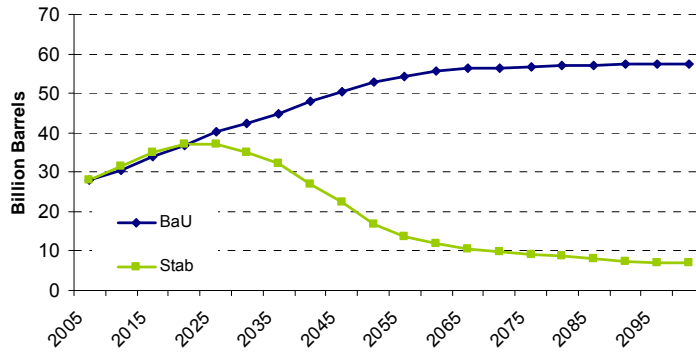


Figure 1

Price of Oil

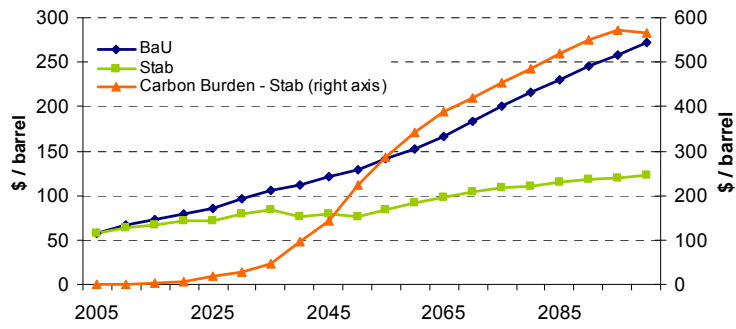


Figure 2

Price of Oil

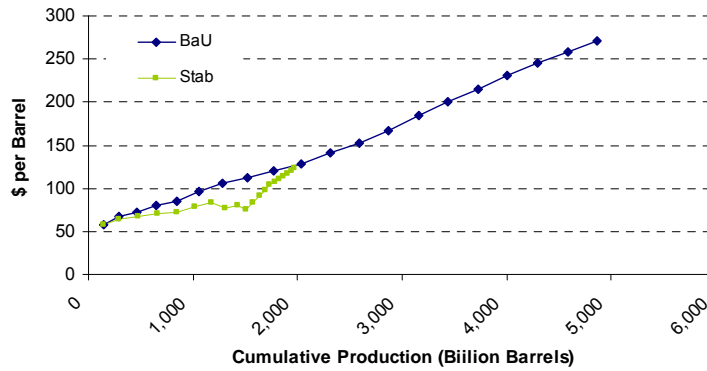


Figure 3

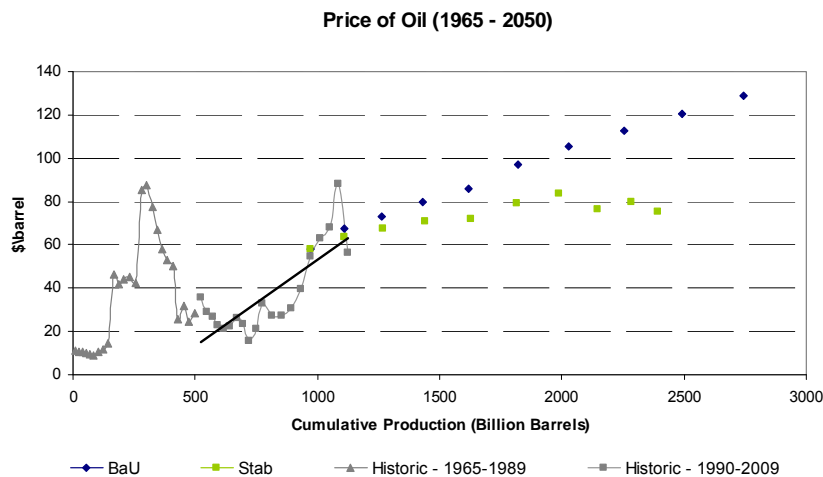


Figure 4

The Stabilisation Scenario is constructed assuming that all regions agree on a global trajectory of emissions to stabilise GHGs concentrations in the atmosphere at 550ppm CO₂-eq at the end of the century. The policy tool used is a global emissions trading system that allows separating efficiency and equity considerations (Coase 1960). Different stabilisation targets could be used, but the focus of this paper is to provide an illustrative example of the new model specification rather than estimating the implications of a specific policy target. We do not show the time path of carbon price that endogenously emerges from the international trading scheme. It is sufficient to mention that it starts from 3.5 \$/CO₂-eq in 2010, it reaches 69 \$/CO₂-eq in 2030, 529 \$/CO₂-eq in 2050 and eventually ramps up to 1326 \$/CO₂ in 2100. This entails a heavy “carbon burden” on each barrel of oil, as we show in Figure 2, where we plot the cost to cover with emissions permits emissions from each barrel of oil (right axis) together with the international oil price (left axis). In 2010, it is necessary to spend 1.5\$ in carbon credits per each barrel of oil, about 2% of the price of oil. In 2030, it is necessary to spend 30\$ per barrel of oil, 37% of the price of oil. In 2050, the cost of carbon increases to 225\$ per barrel, an astonishingly 300% of oil price. Between 2035 and 2040, the expenditure for carbon becomes equivalent to that of oil extraction. It is then of stark evidence that the scarce and valuable commodity is carbon (underground) in a Stabilisation Scenario and not the fossil resource. We have not included in the carbon burden the additional cost to cover emissions from the extraction process of non-conventional oil resources. This consumption is a luxury that the world cannot afford if it wants to stabilise concentrations of GHGs at safe levels.

**Average Cost of Additional Oil Extraction Capacity
(all cat.)**

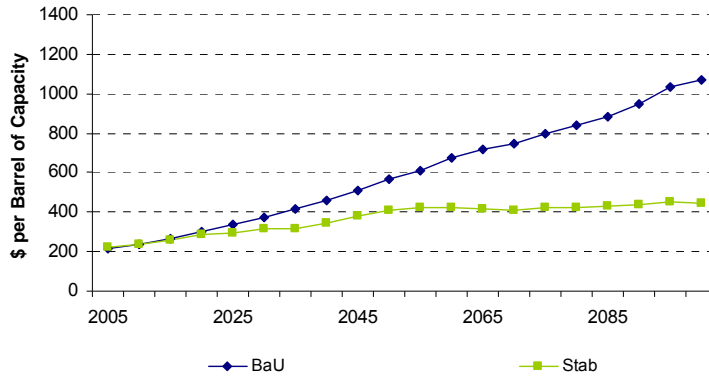


Figure 5

**Average Cost of Additional Oil Extraction Capacity
(all cat.)**

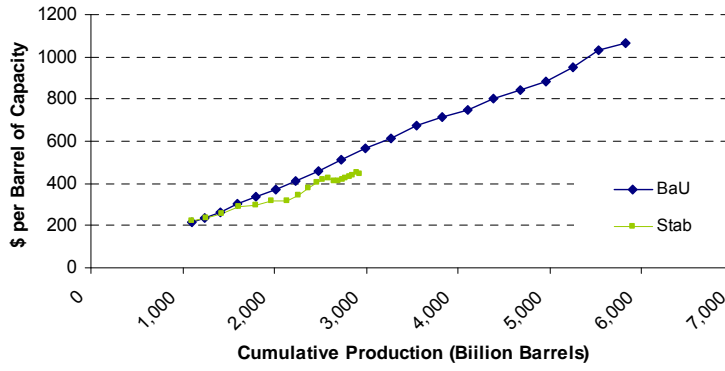


Figure 6

**World Additional Oil Extraction Capacity
(all Categories)**

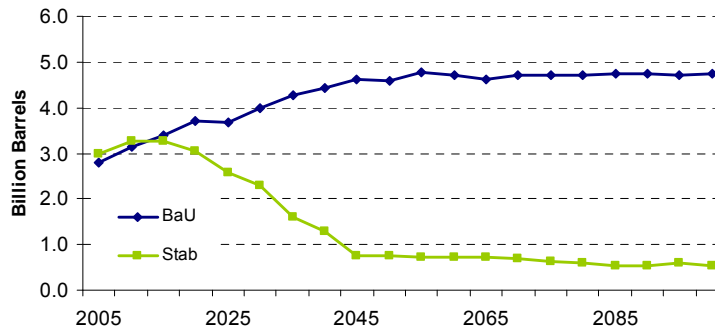


Figure 7

Therefore, consumption of oil falls dramatically from 2025 onward, with a five-fold contraction at 2105, with respect to the BaU Scenario (Figure 1). Interestingly, in the first years, oil consumption increases slightly with respect to the BaU Scenario. This only partly confirms the theoretical postulate of the “green paradox”, advocated by Sinn (2008). We are in fact examining a global commitment to reduce GHGs, with stringent caps on emissions worldwide. The anticipation of extraction is therefore not the effect of carbon leakage, but rather a mild, short term effect in which a lower discounted value of resources in the future induce faster extraction in the present, at global level, inducing substitution effects in the energy mix.

Additions of extraction capacity anticipate the movements of oil supply in the Stabilisation scenario and peak around 2015. A closer look at Figure 7 shows that additional capacity in the first years is higher in the Stabilisation Scenario than in the BaU, allowing higher consumption of oil in the early phases of the Stabilisation policy.

The price of oil in the Stabilisation scenario (Figure 2) is always lower than in the BaU Scenario. At 2105, the oil price is fifty percent lower than in the BaU Scenario. Interestingly, in the Stabilisation scenario, costs grow at a slower pace than in the BaU Scenario if mapped against cumulative extraction (Figure 6). This is explained by the presence of the short-term cost component that mimics frictions that arise when there is a fast expansion of the oil sector. Not only is less oil consumed in the Stabilisation scenario, but the oil sector also shrinks and this leads to a less than proportional relationship between cumulative extraction and costs.

