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Oil and nuclear power: Past, present, and future☆

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Abstract

The relationship between oil and nuclear energy in the global energy scene over the past 50 years is analysed. The former nuclear–oil product competition in power generation and various end-use markets is found to have transformed into a complementary relationship. Current concerns associated with both energy sources and related technologies, including price volatility, supply security, geopolitical sensitivity, depletion alarms, and environmental pollution issues for oil, economic performance, operational safety, proliferation, terrorism, radioactive waste disposal, and the resulting public acceptance for nuclear are examined as determinants of their future roles in the world energy balance. An assessment of the long-term prospects for oil and nuclear energy is presented at the scale of a century to support further economic and energy policy analyses. It is the first in-depth study of global energy projections based on a comparative examination of long-term socio-economic scenarios and their coordinated quantifications by a set of integrated energy–economy models.

JEL classification: O13; Q42; Q56

Keywords: Oil; Nuclear energy; Long-term scenarios

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1. Introduction

The perceived importance and the actual role of oil and nuclear energy in the global energy scene have changed several times over the past 50 years due to various factors. The oil price shocks in the 1970s and 1980s, and the incidents at Three Mile Island and Chernobyl are some marked examples. Currently, there are several concerns associated with both energy sources and the related technologies. For oil, the list includes supply security, geopolitical sensitivity, price volatility, water pollution from off-shore installations and tanker accidents, soil contamination in processing plants, emissions of substances contributing to acid deposition (SO_x and NO_x) and to global climate change (CO_2), and the spectre of depletion. (See Holdren and Smith, 2000 for a discussion of energy–environment relationships.) The list of worries related to nuclear energy comprises economic performance, proliferation of dangerous material, the peril of terrorism, operation safety, radioactive waste disposal, and, as a result of all these, public acceptance. The resolution of these concerns will be a complex social process involving relatively clear-cut technical, technological, and economic factors as well as particularly contentious social and political choices. The outcome of this process will determine the roles oil and nuclear might play in the world energy balance in the long-term future. What are the main lessons we can derive from the past? What are the possible directions that might emerge from the current situation? What are the long-term prospects at the scale of a century?

This paper briefly surveys persistent trends and key turning points that have shaped the actual utilization of oil and nuclear energy in the past and the policies responding to those events (Section 2). This is followed by a concise assessment of the current situation and the main concerns about these energy sources in the early 21st century (Section 3). Looking into the future, long-term scenarios of the global economy, energy use, and environmental concerns developed by the Intergovernmental Panel on Climate Change (IPCC, 2000) are used to evaluate current expectations about their possible roles in the future under different patterns of social, economic, and technological development (Section 4). This is the first systematic in-depth comparison of the IPCC projections from the perspective of the oil–nuclear relationship at the century scale. The analysis provides some new insights about the differences in both the relative and absolute importance of these two energy sources across the IPCC scenarios and their model-based quantifications. The main findings are summarized in Section 5.

2. The past: from competitors to complements

Century-scale studies of the history of the global energy system show a rather persistent pattern of the rise and decline of different primary energy sources. The logistic substitution model of Marchetti and Nakicenovic (1979) captures in a simple, but insightful scheme the complex web of interactions among the driving forces (resource availability, technologies, delivery systems, and costs determining supply on the one hand, lifestyles, tastes, preferences, and income levels influencing demand on the other hand) that shape the energy sector. The emerging patterns of long-term dynamics suggest that the share of oil in the global primary energy supply peaked in the third quarter of the 20th century, approximately when, although not only because of, nuclear energy entered the scene (Nakicenovic, 1996). The persistent rise of oil through the first half of the past century gained additional momentum in the 1950s and 1960s from the post World War II reconstruction and sustained economic growth in OECD countries, the fast expansion of automotive transport, the petrochemical industry, space heating in the residential and commercial sectors, and power generation. In the past few decades, oil kept its overwhelming dominance in road and air transport and as feedstock in several industries, but was seriously challenged by natural gas in the markets of residential heating and industrial process heat, and at least partly by nuclear in power generation. The latter has lead many oil producers to consider nuclear power as a principal competitor to oil. A brief historical analysis reveals to what extent this perception is warranted and whether or not nuclear power has posed a threat to oil export markets.

