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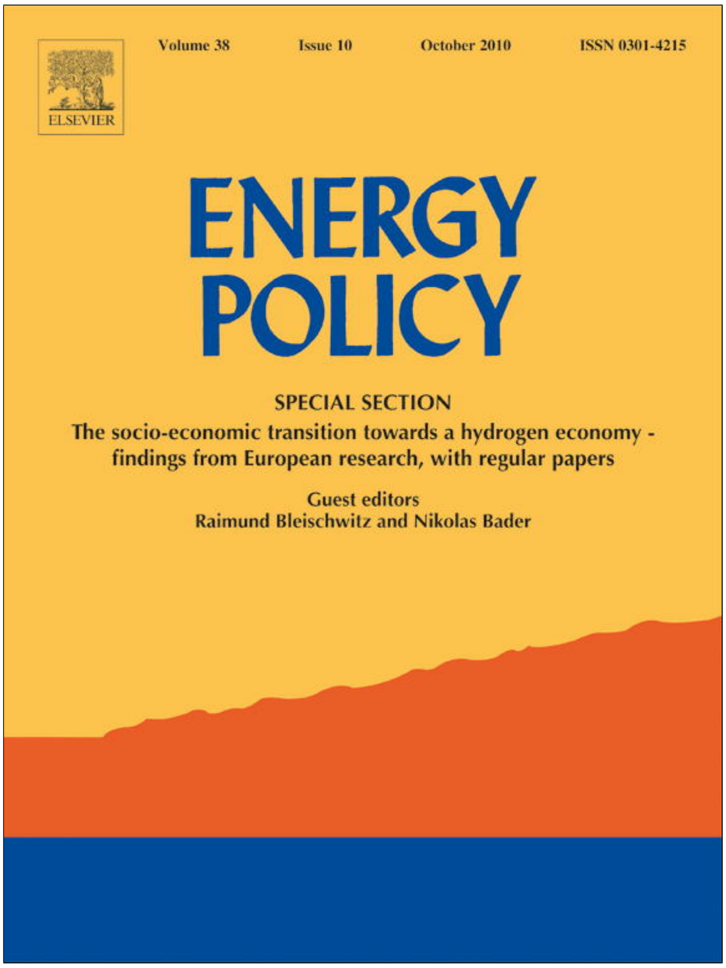

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Energy Policy 38 (2010) 5572–5581

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Views on peak oil and its relation to climate change policy ☆

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A R T I C L E   I N F O

Article history:
Received 23 October 2009
Accepted 2 May 2010
Available online 3 June 2010

Keywords:
Peak oil
Climate change policy
Carbon sources and sinks

A B S T R A C T

Definitions of fossil fuel reserves and resources and assessed stock data are reviewed and clarified. Semantics explain a large stake of conflict between advocate and critical voices on peak oil. From a holistic sources–sinks perspective, limited carrying capacity of atmospheric sinks, not absolute scarcity in oil resources, will impose tight constraints on oil use. Eventually observed peaks in oil production in nearby years will result from politically imposed limits on carbon emissions, and not be caused by physical lack of oil resources. Peak-oil belief induces passive climate policy attitudes when suggesting carbon dioxide emissions will peak naturally linked to dwindling oil supplies. Active policies for reducing emissions and use of fossil fuels will also encompass higher energy end-use prices. Revenues obtained from higher levies on oil use can support financing energy efficiency and renewable energy options. But when oil producers charge the higher prices they can pump new oil for many decades, postponing peak oil to occur while extending carbon lock-in.

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1. Introduction

The article reviews two subjects of high interest at present: peak oil and climate change. The question at the start was what belief in nearby peak oil because of dwindling physical resources in the ground, could mean for designing climate policies. In Section 2, concepts, data and mechanisms of resource exploitation are briefly reminded, with an overview of the oil (and wider: fossil fuel) reserves and resources issues. Reference is made to the standard sequence of exhaustible resource exploitations, i.e. from nearby and easy to far and difficult ores, mines and fields. In Section 3, arguments of peak oil adepts and critics are summarized, showing that semantics contribute to the conflict. Both advocate and critical voices accept the likely sequence of oil resource exploitation from easier and cheaper reserves uphill to more difficult and expensive grades. The latter are available in large quantities.

For framing climate policy, Section 4 places oil production and consumption in the perspective of a sinks–sources industrial metabolism (Ayres and Ayres, 2002). The assessed carbon content of fossil fuel resources on the one hand and the assessed carbon carrying capacity of atmospheric sinks on the other hand, highlight that not fossil fuel scarcity but atmospheric sink constraints are the more binding factor in fuel use. This suggests that peak oil is not a major problem. On the contrary, strict belief in nearby peak oil may stimulate a passive attitude regarding climate policy urgency. This policy urgency is necessary for avoiding further increase in concentration of carbon dioxide in the atmosphere. The latter requires imposed limits on the use of fossil fuels. Section 5 reminds that decreasing energy use necessitates setting higher carbon prices (Stern, 2006). Then the crucial issues are how and who is going to set the higher prices and how the revenues (rents, royalties) will be collected and spent. When the care for the public good atmosphere is left over to private market forces, most rents would be private and available for bringing more and dirtier fossil fuels into use. For avoiding this climate risky future, revenues from higher fossil fuel prices (for example due to levies on oil use) must be directed to stimulating energy efficiency and renewable sources. The article ends with a brief conclusion in Section 6.

2. Concepts and data of exhaustible resources

There are renewable and non-renewable resources (Craig et al., 2001). Renewable resources are not discussed here. The term

Abbreviations: 1P, proved reserves; 2P, proved+probable reserves; 3P, proved+-probable+possible reserves; API-gravity, American Petroleum Institute gravity; ASPO, Association for the Study of Peak Oil and Gas; BGR, Bundesanstalt für Geowissenschaften und Rohstoffe, the German Federal Institute for Geosciences and Natural Resources; BP, British Petroleum; CO_2-eq, carbon dioxide equivalent; EIA, Energy Information Administration; EROEI, energy return on energy invested; GtC, giga-tons of carbon; gCeq, gram carbon equivalent; IPCC, Intergovernmental Panel on Climate Change; MJ, mega Joule; Mb/d, million barrels per day; N_2, nitrogen gas; NO_X, a type of nitrogen oxide; O_2, oxygen; OPEC, Organization of the Petroleum Exporting Countries; ppm, parts per million; SO_2, sulfur dioxide; URR, ultimate recoverable reserves

☆ In-depth critical reviews of earlier versions of this article have suggested many additional insights and improvements, this final version could benefit from. The authors thank the reviewers for their contributions, but remain solely responsible for the views and conclusions finally published.