With its new specification WITCH endogenously determines investment decisions in eight different types of extraction capacity, one for each of the eight categories of oil. The allocation of investments is based on the equalisation of marginal returns of extraction capital across the eight different categories of oil. Since the model is forward looking, investment decisions incorporate future developments of extraction capacity costs, of the oil price, total resources available and of the returns to all other investments in the economy. The mix of investments is therefore the output of a complex optimisation exercise and it deserves a closer look.

Figure 8 gives a synthetic representation of how oil production shifts from one category to the other as time goes by. The light coloured area corresponds to conventional oil resources while the dark area to non-conventional ones. As time goes by, cheap and easy-to-access oil resources are depleted, with a conventional oil peak around 2045. Oil consumption, however, can be fuelled by non-conventional oil, which is available in large quantities.

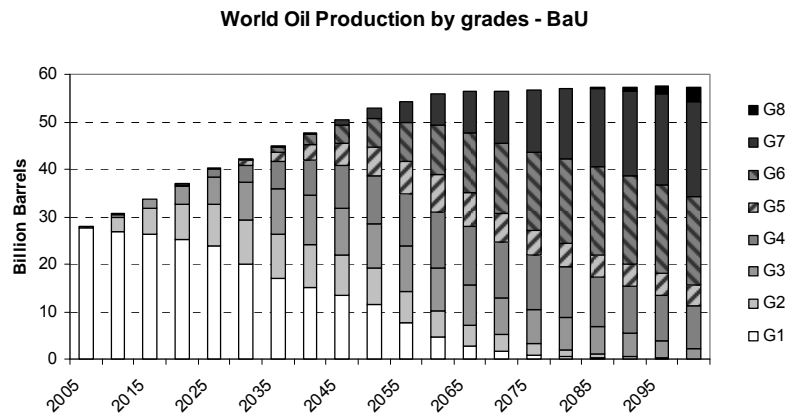


Figure 8

In the Stabilisation Scenario, conventional oil resources are sufficient to cover oil demand, as shown in Figure 9. Oil resources that are easy to access and cheap to extract will cover world oil consumption. This gives a relative advantage to the Middle East and North Africa region, where most of the first quality oil resources are located. However, overall extraction in these countries declines, as well as the oil price, determining a sharp contraction of the value added in the oil sector.

Figure 10 further explores the dynamics of oil extraction in the BaU and in the Stabilisation Scenario. The total production of oil from each category is plotted together with total resources available for that category. While categories 1 to 5 are almost depleted in the BaU Scenario, categories 6 to 7 show very wide margins for higher consumption. In the Stabilisation Scenario oil demand is heavily reduced but consumption does not disappear altogether. Categories 1 to 2 will still be depleted, with the last oil coming from category 3. Unconventional oil and expensive conventional oil resources are not extracted. Figure 11 and Figure 12 provide a closer look at the data with greater time detail. Here we display the share of resources for each category that is extracted at 2030, 2050 and 2100. 60% of resources from Category 1 are already consumed at 2030, and more than 80% at mid-century. Category 2 follows suit, while large margins remain at 2050, for all other categories. In 2030, non-conventional oil resources are almost intact. At the end of the century, categories 1 and 2 are exhausted, category 3 is almost exhausted, and wide margins remain for capacity expansion in categories 4-8. In the Stabilisation Scenario the picture changes radically for categories 3-8, but the exhaustion path of categories 1-2 remains unchanged.

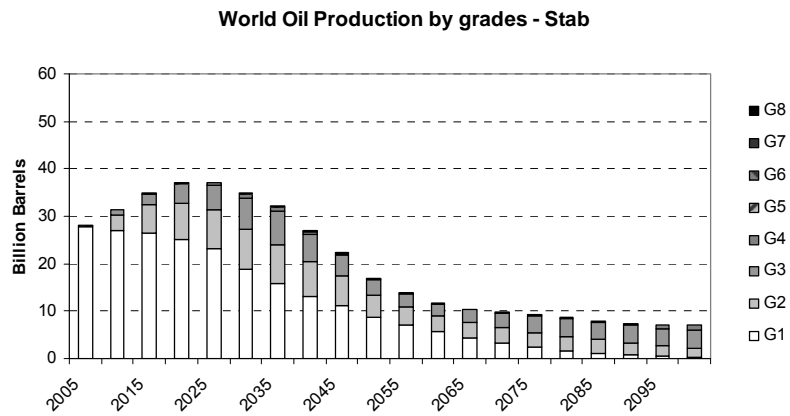


Figure 9

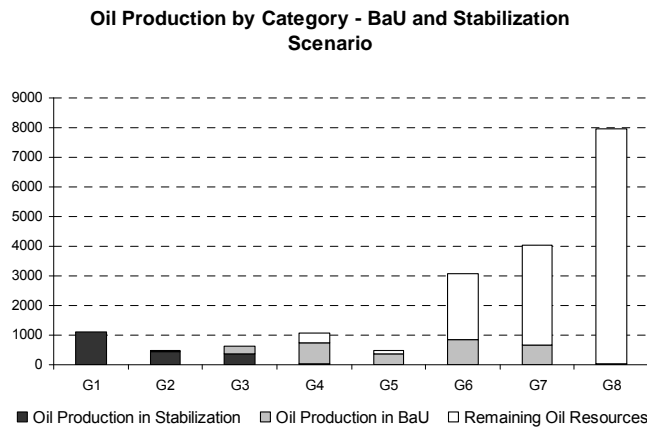


Figure 10

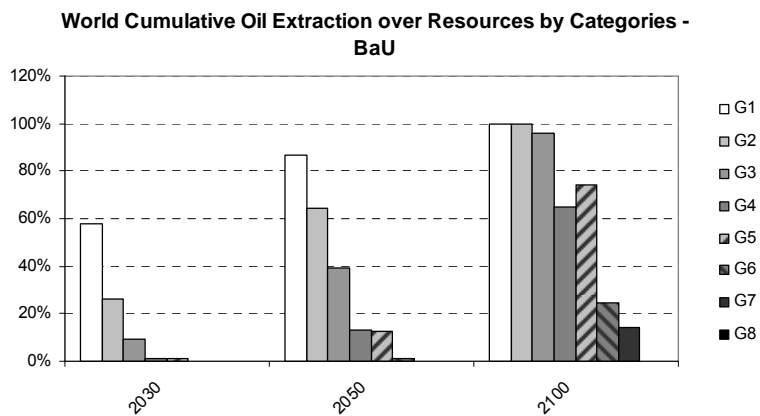


Figure 11

World Cumulative Oil Extraction over Resources by Categories - Stab

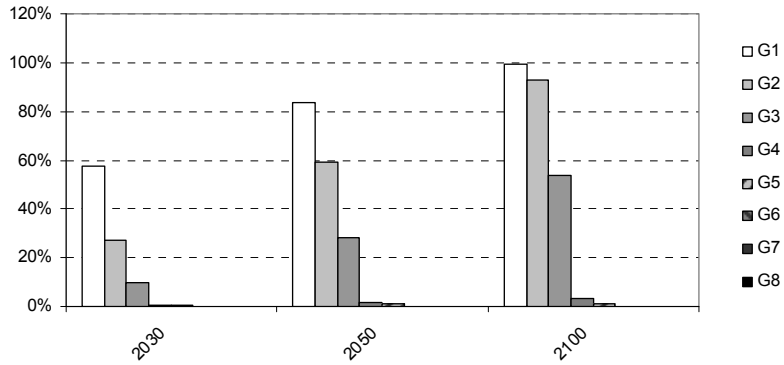


Figure 12

World Oil Extraction Emission by categories - BaU

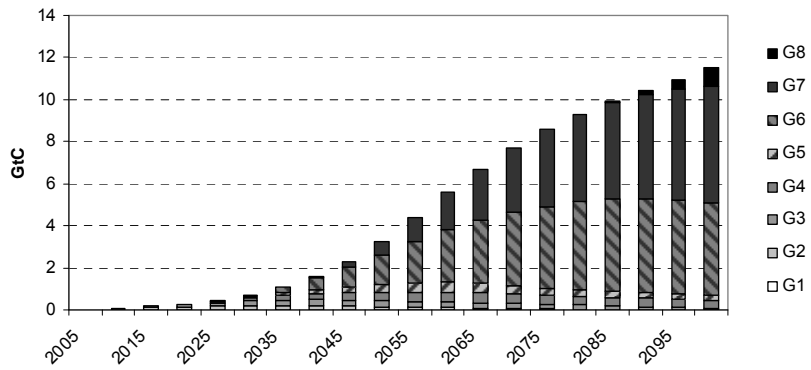


Figure 13

World Oil Extraction Emission by categories - Stab

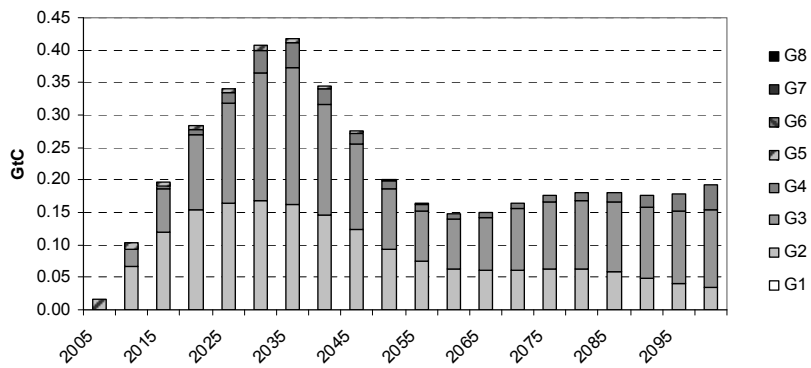


Figure 14

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
BaU												
2005	1%	1%	0%	1%	1%	16%	44%	27%	1%	3%	5%	9%
2025	2%	1%	2%	1%	1%	15%	37%	14%	1%	2%	3%	7%
2050	2%	1%	1%	5%	4%	13%	30%	8%	0%	2%	2%	5%
2075	2%	1%	3%	11%	8%	17%	18%	5%	0%	2%	2%	5%
2100	3%	1%	1%	15%	12%	16%	14%	3%	0%	2%	4%	4%
Stab												
2005	1%	1%	0%	1%	1%	16%	44%	27%	1%	3%	5%	9%
2025	1%	1%	1%	1%	1%	12%	31%	10%	0%	1%	2%	6%
2050	0%	0%	0%	0%	0%	4%	13%	0%	0%	0%	0%	1%
2075	0%	0%	0%	0%	0%	3%	5%	0%	0%	0%	0%	0%
2100	0%	0%	0%	0%	0%	2%	1%	0%	0%	0%	0%	0%