In order to scrutinize a nuclear–oil product competition, one also has to understand in which markets such competition might take place. Competition between nuclear power and oil products may occur along two dimensions. The first one is the electricity generating market where the competition occurs directly between these and, of course, other fuels and generating options. The second dimension involves indirect competition and consists of the various end-use markets where electricity contends for market shares against oil products, natural gas, heat, etc.

2.1. Electricity generation

Starting with *electricity generation*, historical records of the early 1970s show that almost 25% of global electricity was then generated from oil (1973). Nuclear held a market share of some 3% while shares of other sources were as follows: coal 38%, hydro 21%, natural gas 12%, and non-hydro renewables 0.7%. By 2002 the global electricity supply structure had changed—especially for oil products and nuclear power. The oil share declined to 7.2% while nuclear expanded to 16.6%. Coal slightly increased its share to 39.0%, hydro dropped to 16.2%, natural gas 19.1%, and non-hydro renewables 1.9%. Of the 18 percentage points lost by oil, nuclear absorbed the lion's share of approximately 75%. No doubt, nuclear power made a major intrusion in the electricity market and that primarily at the cost of oil products. However, looking at absolute market data, the situation for oil is somewhat different. First of all, over the period 1973 to 2002, total electricity production increased from 6100 TWh to 16,074 TWh. At such electricity growth even a declining market share does not necessarily translate into declining absolute supplies. Indeed, oil sales to power generation of 1973 were close to those in 2002 at around 280 Mtoe (IEA, 2004).

Two reasons account for the relative decline of oil as a fuel for electricity generation. The first is technology change. When oil prices collapsed in 1986, oil could not regain lost market shares in the power sector. Rather, natural gas has become the fastest growing fuel for electricity generation. Here the advances in gas turbine and combined cycle technology (high efficiency, low capital costs, peak- and base-load capability, short construction time) supplemented by environmental policy targeted at reducing local air pollution and regional acidification tilted in favor of natural gas wherever its was available or could be made available at reasonable costs.

The second reason is government policy in many OECD countries prompted by the oil market politics of OPEC and the oil price hikes during the 1970s and early 1980s. Especially countries with limited domestic energy resources scrambled for oil substitutes that would ensure long-term protection against supply disruption and reduce energy import dependence. Krichene (2002) specifies a simultaneous demand and supply model for the world crude oil and natural gas markets to estimate the implications of the post-1973 changes in the market structure and finds that demand and supply for both commodities were highly price inelastic in the short run. However, because non-oil technologies and fuel chains were readily available to supply the same commodity, electricity generation was the sector where oil substitution was least cumbersome to accomplish. This has also contributed to the reduction of long-run demand elasticity. In other sectors, e.g., transportation, alternatives were essentially non-existing and the only short-term alternative was a reduction in energy services or behavioral changes.

As supply security became the primary concern in many oil importing countries after the oil crisis of 1973, nuclear has become a prime competitor to oil in electric power generation. Political pronouncements fostered this trend, like the one by USA President Ford in 1973 about the goal to reduce USA oil imports by one million barrels per day by the end of 1975 and to reduce the number of oil-fired generating plants by 1980. These political goals also triggered a large number of analyses to explore the implementation strategies. The primary candidate in the power sector was nuclear. For example, Hollomon et al. (1977) use energy analysis to establish optimal levels of oil displacement as a function of the expansion rates of nuclear power, considered on the order of 4–5 years of doubling time (that means the doubling of installed capacity in every 4–5 years). This expansion rate was not sustained for longer periods in any country.

Yet, energy policy favored nuclear power in many industrialized countries for its intrinsic benefits such as low fuel costs, low fuel and waste volumes, its vast resource base which is geographically more uniformly distributed than oil, the possibility to store fuel for extended periods, its high-tech appeal and potential for large-scale spin-offs. In addition, for countries like France, Sweden, Japan, Switzerland, Republic of Korea, Belgium or Germany, nuclear power offered technology diversification and supply security. Energy policy to move away from oil was also driven by the perception of a fast approaching end of the oil age (based on the assumption of prices being an indicator of resource scarcity) and the opinion prevailed that oil needs to be preserved for premium markets such as transportation and as a chemical feedstock and not be burnt in the bulk market electricity generation.