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doi:10.1016/j.enpol.2010.05.002

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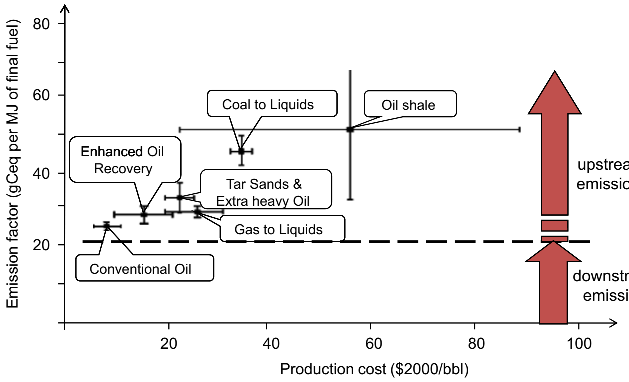

Fig. 1. Emission factors of liquid hydrocarbon resources, related to production costs (based on Brandt and Farrel, 2007).

"resources" refers only to the non-renewable resources occurring in finite quantities that natural processes cannot augment or replenish in short time. Examples are fossil fuels (coal, oil and natural gas) and metallic ores. Resources are of varying densities and qualities. Some deposits of a resource are highly concentrated with the complement of the resource stock being thinly concentrated.

2.1. Conventional and non-conventional oil resources, and their carbon load

Crude oil is a mixture of thousands of hydrocarbon compounds C_nH_{2n+2}. The actual composition of crude oil varies with the area of origin. Conventional oil is a liquid lighter than water (API-gravity > 10) of which 20–30% of the oil in place may flow naturally from the bore hole because of the pressure within the reservoir or can be pumped by simple mechanical force (primary recovery) (Craig et al., 2001). A higher extraction rate of the conventional oil in place requires *enhanced oil recovery techniques* (e.g. water flooding, steam injection and CO_2 pressurizing) at higher production costs (see Fig. 1). Non-conventional oil is the rest, encompassing extra heavy oil, oil sands, oil shale, gas to liquids and coal to liquids.

The carbon intensities of non-conventional resources are high (Brandt and Farrel, 2007). In Fig. 1, sources bottom-left are high quality and sources top-right are low quality in relative terms. Conventional oil has low production costs and relatively low carbon emissions per ton. The production costs rise with heavier and dirtier feedstock. Petroleum products from non-conventional feedstock are dirtier and costlier and only financially interesting when oil prices are high. Shaded areas in Fig. 1 express uncertainties about costs and emission factors of the resources (Brandt and Farrel, 2007).

We distinguish upstream and downstream processes. Upstream, crude oil is made available for consumption. Downstream, oil is consumed, mostly combusted. Per MJ fuel delivered conventional crude oil causes upstream emissions between 4 and 6 gCeq. Petroleum from non-conventional resources causes upstream emissions in the range 7.1–50 gCeq/MJ[1] (Brandt and Farrel, 2007). Downstream emissions are almost constant at 20 gCeq/MJ.

Other authors publish emission intensities different from the ones shown in Fig. 1. For example, compared to conventional oil Newell (2006) mentions tar sands at 25% higher emissions, oil shale about 65% and Coal to Liquids about 75% higher.

Charpentier et al. (2009) report CO_2 emissions[2] of exploiting Canadian tar sands, based on several studies. They distinguish extraction techniques in surface mining and in situ extraction.[3] The lower bound of emissions from tar sand oil production compared to the lower bound in case of conventional oil production shows excess emissions of 10% (surface mining and upgrading) or 30% (in situ and upgrading). Comparing the upper bounds reveals excess emissions of 13% (surface mining and upgrading) or 24% (in situ and upgrading). Brandt (2008, 2009) provides recent numbers for oil shale emissions much lower than the Brandt and Farrel (2007) numbers shown in Fig. 1. For the in situ processes, Brandt (2008) finds full LCA emissions 21–47% higher compared to conventionally produced petroleum, while the same author (Brandt, 2009) reports for ex situ processes emissions are 50–77% higher. Jaramillo et al. (2008) publish upstream emission intensities for synfuels derived from gas or coal, ranging from comparable to petroleum based intensities to their double.

Carbon intensities of fuels are related to their EROEI,[4] being the ratio of MJ energy output to MJ energy input for generating the output (Hall et al., 2008). The average EROEI for finding and producing US domestic oil has declined from higher than 100 in the 1930s to about 30 in the 1970s to between 11 and 18 nowadays (Hall et al., 2008). For enhanced recovery additional processes are required, decreasing the EROEI and increasing upstream carbon emissions.[5] For oil shale, Brandt (2008, 2009) publishes EROEI ranges 1.2–1.6 for in situ production and 1.1–1.8 for ex situ[6] production.

Total carbon emissions from oil may increase at lower oil consumption when substituting non-conventional for conventional sources. Farrell and Brandt (2006) confirm the environmental risks associated with the transition to non-conventional resources and discuss as well the economic and strategic risks related to the transition.

2.2. Taxonomy of reserves and resources

Along conventional and non-conventional oil, reserves and resources are distinguished. (Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), 2007; Society of Petroleum Engineers, 2007) ***Reserves***: *The quantity that can be recovered economically from a mineral deposit at current prices with current technology. Reserves must be discovered, recoverable and commercial. They are further categorized in accordance with the level of certainty.* ***Resources***: *Discovered quantities that are potentially recoverable but cannot be recovered at current prices with current technology* (*contingent resources*)*, as well as the undiscovered but potentially recoverable quantities having both an associated chance of discovery and a chance of economic development* (*prospective resources*).

There is no consensus on how to assess reserves and there is no world organization to enforce one (Bentley, 2002; Laherrere, 2006). Three levels of confidence regarding reserve estimates are

[1] The emissions rate 7.1 corresponds to the lowest value for GTL and 50 to the highest value for shale oil.

[2] The numbers are well-to-wheel LCA emissions. The authors add that reliable LCA for oil sand production is challenging because of limited data availability, rapid expansion of the industry, evolving technologies and the unique nature of each project.

[3] In situ extraction: steam is injected in the oil sands, for lowering the Bitumen's viscosity allowing its extraction through wells, with the sand staying in place.

[4] The correlation between carbon intensities of fuels and EROEI is much dependent on the carbon intensity of the energy sources used in producing oil (e.g. oil shale extraction powered by fuels or by wind turbines).

[5] Energy for enhanced oil recovery is typically coming from combusting fossil fuels.

[6] Ex situ is mining, displacing and treating oil shale in ground-level facilities; in situ is processing at the place of mining.