Table 4. Oil GDP (% of total GDP)

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
BaU												
2005	2%	1%	3%	2%	1%	33%	64%	36%	4%	6%	10%	16%
2025	3%	1%	2%	3%	4%	23%	60%	29%	2%	4%	7%	10%
2050	5%	1%	1%	18%	12%	31%	40%	11%	0%	6%	3%	10%
2075	5%	2%	0%	22%	16%	31%	32%	10%	0%	5%	6%	9%
2100	5%	4%	5%	29%	23%	30%	27%	2%	0%	6%	17%	7%
Stab												
2005	3%	2%	3%	2%	2%	33%	62%	38%	4%	6%	10%	16%
2025	2%	1%	5%	1%	1%	15%	51%	19%	1%	3%	4%	6%
2050	0%	0%	0%	0%	0%	7%	27%	0%	0%	0%	0%	0%
2075	0%	0%	0%	0%	0%	7%	7%	0%	0%	0%	0%	1%
2100	0%	0%	0%	0%	0%	3%	2%	1%	0%	1%	0%	1%

Table 5. Oil Investments (% of total Investments)

Under climate policy, a major incentive to keep unconventional oil resources untouched comes from the high consumption of fossil fuels in the extraction process, as it emerges from an analysis of Figure 13 and Figure 14. The amount of emissions associated with the extraction of categories 6, 7 and 8 is extremely high, increasing from 60 to 70 percent the emissions content of each barrel of oil consumed in the economy (See Footnote 14 at p. 2). The real threat for our century is not the scarcity of oil, but rather the possibility that relatively inexpensive unconventional oil might cause enormous growth of GHGs concentrations in the atmosphere. We abstract from further considerations on other negative externalities in the environment for example, on water and biodiversity that a large exploitation of unconventional oil might arise. These negative externalities might in fact limit the use of non-conventional oil well below the optimal path in our BaU Scenario. For this reason we generate a BaU and a Stabilisation Scenario in which non-conventional oil is not used in the sensitivity analysis presented in Section 5.

An interesting feature of our modelling approach is the possibility to monitor how investments in the oil sector evolve across time. We can therefore study the optimal transition pathway to the new equilibrium allocation of investments.

For big oil producing countries, climate policy requires a strong reallocation of investments away from oil extraction. So far the analysis of the economic consequences of this radical transformation of oil-based economies has been too often overlooked. Also the wide range geopolitical implications of an imperfect adaptation to the new economic conditions have been neglected. For example, if Northern African and Middle Eastern countries fail to thoroughly restructure their economies, a high immigration pressure might arise along the Mediterranean basin. It is not our intent to explore these far reaching implications of climate policy. We leave them for further research. We rather provide a representation of basic dynamics of oil and non-oil GDP, as well as of investments, in the BaU and in the Stabilisation Scenarios.

In the BaU Scenario the share of GDP of oil exporting regions from the oil sector remains roughly stable around 6%, reflecting a balanced expansion of the economies (Table 4). The oil sector is particularly capital intensive and therefore absorbs a higher share of total investments than other economic activities. The share of total investments (Table 5) that go to the oil sector increases until mid-century, when the sector absorbs 16% of total investments in oil exporting countries. However, in the second part of the century the relative share declines and the economies begin to expand more the non-oil sector. The contribution of the oil sector to the overall economy remains high thanks to a growing price of oil.

The Stabilisation Scenario shows a very different pattern of the optimal distribution of economic activity between the two sectors (Table 4 and Table 5). Investments in the oil sector decline rapidly and become irrelevant from a macro-economic point of view, even for regions that remain big oil exporters in the Stabilisation Scenario (MENA, TE and LACA). By allowing full flexibility to restructure the economy (the two sectors add up linearly), the model describes an optimistic condition in which there is no restraint to reallocate resources away from oil production. Each region can freely redirect investments in order to maximise returns. The model also displays perfect foresight. Therefore social planners in oil producing regions can plan the transition to a new economic paradigm with large advance. However, the collapse of the international demand of oil drastically reduces aggregate demand in oil exporting regions and this represents a net loss that they cannot cope with. The inflow of capital from importing countries is a source of revenue that they are not able to replace.

A few caveats apply to these conclusions. First, as already discussed above, we are unable to model the large oil rents in regions like MENA where extraction costs are well below the international price of oil. A wise, long-term, economic planning can build the basis for the growth of the non-oil sector. We might underestimate this effect, but the dynamic of our BaU Scenario already shows that economies will optimally move away from the oil sector. The degree to which a better model specification might deliver milder effects of the Stabilisation policy on total economic activity is therefore unclear. Second, we are not modelling the market for natural gas with the same degree of detail as in the oil market. In the short-term, the effort to reduce carbon emissions might push to substitute gas fired to coal fired power plants worldwide, determining a short- to medium-term expansion of gas demand. Since oil production countries are also natural gas producers, the gasification of power supply might mitigate the contraction of oil demand. If it will be economical and technologically feasible to run gas-fired power plants with CCS, natural gas might have an even larger role in the long-term. Third, we do not model the possibility to generate electricity by means of concentrated solar power plants in Northern Africa and to ship it by means of super grids to Europe (Battaglini et al. 2008; Trieb 2006). The revenues from the international trade of electricity might trigger a prosperous business in Northern African countries, however, from preliminary results obtained with a new version of the WITCH model. The value of this new market is likely to be several orders of magnitude smaller than the market of oil (Masseti and Ricci 2010).

4.2. A Regional Outlook

The distribution of conventional and non-conventional oil resources is uneven across regions. Middle East and North Africa (MENA) have the highest share of conventional oil reserves (see Table 3), with 41% of total resources; Transition Economies (TE) and Latin America and the Caribbean (LACA) follow with 16% and 14%, respectively. The regions with the largest resources of non-conventional oil are Venezuela (in the Latin America and Caribbean, LACA, regional aggregation), the Middle East (aggregated with North Africa in the MENA regional aggregation), Canada (aggregated together with Japan and New Zealand in the CAJANZ region), the United States (USA) and China. The endowment of oil resources directly affects production patterns, shown in Figure 8 and Figure 9. In the BaU Scenario, large resources of conventional oil allow MENA to remain the largest oil producer throughout the century. The share of global oil production grows from 36% in 2005 to 38% in 2035; after 2040, the exploitation of non-conventional oil resources allows other regions to gain shares of the market.

MENA remains the largest oil producer in the world, but its share declines to 20% at the end of the century. LACA and TE lose some shares of the market declining from 15% to 11% between 2025 and 2065, but the race to non-conventional oil allows them to regain the initial 15% by the end of the century. The USA and CAJAZ gain large shares of global oil production during the century: the USA moves from 7.6% to 12.6%, CAJAZ from 4% to 13.5%. The increase of total oil production in 2100, with respect to 2005, is equal to 240% in the USA, 575% in CAJAZ, 74% in TE, 10% in MENA, 300% in CHINA, 80% in LACA. Sub-Saharan Africa represents an exception, with a contraction of 77%. The Herfindahl-Hirschman Index (HHI) gives a synthetic measure of the degree of concentration in the global oil market. If we denote with s_i the market share of region i , then $HHI = \sum_{i=1}^N s_i^2$, with $1/N \leq HHI \leq 1$. The closer the HHI is to 1, the greater the concentration is in the market. In our case, with $N=12$ we have $0.083 \leq HHI \leq 1$. In the BaU Scenario the concentration of the oil market remains stable with an HHI around 0.20 until 2050, and then it declines smoothly until the HHI becomes equal to 0.12 at the end of the century. This implies that in a world in which it is possible to use the abundant resources of non-conventional oil, production becomes more evenly distributed across macro-regions than it is today. Issues related to strategic security of supply and geo-political considerations might become less relevant than they are in the present.

The regional distribution of oil consumption is depicted in Figure 15. At the beginning of the century oil consumption is more evenly spread among regions than oil production. The block of high-income regions (USA, WEURO, EEURO, KOSAU and CAJAZ) account for 56.5% of world demand, with the rest going to Transition and Developing economies. China has a soaring consumption of oil, but at 2005, it requires only 10% of global demand, while the USA absorbs one quarter of global oil production. As developing regions expand their economies oil consumption increases in absolute numbers and in share. They overtake high-income economies as early as 2025, and they absorb about two thirds of global production at the end of the century. Global oil consumption becomes more evenly distributed among world regions. The HHI index for consumption declines from 0.13 to 0.12, in the BaU Scenario, during the century.