2.2. Indirect competition

The second dimension of the oil–nuclear competition is indirect: nuclear *electricity versus oil products* at the level of end-use. It involves many factors including economics, productivity, convenience, regulation, availability, product quality, and social preferences. These factors limit the room for competition between electricity and oil products (and vice versa) in the residential, commercial, industrial, feedstock and transportation markets. Here the characteristics of fuels and associated conversion technologies can be an advantage or disadvantage in meeting a particular energy service demand. As we have witnessed over recent decades, transportation services have remained the domain of oil products despite many government policies targeted at the introduction of non-oil based transportation fuels including electric cars. Likewise, many energy services are exclusively a domain of electricity (information/communication, lighting, control, etc.) where oil products are essentially excluded. Electricity is an end-use energy technology without any emissions, highly efficient, versatile, and convenient to use. No wonder then that it has been the fastest growing end-use energy carrier worldwide. Oil use outside the transportation and chemical sectors (feedstock) and non-energy use has declined in the residential, commercial, and industrial sectors of the OECD countries (1973: 707 Mtoe; 2002: 403 Mtoe) in large part as a result of increased use of electricity and natural gas. In developing countries, oil use in these sectors has been increasing from 124 Mtoe to 354 Mtoe over the 1973–2002 period (IEA, 2004). Globally, however, oil use in these sectors has declined from 960 Mtoe to 811 Mtoe over this period.

Another, to some extent related form of indirect linkage is the substitution by nuclear of other energy sources for electricity generation that can then be used to substitute oil in other market segments. In particular, nuclear may replace natural gas in power generation and this would then free natural gas that could replace oil in the transportation sector or heat market.

In as far as the indirect competition between nuclear electricity and oil products is concerned, it is useful to analyze the market share of electricity in total final energy as a function of nuclear electricity generation in different countries. In France, for example, nuclear accounts for 78% of electricity production while electricity holds a share of 20% of final energy. The corresponding indicator pairs for other countries are: Germany: 29%/18%; USA: 20%/19%; Japan: 27%/24%. In contrast, in countries with no nuclear power, the electricity share is 23% in Australia, 19% in Austria, 18% each in Italy and Denmark. In short, at a first glance there is little evidence that suggests a strong influence of the level of nuclear presence in electricity generation on the electricity market share in final energy and hence a significant indirect competition between nuclear power and oil.

In summary, since 1973 nuclear power expanded its market share in electricity generation essentially at the cost of oil. In absolute terms, however, oil sales to power generation did not decline—rather increased slightly. The decline in oil product use in the non-transport end-use sectors is hardly attributable to nuclear power. There are some exceptions and special cases like Sweden where nuclear-generated electricity replaced oil in residential heating and to some extent even in district heating. By and large, however, numerous factors have contributed to the relative decline of oil use in the OECD region with OPEC geopolitics and pricing being the largest ones.

3. The present: market positions and public concerns

The current relationship between nuclear power and oil has become distinctly different than it was a few decades ago. At the onset of the 21st century, nuclear and oil for electricity generation are targeting different electricity market segments with little overlap in the longer run. Oil for electricity generation in most industrialized countries serves, where not barred for environmental reasons, more the function of the disposal of residual oil for which no other applications can be found. However, advanced refineries converting larger portions of the barrel into premium products and stringent environmental regulation constrain the use of residual oil for power generation. Other uses of oil products include peak supply, back-up fuel, and dispersed non-grid generation. These markets have been relative captive for oil but this may change in the future with the advent of fuel cells. Since nuclear power has no role to play in these captive markets, growth prospects for oil are unaffected by a nuclear presence in the electricity generating market.

Diesel generation is often the only dependable electricity supply route in remote, not grid connected areas—hence out of reach for nuclear power (at least for present nuclear technology). Remote markets in industrialized countries, however, are often associated with pristine natural environments where the current tendency is to deploy renewable forms of electricity supply. Remote electricity markets are unlikely to grow in the OECD countries as grid-connected electrification has already reached more than 95% area coverage.

This is certainly not the case in developing countries where almost 2 billion people mostly in rural areas have no access to electricity. Two reasons account for this: the lack of electricity generation, transmission, and distribution infrastructures and the low level of affordability. In addition, grids are often small and fragile thus unsuitable to accommodate nuclear power. Therefore, oil remains an ideal fuel for distributed power generation. Economics (fuel prices), reliability, and convenience are decisive factors whether or not oil can be challenged by renewables in these markets—not by nuclear power. Kolhe et al. (2002) analyze the economic viability of stand-alone solar photovoltaic systems relative to diesel generation by using a life-cycle cost computation under conditions prevailing in India. They find that, depending on the performance of the solar photovoltaic system, it provides the lowest cost option up to 15 kW h daily energy demand under unfavorable economic conditions, but this threshold increases to 68 kW h/day demand in favorable circumstances.