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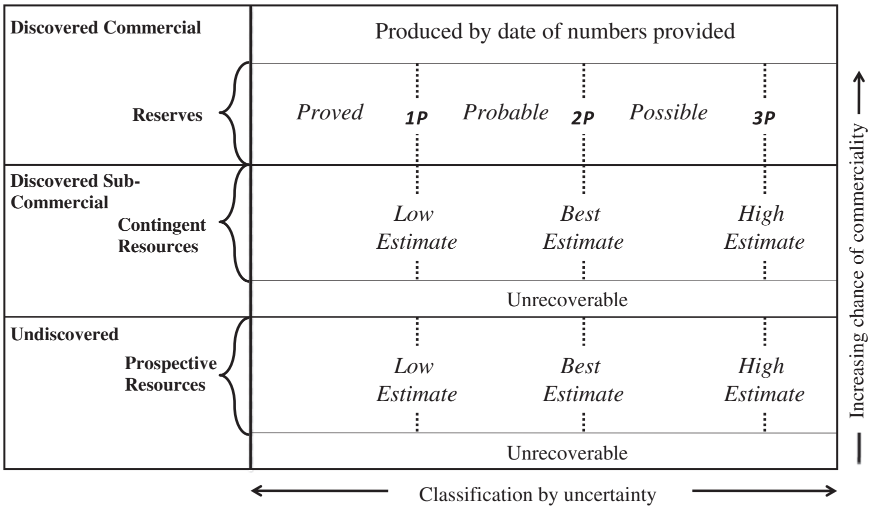

Fig. 2. Reserves/resources classification system for Petroleum and Natural Gas (Society of Petroleum Engineers, 2007).

Table 1
Fossil fuels 2P reserves and best estimate resources (assessed end 2007 by BGR).

Fuel	Reserves		Resources	
Status 31.12.2007	EJ (10^{18} J)	Share in reserves	EJ (10^{18} J)	Share in resources
Conventional crude oil	6835	18.24	3430	0.69
Oil sands/extra heavy oil	2720	7.26	2761	0.56
Oil shale	42	0.11	7699	1.55
Total oil	*9597*	*25.61*	*13,890*	*2.80*
Conventional natural gas	6948	18.54	7857	1.58
Non-conventional gas	76	0.20	58,335	11.75
Total natural gas	*7024*	*18.74*	*66,192*	*13.33*
Total coal	*20,852*	*55.65*	*416,516*	*83.87*
Fossil fuel total	**37,473**	**100**	**496,598**	**100**

standard: *proved*, *probable*, *possible*. An oil or gas field is considered as *proved or* **1P** *reserves* if the chance that the field will effectively be developed is higher than 90%. For *probable reserves* the chances of being available for mining technically and economically are estimated at 50–90%. *Possible reserves* are claimed to have at least a 10% certainty of being produced. The aggregates of proved and probable reserves are **2P** reserves, and with further adding possible reserves one obtains **3P** reserves. Oil industry data typically refer to 2P reserves, while the financial sector awards loans for project developments of 1P reserves. Fig. 2 gives an overview of the classification system as used by the Society of Petroleum Engineers, the World Petroleum Council and the American Association of Petroleum Geologists.

Table 1 shows fossil fuel 2P reserves and Best Estimate resources, as assessed by BGR. Non-conventional oil resources (2761+7699 EJ) are larger than total oil reserves (9597 EJ). The same holds for natural gas. Tremendous coal and gas reserves and resources may deliver synfuels that enlighten oil supply restrictions for the foreseeable future. Bentley (2002) and Kjärstad and Johnsson (2009) question whether synthetic crude oils and synfuels can be produced at similar flow rates as conventional crude, and argue that non-conventional sources cannot get on-stream fast enough to fully compensate the decline in the production of conventional crude. Non-conventional oil projects tend to have long and uncertain lead times (Bentley, 2002; Tsoskounoglou et al., 2008).

With sufficient non-conventional oil resources and reserves physically available, other constraints may limit their extraction. For example: the production of one barrel of oil from Canadian tar sands requires [in 2008] 2–4.5 barrels of water. In 2008 oil production was at 1.3 million barrels per day (CAPP (Canadian Association of Petroleum Producers), 2008), with planned expansion to 3 million by 2015. At constant water use per barrel, the local river Athabasca cannot meet the expanded water demand. The ecological viability of the river is already threatened by low flows and low oxygen levels (WWF, 2008). Predictions on non-conventional oil show peak production[7] ranging from less than 12.5 Mb/d to more than 112 Mb/d for oil sands only, with as best guess 60 Mb/d in top year 2077 (Mohr and Evans, 2009).

The earth contains large amounts of resources, but economics (e.g. higher extraction costs) and politics (e.g. limits on carbon emissions and OPEC restrictions) may cause a peak in fossil fuel supplies before absolute physical and geological limits become binding.

2.3. Standard sequence of resource exploitation

Resources are not homogenously distributed in the Earth's crust. The American Nuclear Society (2001) provides a clear illustration[8] for uranium. Typical global resource density functions show small amounts of high grade and large amounts of low grade stocks. Resource exploitations are observed to start at cheap and easy deposits, being mostly high grade seams, wells and ores

[7] Total oil production in 2007 amounted to 81.5 Mb/d (BP, 2008).
[8] See: http://www.americanenergyindependence.com/library/images/nuclear/Uranium01.htm.

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(Craig et al., 2001). Costs of mining and treatment are minimized because a relatively large share of gross extraction is useful material. With depletion of high grade resources producers shift to lower grades at higher production costs. This pushes supply prices upwards, with market prices following the same trend when demand remains stable or grows. Less economic but often more widely available lower grade stocks become economical to mine. This is the economic logical order (Herfindahl, 1967) in exhausting resources along decreasing ore grades, from cheap and easy to expensive and difficult (Fig. 1; Craig et al., 2001: p. 173), and therefore also considered the evident chronological order. Norgaard (1990) however questions the smoothness of this downhill ride, observing "a history of using low quality resources before learning led to the exploitation of higher quality, less costly resources" (named the "Mayflower Problem"). A bumpier ride reflects uncertainty and ignorance about the actual resources available on earth, technological development over time to explore and exploit resources globally, as well as limited extraction capacities at a given time, inertia and lock-in (Kemp and Long, 1980; Amigues et al., 1998; Holland, 2003).

Following standard economic logic, higher oil prices lead to the use of non-conventional sources which are more carbon intensive (Newell, 2006), but abundant (Table 1). Once the large reservoirs depleted, producers shift to smaller and more remote reservoirs with a shorter production lifespan. More remote reservoirs require higher investments (for example offshore oil exploitation) and smaller reservoirs produce less oil at given investment costs pushing up the average cost per barrel.