Trade patterns are determined by the imbalances between national production and national consumption and are described in Figure 16 and Figure 17. In the BaU Scenario MENA dominates the oil market throughout the century, with decreasing prominence during the second half of the century, when it is followed by TE, Canada in the CAJAZ region and Australia

(aggregated with Korea and South Africa, KOSAU aggregation). Oil imports are directed towards the USA, Western Europe (WEURO) and developing Asia until mid-century; afterwards, CAJAZ becomes a self producer, Western Europe and the USA continues to buy substantial amounts of oil and India (aggregated with Pakistan and other South Asian states, SASIA aggregation) becomes the largest oil importer, followed by CHINA. Interestingly, at the end of the century the greatest part of international trade of oil will be directed towards Asian economies (CHINA, SASIA and EASIA), accounting for 68% of global oil imports.

While world consumption of oil doubles during the century, the volume of oil traded internationally increases only by 60%, as depicted in Figure 18. This is explained by a growing proximity of production and consumption areas, thanks to the exploitation of vast non-conventional oil resources in countries with high domestic demand. The value of oil traded internationally, measured as the volume of oil times the price that emerges from the market, continues to increase thanks to the growing price of oil. MENA, TE, CAJAZ and LACA are the regions that absorb the largest part of the financial flows from oil trade and for this reason they are also the regions that are affected the most in the Stabilisation Scenario.

The regional outlook of the oil sector changes dramatically in the Stabilisation Scenario. Oil consumption (Figure 20) drops substantially in all regions, with respect to the BaU Scenario. With respect to 2005, aggregate consumption of Transition and Developing economies grows until 2025, while consumption in high-income economies peaks as early as 2015. At the end of the century our Stabilisation Scenario shows that 95% of oil is consumed in Transition and Developing economies.

Also production of oil changes substantially under climate policy. Non-conventional oil is extracted only in minimal quantity and MENA with TE are able to supply all oil needed until the end of the century. MENA countries dominate the oil market, as depicted in Figure 22, and oil production is more concentrated than in the BaU Scenario. The *HHI* peaks in 2060, with a value equal to 0.45 and it then declines to the level of 2005. The dominance of MENA countries is even more marked if we consider international trade flows of oil. Between 2040 and 2085 international oil trade is a business of only two macro-regions: the Middle East and North Africa and Transition Economies. The rest of oil producing countries tends to satisfy the (modest) oil demand in autarchy. Imports see a lower regional dispersion than in the BaU Scenario (Figure 23), with India (in SASIA) dominating the market in 2105.

Oil Consumption - BaU

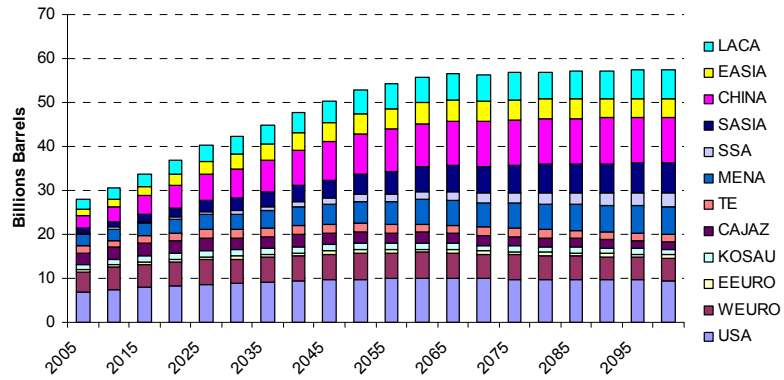


Figure 15

Oil Exports - BaU

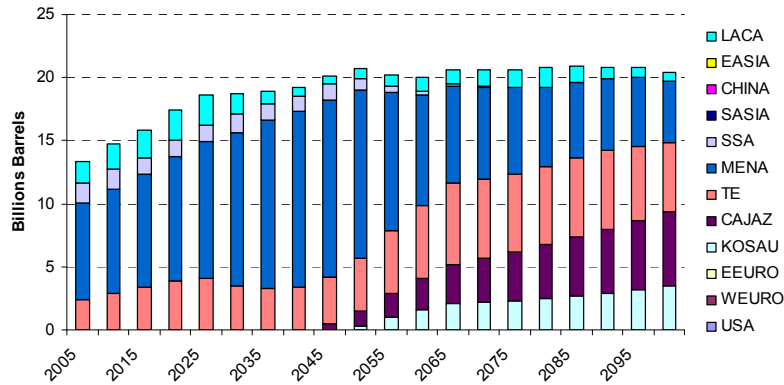


Figure 16

Oil Imports - BaU

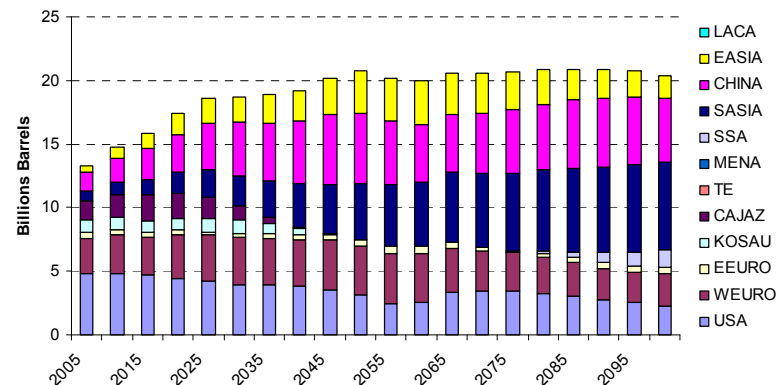


Figure 17

Oil Traded Internationally

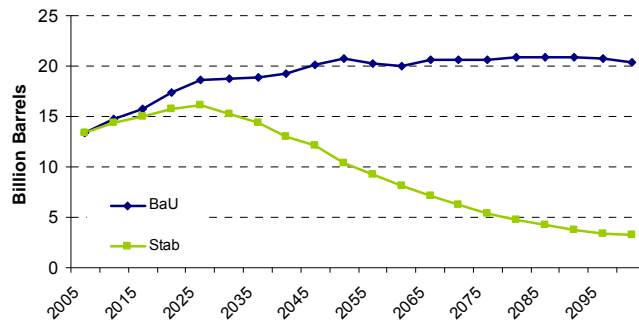


Figure 18

Value of Oil Traded Internationally

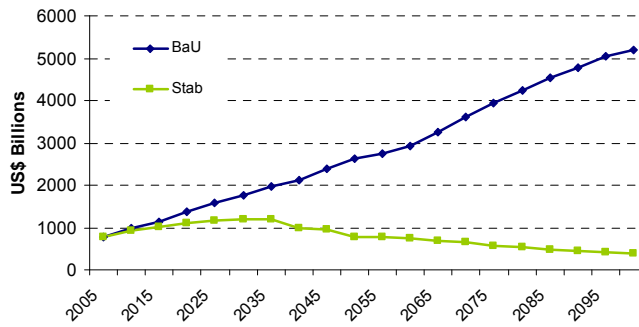


Figure 19

Oil Consumption - Stab

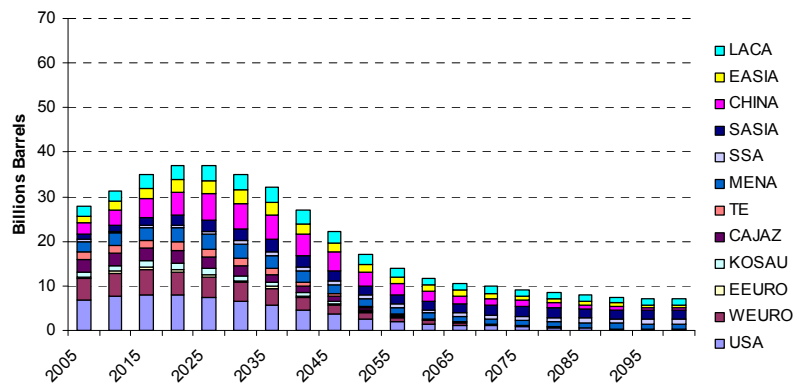


Figure 20

Oil Extraction - Stab (all cat.)