Issues concerning energy demand, supply, technologies, resource base, security, prices, and the implications of all these for economic development have been high on the social agenda for decades. In recent years, however, we witness a new wave of debate about the appropriate sources of energy supply, about the socially optimal level and forms of energy sector deregulation and liberalization, with the additional dilemmas of privatization in developing countries and economies in transition, about the suitable responses of the energy sector to environmental problems like acid rain and climate change, about the dilemmas of getting prices reflect the full social costs of energy commodities (see, for example, Krewitt, 2002), simultaneously with concerns about availability and affordability of energy services for the poorest social groups as part of the sustainable energy development strategy.

Let us look at the new components of this complex debate that are most relevant concerning the current dilemmas surrounding oil and nuclear energy and the directions of possible resolution with implications for the future. Oil certainly has had more than its fair share in the depletion debate of non-renewable resources. Irrespective of the insights provided by natural resource and energy economics and the dynamics of technological change, some analysts had from time to time pointed to the risk of the imminent exhaustion of the last oil well. A recent example is the work of the Association for the Study of Peak Oil and Gas (ASPO). The group estimates global oil production to peak in 2008 and proposes an international accord (The Uppsala Protocol) to prevent major economic and supply disruptions in the transition to a post-oil world (ASPO, 2004). While it is clear that a finite resource will ultimately be phased out from the global energy balance, both the quantity and the timing aspects of the phase-out are highly uncertain; see, for example, Odell (2004) This uncertainty will also be illustrated by a set of scenarios in the next section. The second critically discussed topic currently is supply (in)security. The high degree of concentration of supply sources in a geopolitical region with a mixed record of political stability in recent years (or even decades) clearly involves risks in terms of the reliability of supply. However, preserving the security of supply is also in the best interest of the countries in this supply region. If hedging costs or damages from supply disruptions exceed certain thresholds, this may well trigger policy and technological responses in the main consuming regions that might undermine the medium and especially long-term market prospects. Another problem often mentioned in the current energy debates is the price volatility of oil. Several instruments have been invented and introduced to manage this problem. They range from longer-term delivery contracts to various financial instruments to provide hedging against unexpected spikes in crude oil prices.

Nuclear power is totally unaffected by these concerns. Uranium resources are abundant and spread in several world regions (see Rogner, 2000), a nuclear power plant can easily store several years worth of fuel stock in a backroom, uranium ore accounts for only 2–3% of nuclear generating costs (fuel can reach 0.6 USc/kW h), prices of nuclear fuel have been stable at a low level over a long period. The worries about nuclear energy are of totally different nature.

Although nuclear power dominates electricity generation in several countries, the prospects of nuclear power are clouded by the ongoing controversy about its economic necessity, operating safety, waste disposal, and proliferation risk. Moreover, in Western Europe and North America, a combination of slow economic growth, over-capacity in the generating industry, and market deregulation has resulted in very limited amount of large capacity base-load construction of any kind in recent years. This may well change over the next two decades when a sizable share of current fossil and nuclear base-load capacities will approach retirement age. Although there is much talk about dispersed generation based on gas-fueled turbines, renewables, or even fuel cell arrangements, there will remain a large demand for base-load capacity. Nuclear is certainly a mature, readily deployable option for meeting base-load electricity demand. A large number of analyses of current and expected future worries about economic and environmental issues in energy supply conclude that nuclear energy needs to remain a significant part of the global energy portfolio (Rhodes and Beller, 2000; Sailor et al., 2000; Radetzki, 2000; Rothwell, 2000, 2004). An increasing number of studies conclude that nuclear energy should be an important part of the strategies towards sustainable energy development (Haldi et al., 2002; Zink, 2002) although some analysts maintain that it does not fulfill all essential requirements for creating sustainable energy paths (Brugging and van der Zwaan, 2002).