2.4. Uncertainty about capacities of single sources and of aggregates of sources

Fig. 3 represents exploitation of a single oil deposit over time, following a plateau pattern (Campbell and Laherrère, 1998). Production gradually increases to some maximum output followed by a long plateau, ending in a gradual decrease. Added is the possibility of life extension by improved technology when time passes. The area under the plateau(s) shows the amount of oil pumped. With longer time spans (several decades), uncertainty on the tails of the curves is growing. Improved geological exploration techniques and methodologies, and improved recovery technologies and enhanced recovery investments can paste areas to the plateau-curve larger than the originally designed coverage. Maugeri (2004) illustrates the dynamic character of reserves and resources with the Californian Kern River field, discovered in 1899, assessed at 54 million barrels in 1942 (after 43 years of extraction), while in 1986 it had produced 736 million barrels and still held another 970 million barrels. The field did not change, the knowledge did. Combining

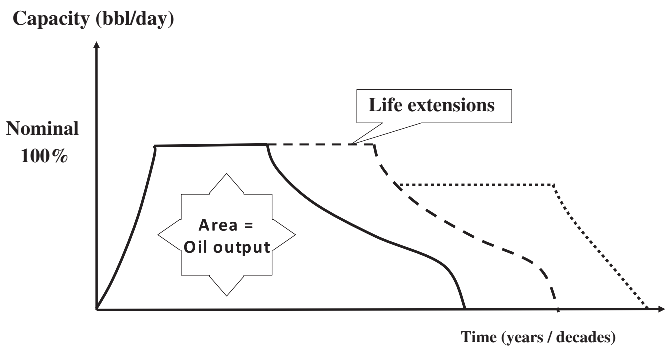

Fig. 3. Exploitation pattern of an oil deposit.

the exploitation patterns of many fields[9] will result in a bell-shaped curve, becoming smoother as more wells are added (Fig. 4). The US-48 lower states had about 240,000 production wells in 2002.

In the peak oil debate aggregates of individual sources are handled. Every aggregate is contingent on its geographical scope and temporal horizon. Conclusions based on aggregates vary with the scope of such aggregates. Sometimes lessons from a limited area (e.g. USA) are extrapolated for the rest of the world, without detailed qualification of the differences. For example the Hubbert curves may be valid for stable areas (the USA-48 lower states), not disturbed by political turmoil, deep recessions, domestic wars, etc. In other regions of the world, depressing events often distort exploration and extraction rates ending in more irregular shapes of the aggregate exploitation curves. Oil production in a limited area (USA) is affected by other drivers than only geological and exploitation cost conditions of the domestic stocks. In particular the ratio of the domestic production cost to the CIF (cost, insurance and freight) delivered barrel from the world oil market, is decisive in explaining ups and downs of domestic exploitation. When world oil prices slump, domestic production will be lowered (postponed), and vice versa.

3. Peak oil

Peak oil propositions receive a lot of new attention since 2003 with the price of oil climbing, peaking in mid-2008 (Leder and Shapiro, 2008; Tsoskounoglou et al., 2008). Hubbert's predictions are revisited from 2008 evidence (Section 3.1). The main arguments of peak oil supporters are summarized in Section 3.2, and the non-alarmist views in Section 3.3. In Section 3.4 the differences between both are considered.

3.1. King Hubbert's peak in 1956 and in 2008

Hubbert graphs (Fig. 4) approval rate was rising spectacularly after 1970, the year USA oil production peaked, precisely the year of one of the cases forecasted by Hubbert 1956. US annual production at the high point in 1970, however, was 600 million barrels (20%) higher than Hubbert's projection of peak production for the US lower 48 (Jackson, 2006; Fig. 4).

Fig. 4 illustrates the high impact of geographical definitions on peak oil production, comparing USA oil production without and with Alaska included. The observed data also tend to reject the symmetry of the production bubble assumption. Several investigations find the curves are not symmetrical (what Hubbert suggested). The right end of the curves is the predicted part and predictions seem to underestimate actual outputs skewing the curves at their right side (Watkins, 2006; Jackson, 2006; Brandt, 2007). One cause may be that past and present technologies extract only 35% of the oil from the fields, leaving huge potentials in the ground (Hall et al., 2008). The huge potentials could be accessed through Enhanced Oil Recovery delaying the decline of the individual production curves (Fig. 3). Aggregated curves then also change from Gaussian symmetry into multi-modal shapes. Some authors handle the "multiple-Hubbert" approach producing aggregated curves with multiple 'bubbles' (e.g. Maggio and Cacciola, 2009).

Predictions of the exact height and time of "the" oil peak are sensitive to assumptions concerning the shape of the curve

[9] A small number of large fields at the beginning and a large number of small fields at the end mirror is the reality in the oil industry.

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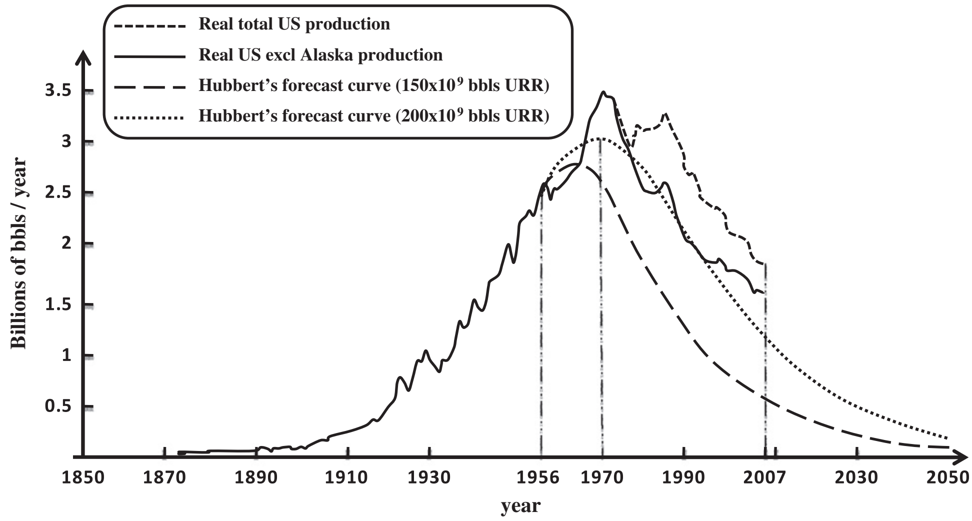

Fig. 4. Actual US production and predictions by Hubbert in 1956 (US Energy Information Administration (US EIA), 2008a; Hubbert, 1956).