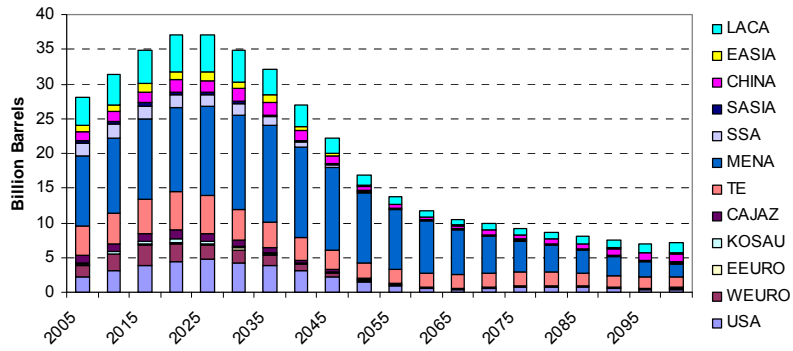


Figure 21

Oil Exports - Stab

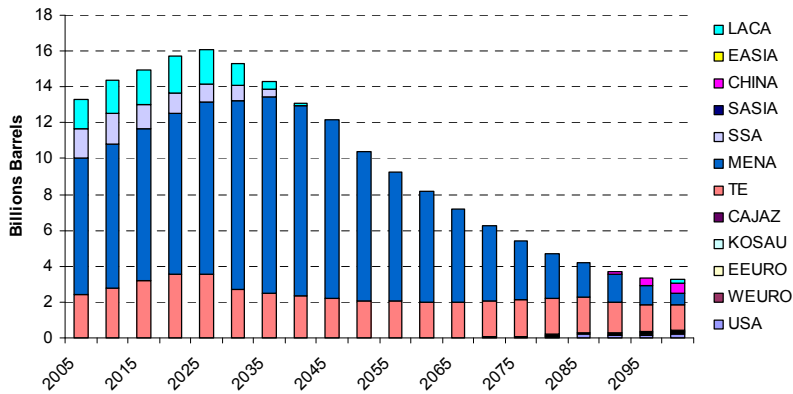


Figure 22

Oil Imports - Stab

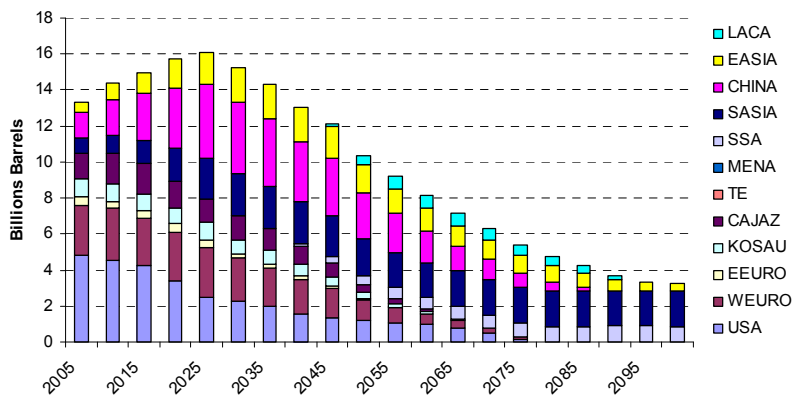


Figure 23

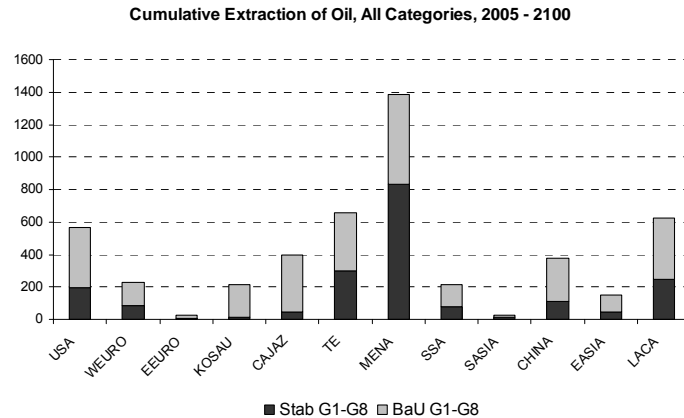


Figure 24

The pattern of oil production triggered by the stabilisation policy entails that CHINA and the USA increase their reliance on foreign oil to supply their domestic consumption over the century (see Figure 24 and Table 6 for greater regional and temporal detail). In Western Europe, the share of oil consumption imported from other regions increases from 61% to 81% in 2075 (Table 6). If we take the ratio of foreign to domestic production as an indicator of the security of oil supply, the stabilisation policy increases, rather than reducing, the dependence from traditional oil exporters. However, the total demand of oil decreases substantially in the Stabilisation Scenario, to become an irrelevant component of total primary energy supply (TPES) at the end of the century (Table 6). MENA, LACA and TE will dominate a market that rapidly shrinks but they are net losers and their grip on the energy systems of Europe, the USA and China is doomed to vanish.

Climate policy induces a contraction of oil production that is not equal across regions. Regions with large resources of non-conventional oil are those in which production drops the most for two reasons. First of all, there is a global contraction of oil demand that reduces the need to use expensive non-conventional oil resources. Second, the stabilisation policy penalises non-conventional oil with respect to conventional oil, due to the large amount of emissions associated with the extraction process. Figure 24 and Figure 25 synthesise the contraction of the oil extraction in the twelve regions of WITCH. Conventional oil rich regions like MENA, TE and LACA have a sharp contraction of oil production, but not as dramatic as in the USA and in the CAJAZ aggregate. Preventing the exploitation of non-conventional oil in countries that are presently not large exporters of oil, the stabilisation policy concentrates oil extraction in traditional oil exporting regions such as, MENA, TE and LACA.

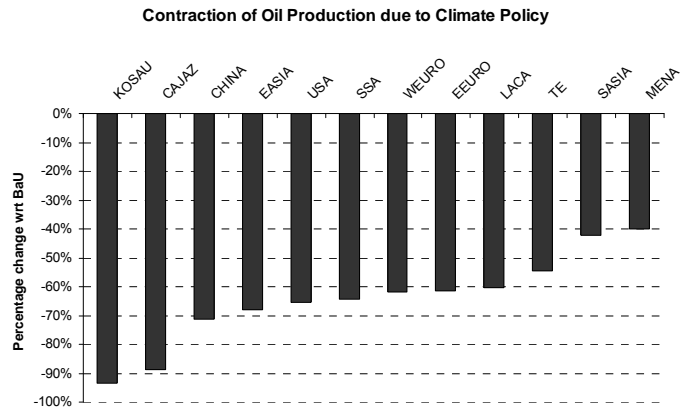


Figure 25

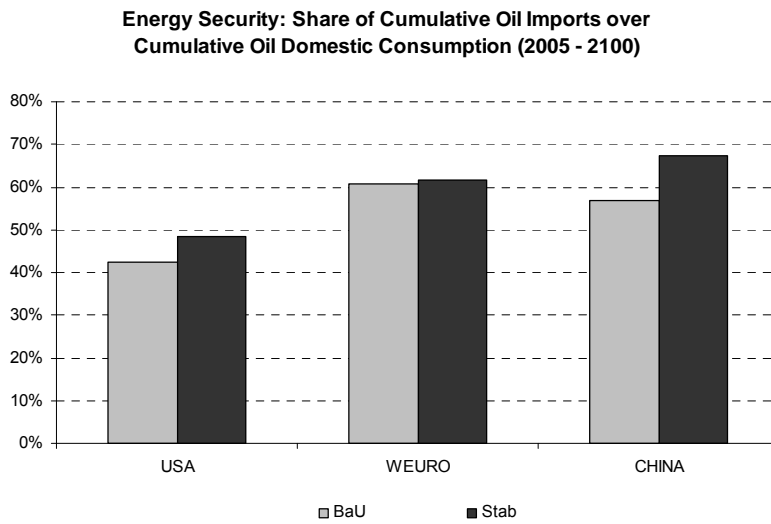


Figure 26

		USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
Share of oil Imports on Oil Consumption													
	BaU												
	2005	69%	61%	95%	81%	56%	0%	0%	0%	75%	52%	37%	0%
	2025	49%	65%	43%	78%	55%	0%	0%	0%	87%	63%	66%	0%
	2050	35%	67%	68%	0%	0%	0%	0%	0%	93%	61%	73%	0%
	2075	37%	55%	28%	0%	0%	0%	0%	0%	98%	50%	64%	0%
	2100	30%	48%	77%	0%	0%	0%	0%	31%	99%	52%	45%	0%
	Stab												
	2005	69%	61%	95%	81%	56%	0%	0%	0%	75%	52%	37%	0%
	2025	36%	59%	71%	73%	53%	0%	0%	0%	90%	71%	63%	0%
	2050	51%	78%	57%	85%	79%	0%	0%	57%	96%	82%	87%	29%
	2075	26%	81%	0%	68%	0%	0%	0%	77%	98%	60%	96%	35%
	2100	0%	0%	0%	0%	0%	0%	0%	72%	98%	0%	82%	0%
Share of oil Consumption on TPES													
	BaU												
	2005	46%	48%	30%	40%	52%	25%	59%	38%	23%	22%	46%	47%
	2025	44%	47%	30%	39%	50%	23%	52%	40%	35%	29%	50%	47%
	2050	41%	44%	29%	39%	47%	21%	43%	40%	35%	29%	48%	44%
	2075	38%	40%	27%	38%	43%	19%	37%	37%	31%	27%	43%	40%
	2100	37%	37%	26%	39%	42%	17%	32%	34%	29%	25%	40%	36%
	Stab												
	2005	46%	48%	30%	40%	52%	25%	59%	38%	23%	22%	46%	47%
	2025	44%	43%	36%	47%	49%	25%	50%	40%	43%	38%	53%	48%
	2050	19%	17%	11%	20%	18%	4%	23%	26%	28%	19%	32%	27%
	2075	7%	3%	0%	5%	1%	0%	11%	22%	18%	9%	18%	16%
	2100	3%	0%	0%	0%	0%	0%	8%	20%	12%	4%	11%	11%

Table 6. Energy Security Indicators.

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA	WORLD	OIL EXP	OIL IMP
WITCH OIL	-3.5%	-1.5%	-4.6%	-7.2%	-4.2%	-17.9%	-19.6%	12.7%	3.7%	-6.8%	-0.3%	-8.3%	-4.3%	-8.1%	-3.3%
WITCH	-2.4%	-0.3%	-3.6%	-3.1%	-1.4%	-9.0%	-6.0%	18.8%	5.1%	-5.0%	1.4%	-4.3%	-1.7%	-2.5%	-1.3%

Table 7. Discounted Stabilisation Policy Costs (3% declining).

The implications in terms of GDP losses of the collapse of the oil market, and especially of the non-conventional oil market, under a stabilisation policy are represented in Table 7. Oil exporting regions have a dramatic contraction of economic activity.¹⁶ MENA and TE lose, respectively, the 19.6% and 17.9% of their GDP. Non-conventional oil rich Canada (in CAJANZ) suffers a sharp contraction (-4.2%) due to the collapse of non-conventional oil extraction. The USA suffers much more than Western Europe because of income losses in the non-conventional oil sector. Oil rich countries like LACA, KOSAU and CHINA are also severely affected regions. Compared to previous stabilisation cost estimates (see Bosetti et al 2009), we find that stabilisation costs in major oil-exporting regions increase considerably. In TE stabilisation costs double and in MENA they are more than three times bigger than what

¹⁶ Oil exporting regions are KOSAU, CAJANZ, TE, MENA, SSA, LACA. Stabilisation costs (benefits) are calculated as the discounted sum of the GDP difference between the BaU and the Stabilization Scenario. The discount rate used starts at 3% in 2005, and then declines throughout the century. Costs are finally expressed as a share of discounted GDP.

previously estimated. Globally, stabilisation costs double when oil extraction and trade are modelled.