Nevertheless, based on short-term economics of capital investment costs and projected fuel costs alone, most of the additional electricity production in OECD countries is likely to be fueled by coal and natural gas (and renewables where legislated by law or heavily subsidized). Indeed, coal and natural gas are plentiful in the OECD region and the considerably lower capital costs (and associated amortization periods) of fossil fuel conversion appeal to capital-strapped utilities and financing institutions alike. Although nuclear power in many instances can supply base-load electricity at life-cycle costs comparable to, or cheaper than, those of coal-fired power generation, its longer amortization horizon and higher up-front capital cost appear to be barriers to its large-scale deployment.

Since the 1990s the emphasis of nuclear construction has shifted towards Asia and developing countries. New nuclear power plants are most attractive where energy demand growth is rapid, alternative resources are scarce, energy supply security is a priority, or nuclear power is important for reducing air pollution and greenhouse gas (GHG) emissions. One or more of these features characterize China, India, Japan, and the Republic of Korea, where most current construction is taking place.

Nevertheless, despite slow but continuing capacity growth worldwide, growth in nuclear electricity *generation* has been greater than growth in *capacity*, as better management enforced by the pressure of competition has steadily increased the average availability of nuclear plants to the equivalent of 30 GWe additional nuclear capacity without any construction. Today, the bulk of the existing nuclear power fleet is among the lowest cost electricity generators.

Despite the excellent safety records over the past 18 years, operational safety remains a widespread public concern in many countries. Shutting down reactors occasionally due to security concerns demonstrates the implementation of high and ever-increasing safety standards: operators shut down and check the plant whenever the slightest suspicion of a malfunction arises.

There has been no credible documentation of health effects associated with routine operation of commercial nuclear facilities anywhere in the world. Widely accepted studies demonstrate no correlation between cancer deaths and plant operations. Yet attribution of certain morbidity anomalies remains widely debated. Guizard et al. (2001) and Dickinson and Parker (2002) investigate childhood leukaemia in two regions and find statistically discernable relationships between location and ancestry and leukaemia occurrence, although it is difficult to control for historical heritage of radioactive material, like the residues of phosphate production at Sellafield during World War II. Other studies report lower probabilities of death from cancer or non-cancer diseases for the USA nuclear power workers than the general population (Howe et al., 2004). Nonetheless, safety remains a key issue. What the public is not aware of are the permanent improvements of operational safety standards and solutions for power plants currently in service. The Three Mile Island accident in 1979, even though it did not spread any radioactivity into the environment, triggered extensive safety reviews, thus strengthening nuclear safety in the Western world. The Chernobyl accident in 1986, instigated by peculiar causes under peculiar circumstances, similarly led to reviews and new safety measures and upgrades in the Former Soviet Union and Eastern Europe. The results of these measures are demonstrated by the improved production figures of nuclear power plants around the world. These indicators show lower doses to their personnel and fewer unplanned stoppages in currently operating nuclear plants.

Nonetheless, those disastrous events still overcast the fact that by now the world has the experience of some 11,000 reactor-years of operation without any other major incidents. With time, however, objections to the use of nuclear power on the grounds of operating safety may gradually be answered by positive experience. Especially because safety is a dynamic concept. The new reactor designs feature drastically improved safety characteristics, including inherently safe technologies (see Williams, 2000). These advanced reactors have new security features and can be expected to have even better records on reliability and safety than the current dominant reactor types.

The second aspect of public concern about nuclear power generation is the storage of spent fuel and other radioactive wastes, especially those with long half-times. Material science, geological research, and other disciplines have made significant progress recently and seem to lead to generally acceptable solutions to the problem. In this context, it is interesting to compare the waste production from different generation technologies. A 1000 MWe nuclear power plant produces annually some 30 tons of high-level radioactive spent fuel and 800 tons of low- and intermediate-level radioactive waste. Significant reductions in the volume of low-level waste can be made through compaction. In contrast, a 1000 MWe coal fired power plant generates annually some 320,000 tonnes of ash containing about 400 tons of heavy metals and radioactive material from combustion alone without considering energy chain activities such as mining and transportation. Oil scores somewhat better. An oil-based power plant of the same capacity would produce a relatively small amount of ash (about 20 thousand tons a year), but, depending on the grade, about 230–250 thousand tons of waste from flue gas desulfurization. Although it is not adequate to directly compare volumes of very different materials and of different hazard categories, the 3 to 4 orders of magnitude differences are remarkable.