(growth and decline rates) and on the URR.[10] Estimates often omit important factors, like constraints on the maximum annual production growth rates by technological, socio-economic or physical factors (Kjärstad and Johnsson, 2009), and the influence of domestic consumption on the export capacities of oil producing and exporting countries (Hallock et al., 2004). Investigating the assumption of symmetric bell-shape curves of oil production, Brandt (2007: p. 3085) concludes: "had history progressed differently and Hubbert used a linear model rather than a bell-shaped model, he would likely still have been hailed as correct due to the extremely good fit of US production to the linear model as well as the Gaussian model. Or, had Hubbert analyzed a different region than the US, he would have almost certainly been less correct, simply because US production is quite symmetric compared to the global average".

3.2. *Today's peak oil vision: ASPO*

The ASPO follows Hubbert in generating bell-shaped production forecasts for the world (www.peakoil.net). The similarity of the global production curve with the Hubbert Curve is clear up to the 1970s when the oil crisis influenced the shape of the curve. Peak oil models predicted the global oil production peak several times in the past (Lynch, 1999). These predictions never came out so far. The predicted peak was repeatedly *increased* and *postponed* a few years into the future. Campbell for example once predicted that 1989 was the year of 'peak' production (Maugeri, 2004: p. 1114).

Peak oil is developed and supported most by geologists, e.g. Hubbert (1956), Campbell (1994, 2006), Campbell and Laherrère (1998), Bentley (2002) and Hirsch (2007). Oil deposits are non-renewable and fixed, making stocks decrease with consumption. Simmons (2008) derives his pessimistic view from analyzing financial flows in the oil exploration and exploitation business. Peak oil authors argue that many estimates of oil reserves and resources are non-reliable and overestimated. Estimates are generated by producing countries themselves. Some countries may manipulate estimates for own gain, in particular OPEC countries declaring upward-biased reserves because OPEC assigns production quota along the size of its members' oil reserves. Suspect reserves stay constant year after year (i.e. new discoveries exactly match production) or increase suddenly by large numbers (Campbell, 1994).

Another argument is the decreasing discovery rate. The largest fields are found first because they are 'too big to miss'. The large fields are aging and fewer are discovered, while production mirrors discovery with a time-lag. Campbell (2006) states that in 1981 the world started to consume more oil than it found and that the gap between discovery and production is widening. Based on historical discoveries and stochastic simulation of future discoveries, Shell finds a normal distribution for new discoveries of regular conventional oil when smoothed for a 20-year moving average (Tsoskounoglou et al., 2008: p. 3800). The year 2005 knew the lowest oil discovery level ever and in 2008, the world consumed 2–3 barrels (Tsoskounoglou et al., 2008: p. 3800) or even 4–5 barrels (Hall et al., 2008: p. 113) for every new discovered oil barrel.

Peak oil authors state that the largest and most accessible sedimentary areas have already been explored extensively. Therefore, future discoveries will likely occur in smaller quantities and in more remote areas, and production will be more difficult and costly. The rate of worldwide oil discovery has been decreasing and some areas have failed to yield any recoverable oil while once thought to possess significant oil potential (Craig et al., 2001: pp. 168–169).

3.3. *Critical and opposite visions on peak oil*

Critical visions on peak oil are stated mostly by economists. They consider reserves predominantly an economic concept, e.g. Adelman (1990, 1993), Odell (1992), Lynch (1999), Watkins (2006) and Maugeri (2004, 2006). "Oil reserves are the amount of oil that is minable at today's *prices* using existing *technology*". The economist vision rather ignores critical geological features of oil stocks (Hallock et al., 2004). Reserves and resources are no fixed numbers but constitute a dynamic flux depending on prices and technology.

Currently used technologies leave about 65% of the oil in the ground (Hall et al., 2008). Oil shortage will make prices rise. Increased prices convert part of the once uneconomic *resources* (e.g. small or deep oil wells remote from markets) to economic *reserves*. The resources are vastly greater than the reserves (Table 1), so enough material is available if prices are sufficiently high. Long before the last fractions of exhaustible resources could

[10] An accurate knowledge of the ultimate recoverable reserves is required by Hubbert's method, but his 1956 analysis did not incorporate the impact of giant discoveries in Alaska and the deepwater Gulf of Mexico (Jackson, 2006). This type of uncertainty and ignorance is also addressed by Norgaard (1990).

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be extracted, production costs will rise so high that demand will vanish. High prices also provide economic incentives "*to develop new cost-saving technologies, to design products that use fewer resources, to substitute less costly and more abundant resources, to recycle, and to discover new deposits*" (Tilton, 1996: p. 94). Both, decreasing use and the increased rates of discovery and recovery as a result of higher oil prices, will extend the life cycle of the petroleum reserves (Craig et al., 2001: p. 173).

Watkins (2006) criticizes the definition of URR as a fixed, final or fundamental fact. He shows oil production increased by 30% between 1973 and 2003, with reserves to production ratios rising over the same period from 31 to 40 years (i.e. reserves increased faster than production). Watkins (2006: p. 512) argues that the exact estimate of URR, optimistic or pessimistic, would include the knowledge of future science and technology. URR are thus unknowable. Critics of the peak oil vision emphasize the large quantities of non-conventional oil in tar sands and oil shale (Table 1) (Hall et al., 2008).

Peak oil critics mostly share an optimistic view on discoveries. In 1994, Odell (1994) spreads the view that most regions are under-explored because the global oil industry experiences a lack of maturity compared to the USA industry, retarding the exploration of new reserves compared to quick and intensive exploration in the USA. Also high reserves to production ratios retard exploration. Maugeri (2006a: p. 1) argues that during the last 25 years more than 70% of exploration effort took place in the USA and Canada that probably hold only 3% of the world's crude oil reserves. The Middle-East region only experienced 3% of global exploration during the same period while holding around 70% of the earth's crude oil reserves. In the Persian Gulf, less than 100 exploration wells (out of a total of about 2000 wells) were drilled between 1995 and 2004, while 15,700 exploration wells (out of a total of more than one million wells) were drilled in the USA during the same period. Although OPEC countries such as Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates own the largest oil reserves, these countries are still relatively underdeveloped and under-explored (Maugeri, 2006b: p. 150). After the 1970s, most Middle-East countries nationalized their oil industries causing a decline in the regions geological and exploration know-how. Today, Western oil companies only control 8% of the global oil reserves while more than 90% of the world's reserves are located in countries not allowing foreign access and unwilling or being unable to develop new reserves on their own (Maugeri, 2006a: p. 1). Maugeri (2006b: p. 152) emphasizes most oil producing countries pump from old fields, most being in production since the first half of the 20th century, still using 50–60-year-old technology and equipment. Next to OPEC countries, the capacities of the Russian and Caspian regions are seriously underestimated. Maugeri believes current limited spare production capacity is the result of 20 years inadequate investment in exploration. The price collapse in 1986 made OPEC countries worry about overproduction causing several OPEC countries not to develop new fields and only exploiting those already in production to maintain steady production levels. Low prices in the 1990s, limited growth in demand and another price collapse in 1998–1999 reinforced the principle of minimizing excess capacity. Between 1986 and 2005, global spare oil production capacity dropped from 15% to 2–3% of global demand (Maugeri, 2006b: pp. 151–154). High prices are the result of economic disturbances, not of geological limitations. High prices are a prerequisite for greater investment. (Maugeri, 2006a: p. 2) concludes with: '*In other words, there is more than enough oil in the ground*'.