5. Sensitivity Analysis

The results presented in the previous section are subject to a number of limitations. As mentioned above, the major modelling weakness concerns the lack of an appropriate description of the non-competitive structure in the international oil market. The functional form that we choose to describe the cost of new extraction capacity reduces the incentive to expand extraction capacity when oil extraction costs are low but, as a downside, it probably overestimates the investments needed in the oil sector. Oil rents result, therefore, lower than in the real world, and welfare losses that arise from the stabilisation policy might be underestimated. Changing functional forms requires either to use a traditional step function or to model a non-competitive international oil market. The first solution would necessitate a set of exogenous assumptions governing the pace and distribution of oil extraction, something that we want to avoid because it is not coherent with the flexible nature of the model in which investments are determined endogenously. The second solution appears to be complex and is left for future analysis. Therefore, in this section we fix the functional forms used to describe the oil sector and we test alternative assumptions on the amount of oil resources available in each region and on the parameter $\zeta(g)$, the threshold beyond which expanding the extraction capacity of oil in the short-term becomes increasingly expensive. The BaU and the Stabilisation Scenario that we have illustrated in the previous sections represent the “Central Case” around which we test alternative assumptions.

We test the robustness of our results with respect to the amount of oil resources available with two exercises. In the first, we change all oil categories of oil proportionally. In the second exercise, we assume that the highest-grade resources are not available. We start subtracting resources of category 8, and then we increasingly reduce the amount of oil resources by one category until only conventional oil remains. We favour tests that reduce the amount of oil resources because the resource base estimated in Rogner (1997) is quite large and includes large quantities of non-conventional oil.

Sensitivity analysis on the parameter $\varphi(g)$ is performed by selecting values in a symmetric interval around the central value. Table 8 summarises the 14 sensitivity analysis scenarios that are under examination. For each one we produce a BaU and a Stabilisation Scenario.

5.1. Sensitivity Analysis: the BaU Scenario

Figure 27 shows the range that we find for the international price of oil in the BaU Scenario. The sharpest divergence with respect to the central case emerges when all non-conventional oil resources are unavailable (4-8 Cat.). The biggest price increase (three times higher than in the Central scenario) is found when resource category 4 becomes unavailable, signalling that the cheapest non-conventional oil has a major role to fuel a large expansion of oil demand throughout the century. The lowest price path is found when oil resources of all categories are augmented by 25%. Assumptions on the parameterisation of the cost function are less important than those on the amount of oil resources.

In Figure 29 we notice how global investment in the oil sector varies in the different sensitivity scenarios. Interestingly, the two scenarios with limited oil resources (R050 and 4-8 Cat.) lead to very different results. When we reduce resources of all oil categories by fifty percent (R50 scenario) the scarcity component of the cost function determines a quick expansion of extraction costs. Contrarily, when we assume that non-conventional oil resources are unavailable, the cost function of oil extraction capacity for categories 1-3 is not affected, but total oil supply is drastically reduced. In this case, the oil that remains to discover is not expensive, but is limited. In the R50 case there is more oil available, but the average extraction cost is higher because less abundant cheap resources (Cat 1-3) push oil exploration towards expensive non-conventional oil.

Name of the Scenario:	Description:
R125	Oil resources multiplied by 1.25 (all categories)
R075	Oil resources multiplied by 0.75 (all categories)
R050	Oil resources multiplied by 0.5 (all categories)
Esp 1.3	Parameter ζ of the cost function multiplied by 1.3
Esp 1.2	Parameter ζ of the cost function multiplied by 1.2
Esp 1.1	Parameter ζ of the cost function multiplied by 1.1
Esp 0.9	Parameter ζ of the cost function multiplied by 0.9
Esp 0.8	Parameter ζ of the cost function multiplied by 0.8
Esp 0.7	Parameter ζ of the cost function multiplied by 0.7
8 Cat.	Category of oil 8: assumed to be equal to zero
7-8 Cat.	Category of oil from 7 to 8: assumed to be equal to zero
6-8 Cat.	Category of oil from 6 to 8: assumed to be equal to zero
5-8 Cat.	Category of oil from 5 to 8: assumed to be equal to zero
4-8 Cat.	Category of oil from 4 to 8: assumed to be equal to zero

Table 8. Sensitivity scenarios.