A related issue is gaseous wastes, i.e., atmospheric emissions. Along the full source-to-electricity chain including indirect emissions, nuclear power generates two orders of magnitude less CO_2 and virtually no air pollutants responsible for local and regional environmental degradation. Thereby, it currently helps avoid some 8% of CO_2 emissions (some 0.6 GtC) globally each year. A significant potential environmental impact could arise from abnormal events, the probability of which is extremely small in modern nuclear power plants.

Finally, perhaps the most sensitive issue in the early years of the 21st century is nuclear proliferation and the related concern of nuclear terrorism. Events in recent years have revealed loopholes in the current international agreements and their enforcement mechanisms and make it obvious that the major challenge nuclear energy is facing today is to provide an impermeable solution for managing the nuclear fuel cycle in order to prevent proliferation and to eliminate the risk of misusing nuclear material. An increasing number of scientific, technological, institutional, and political studies search for and propose possible strategies to manage these risks. Recent examples include Smith (2003), Zarimpas (2003), Beck (2003) on proliferation, Cameron (1999) and Byrnes et al. (2003) on terrorism, and Mueller (2003) as well as Allison (2004a,b) on both issues. It is difficult to make predictions at this point but it seems to be likely that the solution will need to combine institutional (additional international agreements on monitoring and accounting for nuclear material through the entire fuel cycle) and technical (reactor and fuel cycle technologies drastically reducing or totally eliminating the presence of weapon-grade material) elements.

The resolution over the next few years of these and other related dilemmas for oil and nuclear energy will determine which long-term trajectory they will embark and what will be their contribution to satisfying the unprecedented hunger of the global society for affordable, safe, clean, reliable, and convenient energy services.

4. The future: opportunities and uncertainties

In its Special Report on Emissions Scenarios (SRES), the Intergovernmental Panel on Climate Change (IPCC, 2000) presents a set of hundred-year futures of the world with the main objective of providing a collection of greenhouse gas emission paths. These emission paths emerge from widely diverging but plausible stories of socioeconomic development through the end of the 21st century. Although greenhouse gas emissions are not the subject of the present paper, the IPCC scenarios offer a useful framework to look at long-term energy futures and information concerning the projected role of oil and nuclear energy. The scenarios are based on thorough analyses of plausible paths of socioeconomic development with special attention devoted to demographic, economic, and technological trends. The implications of these trends are traced for energy demand, supply systems, and the resulting resource use and pollutant emissions by a series of global models.

The main directions of plausible socioeconomic development are clustered into four scenario families resulting from combinations of two axes. The first axis distinguishes possible futures according to whether societies will devote more attention to economic or environmental assets (A* versus B* scenarios). The second axis differentiates future trends on the basis of whether the tendency of increasing globalization persists or there will be more heterogenicity and regional seclusion (*1 versus *2 scenarios). The resulting four storylines can be summarized as follows.

The future of the A1 storyline involves low population growth and fast economic growth, partly driven by fast rates of technological development and the quick introduction of new and more efficient technologies. The increasing interconnectedness of the global economy brings along convergence among regions in terms of per capita incomes, partly due to capacity building and increasing social and cultural interactions. Societies and their values under the A2 storyline also emphasize economic welfare but they try to achieve it in a rather heterogeneous world. There is more emphasis on the preservation of local self-identities and economic self-reliance. The rate of population growth remains relatively high because fertility rates decline very slowly in some regions. An important implication is that in the A2 world the achievements in economic development differ across the regions and growth rates are somewhat slower in global aggregate than in the A1 scenario.

The tendency of globalization continues in the B1 storyline but with an increasing importance of the service and information sectors of the economy that leads to quick reductions in material intensity and fast establishment and diffusion of clean and resource-efficient technologies. This “greening” of the global economy takes place in the broader context of transition to sustainability, to global solutions to the economic, social, and environmental challenges albeit without climate protection measures. The future depicted by the B2 storyline is pursuing the sustainability transition by local initiatives and solutions. Although there is a slow-down in population growth, the regionally diverse and on average slower technological development permits only modest rates of economic development. The environmental and social aspects of sustainability are also addressed at the regional or local levels. It should be noted that additional variations are superimposed on these storylines to depict possible variants within the same world future in terms of energy sources, technologies, and emissions.