Odell shows that between 1950 and 1989 only once the annual use of oil exceeded the annual addition to reserves by the global oil industry and states: "the world is running into oil, not out of it" (Odell, 1992: p. 285). We updated Odell's graph, based on BP Statistical Review data for the post-1990 period, and show that Odell's findings hold for the post-1990 period until 2007 (latest data available). From 1990 onward, the 5 year moving average of gross additions to reserves always exceeded yearly production.

Odell's statement of the world running into oil is however based on his original curve (additions to 1P reserves) that ends at the peak in 1989. In the post-1990 period, the moving average curve approaches the production curve. The sharp rise in the second period of the 1980s is partly due to OPEC countries adding large reserves in response to OPEC's quota rules (Section 3.2). The reliability of the additions is low as are the assessments of total stocks. The impact of the oil market conjuncture on the growth of reserves is a subject for further investigation.

3.4. How different are the visions?

Main positions of peak oil followers (Section 3.2) and of critics (Section 3.3.) are summarized in quotes by, respectively, Bentley and Maugeri (our underlining added):

"*The world's production of <u>conventional</u> hydrocarbons will soon decline. Hydrocarbon shortages are inevitable <u>unless</u> radical changes occur in demand, or in supply of <u>non-conventional</u> hydrocarbons… Even with large investments, resource limits will force Middle-East production to decline <u>fairly soon</u>, and hence also <u>global conventional</u> oil production… Best estimates put the physical peak of <u>global</u> <u>conventional</u> oil production between 5 and 10 years from now…*" (Bentley, 2002: p. 189).

"*We are not running out of oil, but <u>high oil prices</u> are needed to find it. There is an alarmist theory that the world is running out of oil. Quite the contrary. There is plenty of oil in the ground, and high prices are just what is needed to tap the earth's vast reserves*" (Maugeri, 2006a: p. 1).

Tilton (1996) attributes the differences between two *opposing camps* to *very different, opposing and competing paradigms*. Others refer to the groups by using antonymous denominations such as *pessimists* versus *optimists* (Tsoskounoglou et al., 2008; Aguilera et al., 2009; Maggio and Cacciola, 2009). But the differences are less dramatic when every statement is fully characterized by content and by context. For e.g. the quotes by Bentley and Maugeri seem very opposite, but in the end they cover different realities. Bentley emphasizes peaking of conventional oil "unless radical changes in supply of non-conventional hydrocarbons" occur. Maugeri replaces the "unless" by "high prices". The emphasis and the language differ as do their analytical perspectives, but we would not call it different paradigms.

Opinions on discoveries and additions to reserves also diverge. Peak oil supporters stress discoveries have decreased meaning less oil is available for consumption. But statistics reveal reserves continue to increase with every year more oil being added to the reserves (Fig. 5). Here again, the two groups talk about two different things. Although proved reserves (1P reserves) do grow over time (BP, 2009), 2P reserves (proved plus probable reserves) remain quasi-constant. Year after year some share of 2P reserves is converted to 1P reserves (Bentley et al., 2007). Fig. 5 gives a clear representation of the additions to 1P reserves and of 2P discoveries, which do not run synchronously. Even without new discoveries oil quantities may be added to reserves because of increasing prices, advancing technologies and increased knowledge and confidence about field volumes (Jackson, 2006). Decreasing discovery rates (Fig. 5) may result from little left to find or from decreasing prospecting efforts and investments, the latter very influenced by the oil market conjuncture.

In comparison to the 1980s, more authors refer to the concept of peak oil for analyzing the patterns of oil exploitation (Victor,

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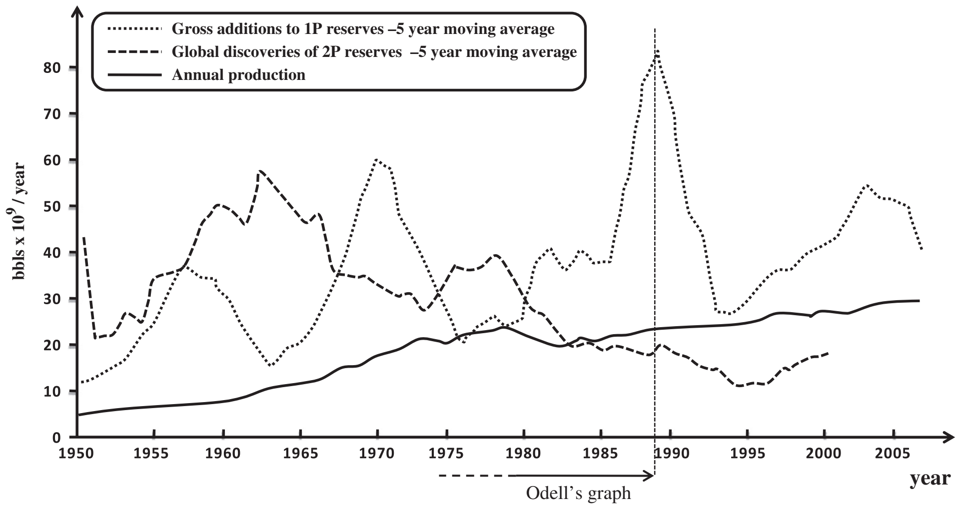

Fig. 5. Annual world oil production, gross additions to reserves and global 2P discoveries (discoveries: Bentley et al., 2007: p. 6369; production/reserves: up to 1989: Odell, 1992–1990 onwards: author's additions based on BP, 2009).

2008: p. 60).There is no consensus on the timing and height of the oil peak. Peak oil dates range from 'already peaked' (e.g. Simmons argued the year 2005) to dates beyond 2035 (Jackson, 2006). Many articles have recently been published to project a peak oil date in the time interval 2010–2040 (Bentley et al., 2007; Hirsch, 2007; Kaufmann and Shiers, 2008; Tsoskounoglou et al., 2008; Leder and Shapiro, 2008; de Almeida and Silva, 2009; Kjärstad and Johnsson, 2009; Aguilera et al., 2009; Shafiee and Topal, 2009). Possible explanations for the different forecasts are: use of different data sources (high or low Middle-East estimates), lack of data transparency, use of different assumptions in the models, use of different analytical frameworks, whether or not including some share of the non-conventional resources, etc.