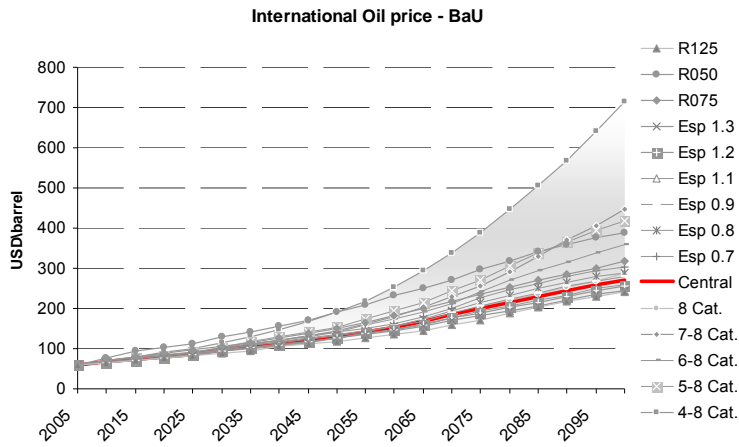


Figure 27

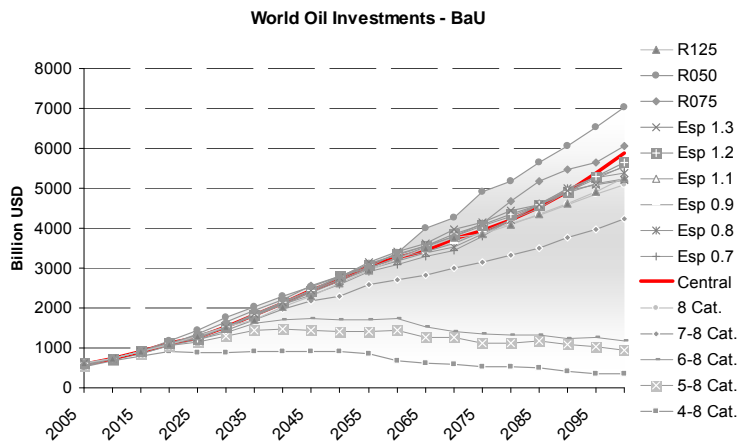


Figure 28

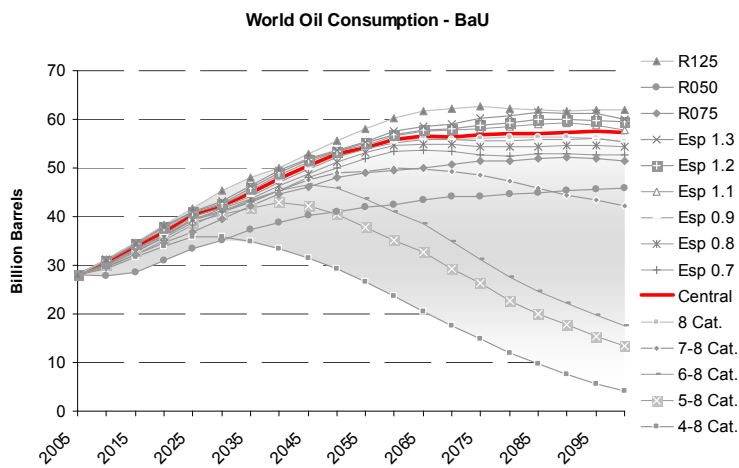


Figure 29

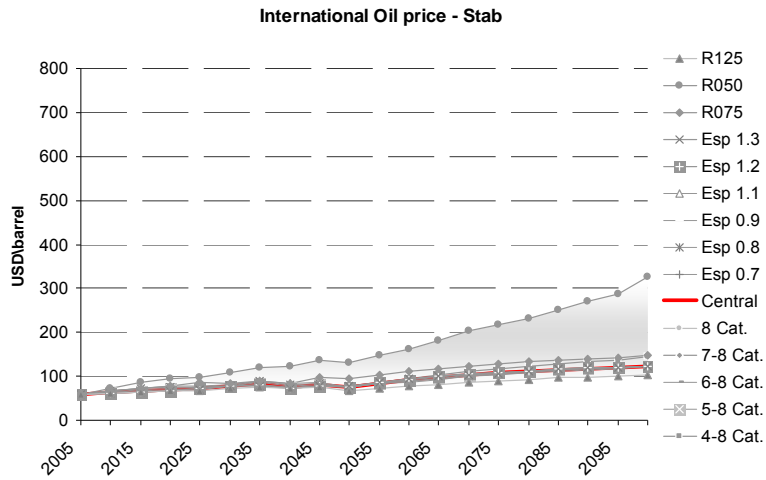


Figure 30

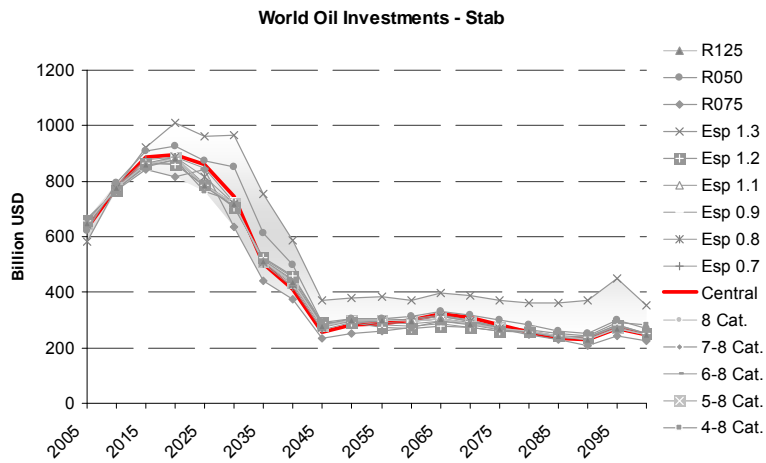


Figure 31

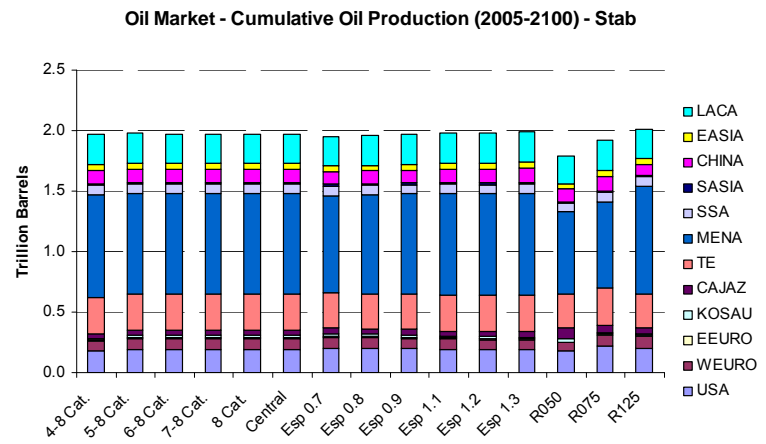


Figure 32

Figure 29 shows global consumption of oil under the alternative scenarios. If all non-conventional oil categories are not available, the price of oil increases substantially and oil consumption declines a great deal. Without unconventional oil supply peaks between 2025 and 2030.

5.2. Sensitivity Analysis: The Stabilisation Scenario

Under that Stabilisation policy the variance of the oil price around the central case is much lower than in the BaU case. Oil consumption is constrained by the cap on emissions and significant divergence emerges only when the contraction of oil resources affects also categories 1-3, as in the R50 scenario. Non-conventional oil is not consumed in the stabilisation scenario and therefore different assumptions on the amount of resources have limited impact on oil price (Figure 30). The same reasoning explains why oil investments are not sensitive to different assumptions on oil availability and on the parameterisation of the cost function (Figure 31).

5.3. Sensitivity Analysis: A Regional Outlook

From a regional perspective, Figure 33 and Figure 34 show that MENA remains the largest producer and exporter of oil in all scenarios that we examine in this sensitivity analysis. When resources of non-conventional oil are restricted, the USA, CAJAZ, TE and LACA experience the sharpest contraction of oil production, as expected. MENA and TE are the main oil exporting regions in all scenarios. CAJAZ and KOSAU export oil only when non-conventional resources are available. The USA is always net oil importers.

When GHGs emissions are constrained, both cumulative oil production and cumulative net imports are rather constant across the different scenario, as shown in Figure 32 and Figure 35.

A world with a lower amount of oil resources is a world in which a stabilisation policy of GHGs in the atmosphere to reduce global warming is less costly. If we measure the discounted cost of the policy as the fraction of discounted GDP that is lost to reduce GHGs emissions, the size of the oil sector is smaller and the penalty inflicted on the economies by the stabilisation policy is lower.

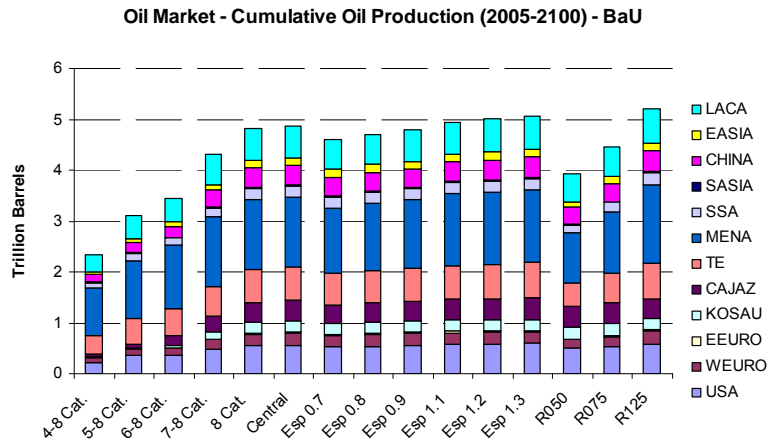


Figure 33

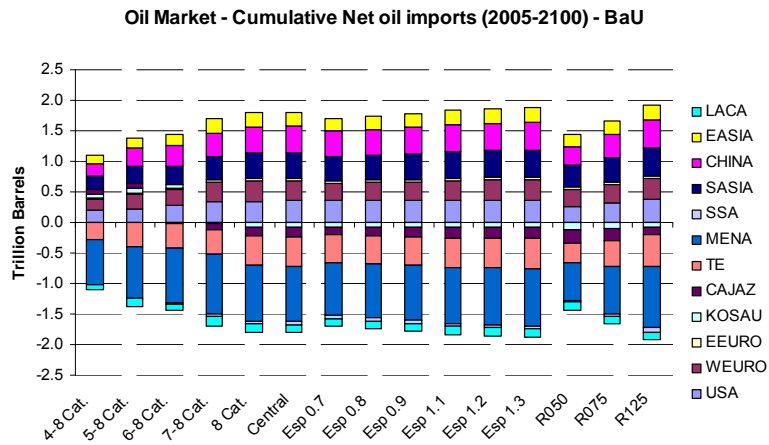


Figure 34

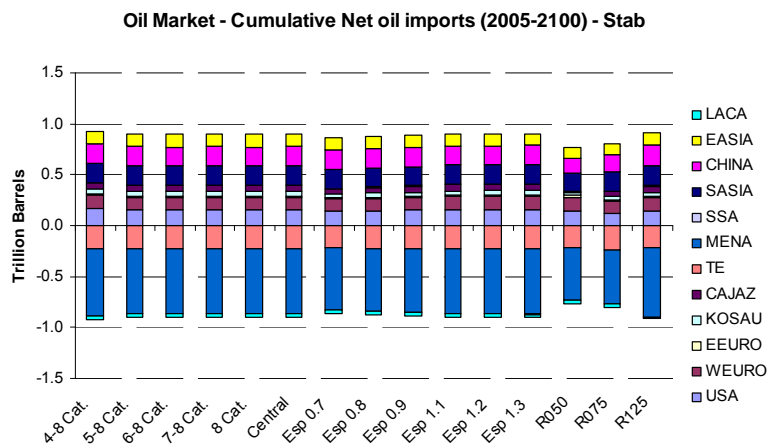


Figure 35

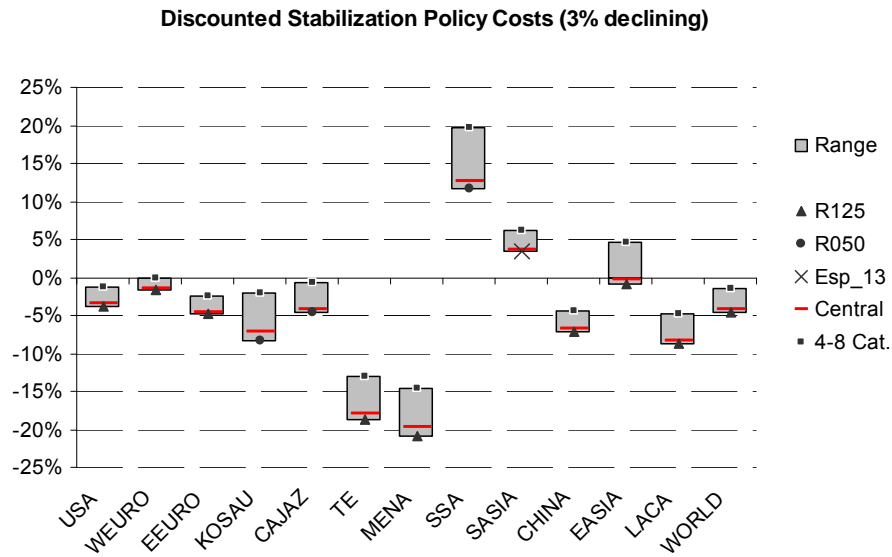


Figure 36

Figure 36 illustrates the impact of the alternative scenarios of our sensitivity analysis by showing the upper and lower bound of stabilisation policy costs estimates. While the lower bound always corresponds to the case in which non-conventional oil resources are not available (4-8 Cat.), the upper bound varies from region to region. In some cases it coincides with a scenario in which oil is abundant (R125) and in others it corresponds to a scenario in which oil of any category is scarcer (R050). Interestingly, WEURO incurs in basically zero costs and in the USA the costs are more than halved when non-conventional oil is not available. At global level, the cost of the stabilisation policy seems to be quite sensitive to assumptions on the availability of the least cost non-conventional oil. This reveals that an accurate description of fossil fuels extraction sectors is needed to assess the macroeconomic consequences of a stabilisation policy.

6. Conclusions

In this paper we model trade of oil among regions in the WITCH model. We model endogenous investments in eight different oil categories. Oil is traded internationally at a price that clears supply and demand in each time period. The cost of additional oil capacity is region-specific and accounts for both long-term exhaustibility and for short-term frictions that might arise in the supply chain when too much capacity is installed in a short time period.

Our main result shows that by introducing a detailed description of the oil sector global stabilisation costs increase significantly and the regional distribution of those costs shifts towards oil-exporting regions.

This result bears important political consequences: climate policy is expected to reshape the geo-politics in oil rich areas of the world. Oil-rich countries will have a strong incentive not to participate in any climate agreement, if not adequately compensated for their losses. In particular, it is possible to imagine that oil-rich countries have the power to seriously jeopardise any climate agreement by flooding the market with abundant oil supply. Oil prices might drop, eventually inducing big oil consumers to deviate from the climate agreement.