When the positions are normalized for semantics, both groups agree on the peaking of conventional, easy-to-access "premium" oil, not too far in the future. An increasing number of oil company executives believe oil production will never exceed 100 million barrels per day (Strahan, 2008). Choking business-as-usual growth for more stable flows in exploration and production over the coming decades may better secure future activities. This strategy is also supported by public concerns about peak oil and climate change.

4. New constraints: the atmosphere and climate change

In this section the emissions of carbon dioxide are placed in the ecological sources–sinks framework (Section 4.1). Carbon stocks in the atmosphere are compared to the ones in the earth's geo- and biosphere (Section 4.2), but we skip the analysis of carbon cycles (IPCC, 2007). The focus here on fossil fuel sources and their carbon dioxide emissions shadows other important sources (land-use, livestock, deforestation, industrial processes) of various greenhouse gases.

4.1. Industrial metabolism: sinks and sources

The ecological economics literature developed the concept of industrial metabolism for describing the interaction between living economies and nature (Georgescu-Roegen, 1975; Daly, 1980; Ayres and Ayres, 2002). As other living organisms, economies take in resources from the environment and discard residuals and waste back to the environment. This sources–sinks concept is useful to discuss peak oil and climate change in context.

External energy is a major input to industrial economies, and the largest share of commercialized energy inflows are fossil fuels (BP, 2009). By obeying the first law of thermodynamics, materials implied in fossil fuel combustion (hydrocarbons, O_2 and N_2 (air) with some more substances) do not vanish but are converted into flue gases (a mixture of N_2, H_2O, CO_2, NO_X, SO_2, unburned or incompletely burned hydrocarbons, particulate matter, and some more substances) and ashes. Inputs and outputs are of equal mass flows in stationary combustion processes.

The basic laws of thermodynamics are well known since the 19th century. It took until the last decades of the 20th century for industrial societies getting interest in the gaseous waste flows of fossil fuel combustion, first because of acid rain and health impacts (dioxins, products of incomplete combustion) and now mainly because of massive emissions of the long-living greenhouse gas CO_2 (IPCC, 2007).

The exploitation and combustion of fossil fuels are directly related to the emissions of CO_2 in the sources–sinks model. Peak oil focuses on the sources side. IPCC focuses on the sinks side. The question comes up what of both sides is the one most constraining our ongoing activities. The answer to this question is important for climate policies, in particular for "setting the carbon price" (Stern, 2006). When the tap of our fossil fuel supplies is running dry before the atmosphere is overloaded with greenhouse gases, emissions reduction can piggyback on the downward slope of the Hubbert bubbles (Chakravorty et al., 1997; Kharecha and Hansen, 2008; Koppelaar et al., 2008; Brecha, 2008, analyze such scenarios). When however the sink must be closed[11] much earlier than the tap is running dry, such piggyback visions and policies are inducing a passive attitude in climate policy making. Therefore we document the magnitude of fossil fuel resources and the filling of atmospheric sinks in carbon numbers.

4.2. Extrapolating emissions

Fig. 6 provides an overview of GtC in the earth's geo- and biosphere. The estimate of fossil fuel carbon stocks is obtained by multiplying estimated resources in EJ (BGR, 2007; Table 1) with

[11] Overfilling sinks is here defined as emitting carbon dioxide more than IPCC stabilization scenarios allow. The limits on emissions are not physically absolute as for example a shortage in combustion air would dictate.

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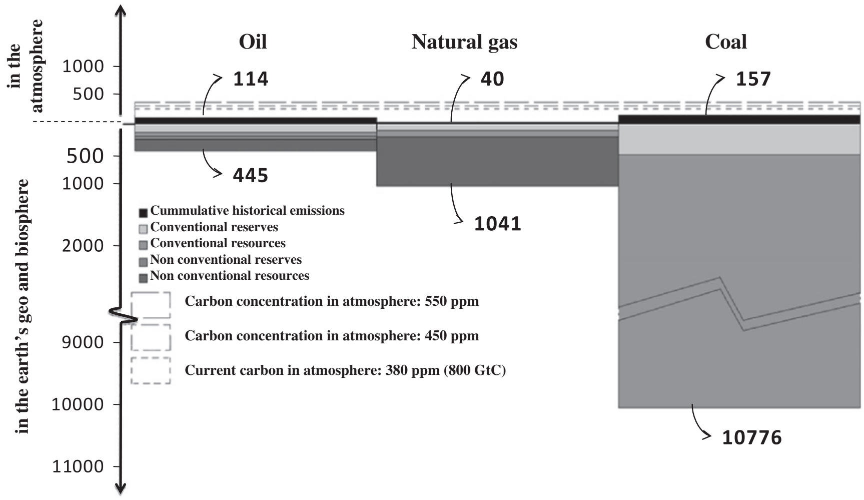

Fig. 6. Carbon stocks in geo- and biospheres and in the atmosphere (Marland et al., 2008; BGR, 2007).

EIA specific carbon intensities (carbon per Joule) by fuel (US Energy Information Administration (US EIA), 2008b). Estimated conventional oil and gas reserves and resources hold about 405 GtC with non-conventional hydrocarbon resources adding 1081 GtC. Transition to massive use of non-conventional fossil fuels with release of its carbon to the atmosphere, would cause disastrous climatic impacts. On top of hydrocarbons, carbon stocks in coal reserves and resources are much larger (Fig. 6).

The atmosphere contains nearly 800 GtC (Folger, 2008). The corresponding CO_2 dioxide concentration in 2005 equals ~380 ppm, while the pre-industrial one was ~280 ppm. The concentrations result from a complex carbon cycle (IPCC, 2007), but the 100 ppm added is mainly due to the anthropogenic emissions of burning an assessed 311 GtC in fossil fuels (Marland et al., 2008; Congressional Research Service, 2009). Emitting more CO_2 in the atmosphere is practically impossible in the future when the temperature increase has to be kept below 2 °C, i.e. obeying the emissions ceilings imposed by the 450 ppm CO_2-eq. stabilization trajectory (IPCC, 2007; Edenhofer, 2008).

Referring back to the metabolism, the real problem is not that the sources will fall dry shortly (peak oil, peak gas and peak coal) but that the sinks are already overfilled. It is difficult to imagine how the world could afford the luxury of the gradual decline in oil production after the eventual occurrence of a peak due to shortage in reserves. More problematic would further be the substitution of non-conventional oil for conventional oil at any significant scale.