At this stage of development of the model we have not introduced coal-to-liquids technologies, which might become competitive with non-conventional oil. We also have not accurately modelled coal markets and natural gas markets. In particular, large amounts of unconventional gas reserves will potentially play a major role as substitutes of conventional oil in the second part of the century. We are also aware that oil markets are not competitive and oil-exporting countries do not play a Nash game. Rather, strategic considerations drive substantial decisions on oil supply and on investments to expand extraction capacity. Ideally, a new algorithm must be developed to account for strategic interactions and we reserve this for future work.

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Appendix

7.1. List of Main Equations

In this Appendix we reproduce the main equations of the model. For a full description of the model please refer to Bosetti, Massetti and Tavoni (2007) and Bosetti et al (2009). The website www.witchmodel.org contains useful information on the model. The list of variables is reported at the end of this Section. In each region, indexed by n , a social planner maximises the following utility function:

$$W(n) = \sum_t U [C(n,t), L(n,t)] R(t) = \sum_t L(n,t) \{ \log [c(n,t)] \} R(t), \quad (A1)$$

where t are 5-year time spans and the pure time preference discount factor is given by:

$$R(t) = \prod_{v=0}^t [1 + \rho(v)]^{-t}, \quad (A2)$$

where the pure rate of time preference $\rho(v)$ is assumed to decline over time. Moreover, $c(n,t) = \frac{C(n,t)}{L(n,t)}$ is per capita consumption.

Oil and Non-Oil Gross Domestic Product:

National Net Gross Domestic Product (GDP) Y can be decomposed in oil (Y_{OIL}) and non-oil GDP (Y_{NONOIL}):

$$Y(t,n) = Y_{NONOIL}(t,n) + Y_{OIL}(t,n). \quad (A3)$$

$$Y_{NONOIL}(t,n) = \frac{GY_{NONOIL}(t,n)}{\Omega(t,n)} - OIL(t,n)[P_{OIL}(t) + MKUP_{OIL}(t,n)] - \sum_z P_z(t) X_z(t,n) - p(t)NIP(n,t). \quad (A4)$$

$$Y_{OIL}(t,n) = \frac{1}{\Omega(t,n)} \sum_g OIL_{prod}(n,t,g) P_{OIL}(t). \quad (A5)$$

$$I_{OILCAP}(t,n,g) = OIL_{capcost}(t,n,g) \Delta(t,n,g). \quad (A6)$$

$$OIL_{capcost}(t,n,g) = \lambda(g) + \varphi(g) \Delta(t,n,g)^{1/\psi} + \varphi(g) \left\{ \left[\frac{\Delta(t,n,g)}{\zeta(n,g)} \right]^\psi - 1 \right\} + \mu(g) \left(\frac{\sum_{s=1}^{t-1} OIL_{prod}(t,n,g)}{\theta OIL_{res}(t,n,g)} \right)^\chi \quad (A7)$$

$$C(t,n) = Y(t,n) - \sum_j I_j(t,n) - I_{OILCAP}(t,n,g) - \sum_g OIL_{prod}(t,n,g) O \& M _ Costs - \sum_z X_z(t,n) \quad (A8)$$

The non-oil sector

Output gross of climate change damages, in the non-oil sector, is produced by combining a capital-labour intermediate input with energy services (ES) in a constant elasticity of substitution (CES) production function:

$$GY_{NONOIL}(n,t) = TFP(n,t) \left[\alpha_Y(n) \left(K(n,t)^\beta L(n,t)^{1-\beta} \right)^{\rho_Y} + (1 - \alpha_Y(n)) ES(n,t)^{\rho_Y} \right]^{1/\rho_Y}. \quad (A9)$$

Total factor productivity $TFP(n,t)$ evolves exogenously with time. The labour force is set equal to population (L), which evolves exogenously. Capital (K) evolves following a standard pattern:

$$K(n,t+1) = K(n,t)(1 - \delta_{GY}) + I(n,t) \quad (A10)$$

Energy services are an aggregate of energy (EN) and a stock of knowledge combined with a CES function:

$$ES(n,t) = \left[\alpha_{HE}(n) HE(n,t)^{\rho_{ES}} + \alpha_{EN}(n) EN(n,t)^{\rho_{ES}} \right]^{1/\rho_{ES}}. \quad (A11)$$

Energy is a combination of electric (EL) and non-electric energy (NEL):

$$EN(n,t) = \left[\alpha_{EL}(n) EL(n,t)^{\rho_{EN}} + \alpha_{NEL}(n) NEL(n,t)^{\rho_{EN}} \right]^{1/\rho_{EN}}. \quad (A12)$$

Each factor is further decomposed into several sub-components that are aggregated using CES, linear and Leontief production functions.

New ideas which contribute to the stock of energy knowledge, $Z_{HE}(n,t)$, are produced using R&D investments, $I_{R\&D}(n,t)$, together with the previously cumulated knowledge stock $HE(n,t)$:

$$Z_{HE}(n,t) = a I_{HE}(n,t)^b HE(n,t)^c HKL(n,t)^d. \quad (A13)$$

The knowledge stock evolves as follows:

$$HE(n,t+1) = HE(n,t)(1 - \delta) + Z_{HE}(n,t) \quad (A14)$$

The oil sector

We reproduce here the equations that have been illustrated in the main text of the paper for an easy reference:

$$OIL(t,n) = OIL_{el}(t,n) + OIL_{nel}(t,n) \quad (A15)$$

$$OIL(t,n) = \sum_g (OIL_{prod}(t,n,g)) + NIP_{oil}(t,n) \quad (A16)$$

$$OIL_{prod}(t,n,g) \leq OIL_{cap}(t,n,g), \quad (A17)$$

$$OIL_{cap}(t+1,n,g) = OIL_{cap}(t,n,g)(1 - \delta) + \Delta(t,n,g) \quad (A18)$$

$$\sum_n NIP_{oil}(t,n) = 0 \quad \forall t \quad (A19)$$

$$\sum_{s=1}^{t-1} OIL_{prod}(t,n,g) \leq OIL_{res}(t,n,g). \quad (A20)$$

Climate Module

Carbon dioxide emissions from combustion of fossil fuels (X_f) are derived applying stoichiometric coefficients to the total amount of fossil fuels utilised. Emissions associated to production of oil categories 2-8 are also tracked. By using carbon capture and sequestration (CCS) it is possible to reduce the amount of CO₂ emissions in the atmosphere:

$$CO_2(n,t) = \sum_f \omega_{f,CO_2} X_f(n,t) + \sum_g \phi_{g,CO_2} OIL_{prod}(n,t,g) - CCS(n,t). \quad (A21)$$

For details on land use emissions and on non-CO₂ gases please see Bosetti et al (2009).

The damage function impacting output is quadratic function of the temperature increase above the pre-industrial level T :

$$\Omega(n,t) = 1 + (\theta_{1,n}T(t) + \theta_{2,n}T(t)^2). \quad (A22)$$

Temperature increases through augmented radiating forcing F , moderated by the cooling effect of SO₂ aerosols, $cool(t+1)$:

$$T(t+1) = T(t) + \sigma_1 \{F(t+1) - \lambda T(t) - \sigma_2 [T(t) - T_{LO}]\} - cool(t+1). \quad (A23)$$

List of Variables

Ω = Climate feedback on the economy

δ = Depreciation rate

C = Consumption

c = Per-capita consumption

CCS = CO₂ captured and sequestered

CO_2 = Emissions from combustion of fossil fuels

Δ = Additional oil capacity

EL = Electric energy

EN = Energy

ES = Energy services

F = Radiative forcing

GY_{NONOIL} = Non oil GDP net of climate change impacts

HE = Energy knowledge

I_{OILCAP} = Investments in additional oil capacity

$I_{R\&D}$ = Investment in energy R&D

I = Investment in the final good sector

L = Population

K = Stock of capital in the final good sector

$MKUP_{OIL}$ = Regional Mark-up on international price of oil

NEL = Non-electric energy

NIP = Net import of carbon permits

NIP_{oil} = Net import of oil

$O\&M_COSTS$ = Operation and maintenance costs associated with oil extraction

OIL = Total consumption of oil

OIL_{cap} = Domestic oil capacity

$OIL_{capcost}$ = Investment cost per barrel of additional capacity

OIL_{el} = Oil used in electricity generation

OIL_{nel} = Oil used in the non-electric sector
 OIL_{prod} = Domestic oil production
 OIL_{res} = Oil resources
 p = Price of carbon permits
 P_{OIL} = International price of oil
 P_Z = a vector of prices for the input vector X_Z
 R = Discount factor
 T = Temperature level
 TFP = Total factor productivity
 U = Instantaneous utility
 W = Welfare
 X_Z = a vector including inputs that are considered a net loss for the economy
 Y = Gross Domestic Product
 Y_{NONOIL} = Non oil GDP
 Y_{OIL} = Oil GDP
 Z_{HE} = Flow of new energy knowledge

7.2. Assigned Values to Key Parameters:

Parameter: λ (g):

	I	II	III	IV	V	VI	VII	VIII
λ (\$ per barrel of oil capacity)	120	190	250	350	380	520	620	1600

Parameter $\zeta(n, g)$:

	USA	WEURO	EEURO	KOSAU	CAJAZ	TE	MENA	SSA	SASIA	CHINA	EASIA	LACA
I	0.212	0.180	0.003	0.023	0.101	0.415	1.009	0.194	0.027	0.127	0.093	0.389
II	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158
III	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158
IV	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158
V	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158
VI	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158
VII	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158
VIII	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158	0.158

Other Parameters:

Ψ	3.00
ϕ	0.04
θ	0.50

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