Therefore not recommended is a relaxed attitude regarding climate change based on the belief that peak oil will salvage energy use from fossil fuel consumption. The carrying capacity of the atmosphere is the real bottleneck, not the exhaustion of oil reserves and resources. When carbon capture and storage (IPCC SRCCS, 2005; Hansson and Bryngelsson, 2009; Gibbins and Chalmers, 2008; Rai et al., 2009) is not developing to scale and diffused widely on oil combustion plants, a peak in oil production is likely to occur. This peak could be read as confirming the predictions of peak-oil believers. This confirmation however would be erroneous because no shortage in reserves and resources occurs but the atmosphere cannot carry more carbon dioxide without jeopardizing human life for many on earth.

5. The role of higher oil prices

Deliberate specific climate policies are a necessity, universally subscribed (UN, 1992). Strong arguments exist for setting there-

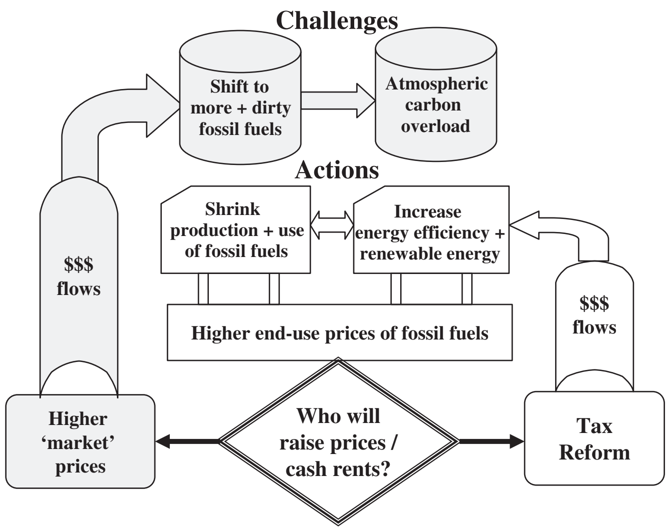

Fig. 7. Two ways of increasing end-use prices of commercialized energy.

fore the carbon and energy prices right (Stern, 2006; Kümmel et al., 2008; Verbruggen, 2009). But political reluctance to clear energy and carbon taxing is deeply rooted (Aldy and Stavins, 2007). In this context, environmentalists welcomed the oil price hikes of 2008. Such hikes indeed have a significant impact on energy use, as evidenced by the statistics of the years following the 1973 and 1979 oil crises (BP, 2009). The experience of the 1970s–beginning 1980s reveals that price hikes are a temporally phenomenon to re-adjust price levels at new conditions of global supply and demand. They provide an impetus to energy efficiency and to the development of alternative energy sources, the latter including higher-cost oil reserves. After the crisis the oil price tends to stabilize within the "target prize zone" of oil exporters (Slaibi et al., 2005), also described as a new price plateau for a longer period (Petkov and Stratiev, 2008). For climate policy one should look deeper into the prices case. The central part of Fig. 7 shows challenges and actions related to climate change. Challenges discussed in this article are the shift to produce more and also dirtier fossil fuels. Because carbon capture and storage is not a mature technology (Rai et al., 2009), this shift would add to the carbon overload in the atmosphere. The main actions to address the challenges are increasing energy efficiency and renewable energy supplies (IEA, 2009). Successful progress in

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such actions is built upon stable, predictable and irreversibly higher end-use prices of fossil fuels. Higher end-use prices of fossil fuels can be set by sellers as higher 'market'[12] prices. A higher price zone provides the financial backing to explore oil wider and deeper, to engage in enhanced recovery, or to add a slice of non-conventional resources to commercial exploitation (Section 3.3). The resulting glut of fossil fuels continues the lock-in of industrial energy economies in incumbent technologies and practices. This is shown as the left side of Fig. 7.

The transition to a high-efficient, renewable energy economy means a complete renovation and innovation of the energy systems, requiring market pulling and RD&D pushing (Fri, 2003). For financing the latter, funds may be recycled from applying levies on the use of fossil fuels and on carbon emissions (Gerlach and Van der Zwaan, 2006). The stalemate between private and public interests in setting the prices and appropriating the rents may surge. Humphreys et al. (2007) emphasize the importance of public governance for directing a fair share of resource wealth to the public interest. For the public interest becoming more successful Kolstad and Wiig (2009) argue for "impartiality enhancing institutions" having a higher chance to flourish in countries with good institutions of democratic accountability and the rule of law.

6. Conclusions

Peak oil again receives public attention because of increasing oil prices since 2003 and price hikes in mid-2008. Confusion is fostered by lack of general agreed upon definitions of conventional and non-conventional, reserves and resources of fossil fuels. Some realities are obvious, for example: the finite size of particular geological stocks; the economical sequence of exploitation from nearby and easy to far and difficult resources; the ample availability of the latter type of resources. Opinions differ on the availability of easy to exploit conventional oil reserves and therefore on the pattern of their exploitation. Peak oil purists refer to given limited ultimate reserves, exploited along logistic curves that would have generated symmetric bell-shaped curves at the end of the oil era. However, too many physical and economic–technological uncertain factors disturb the smooth patterns, mainly in countries of less political and economic stability the USA enjoyed. The concept of ultimate reserves is not a single number but a wide range broadened by new findings, technological innovation and shifting economic conditions. Every higher oil price zone converts more resources into reserves, postponing the occurrence of the announced oil peak moment. Tilton (1996) characterizes the debate in extremes of opposite paradigms but we observe a continuum of positions and many differences due to semantics, what rejects to qualify the differences as paradigmatic.

Oil production and consumption placed in a sources–sinks framework shows that the constraints at the sinks side are the most binding ones for controlling climate change. The insight is growing that we will (have to) leave many oil resources in the ground because the transition to highly efficient, renewable energy based energy economies is urgent. So a peak in oil production may actually be observed within the next decade, not because of oil reserves shortage but because of scarcity of atmospheric space for dumping carbon dioxide from oil winning and oil combustion. Peak-oil belief could stimulate a passive approach in climate policies by suggesting carbon dioxide emissions reduction can piggyback on dwindling oil production and consumption.

End-use prices of fossil fuels are important triggers in the transition to a low-carbon energy economy. When oil producers capture the rents of higher prices, they may use a significant part of it for a further lock-in and extension of non-sustainable energy options. A crucial component of successful climate change policies is recycling the major part of the rents for the transition to highly efficient, renewable energy economies.

[12] 'Market' is written between brackets because a significant share of the prices may consist of rents (royalties), what reveals a high impact of non-market forces.

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