These four storylines are quantified in terms of their main driving forces and are used as input to six global models to assess how the future might unfold at the century scale. Our discussion draws on results of all six models. They are: the Asia Pacific Integrated Model (AIM; Morita et al., 1994), the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE; Messner and Strubegger, 1995), the Mini Climate Assessment Model (MiniCAM; Edmonds et al., 1996), the Atmospheric Stabilization Framework Model (ASF; Lashof and Tirpak, 1990), the Integrated Model to Assess the Greenhouse Effect (IMAGE; Alcamo et al., 1998), and the Multiregional Approach for Resource and Industry Allocation Model (MARIA; Mori and Takahashi, 1999). The six models differ greatly in terms of their conceptual frameworks, methodologies, regional and sectoral resolutions of the world economy, the technological details in their representation of the energy system, and others. (Short summaries of the six models that were used in the development of the SRES scenarios are presented in Appendix IV of IPCC, 2000.) While the diversity of models helps to explore the widest range of plausible greenhouse-gas emissions in the future (a declared objective of IPCC SRES), it makes the comparison of the model results somewhat difficult.

We note that the future role of oil (as well as of gas and coal) in global energy supplies depends on several factors ranging from assumptions on available resource quantities, extraction costs, technological change, demand, energy and environmental policy and potential substitutes. Among all these factors, assumptions on resource availability and technology change are most important in any long-term energy supply analysis. As so often, confusion arises from unclear definitions, boundaries of different resource definitions, and classifications along the dimensions of geological assurance and technical recoverability.

Hence, it is worth reviewing the basic resource classifications. “Occurrences”, the most encompassing category, comprise geological deposits regardless of concentration, accessibility or detailed knowledge of their geographical location. “Resources” are those occurrences that are technologically recoverable, though perhaps not at current prices, with a certain level of assurance of their location. “Reserves” are a flexible portion of resources, defined–at any given time–as those resources that can be profitably produced with current technology and at current prices, and precise knowledge of their deposits. Clearly, as technology improves and prices change, the portion of resources or occurrences that qualify as reserves will also change. Historically, such changes have tended to expand the reserve base.

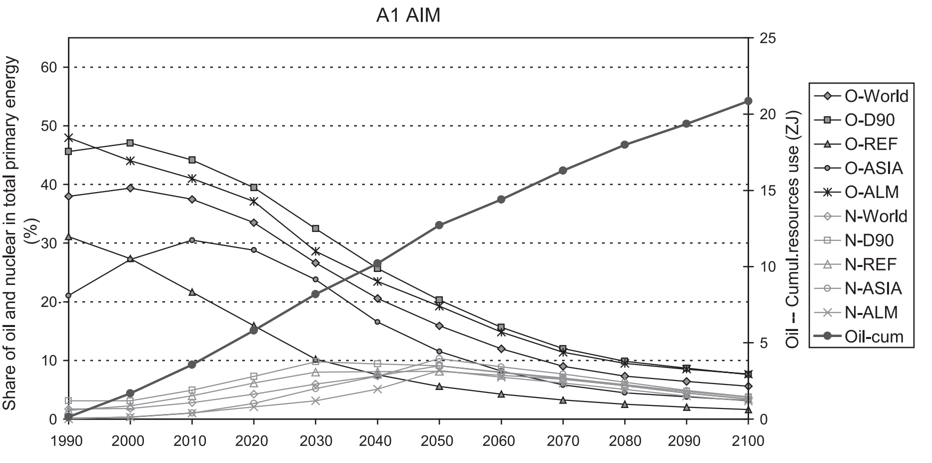
In the oil industry, for example, proved oil reserves are defined as “generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions” (BP, 2003). Thus, reserves can increase with exploration (new or better information), with engineering advances (better economic and operating conditions) and with higher prices (better economic conditions). Reserves can also be depleted through production and can decrease with lower prices. In the past, advances in geosciences, exploration and production technology have repeatedly invalidated previous estimates of oil reserves, i.e., by improving recovery rates from existing reservoirs and enabling the profitable development of fields that were previously regarded as uneconomic or technically beyond reach (expanding the boundary of reserves, and shifting resources into the reserves category). The shift to the production of previously inaccessible resources may even become more important in the context of unconventional oil occurrences. This is to say that the ongoing debate about oil reserves and resources focuses only on "conventional" oil, i.e., oil occurrences characterized by a certain minimum viscosity and density more than 20° API.

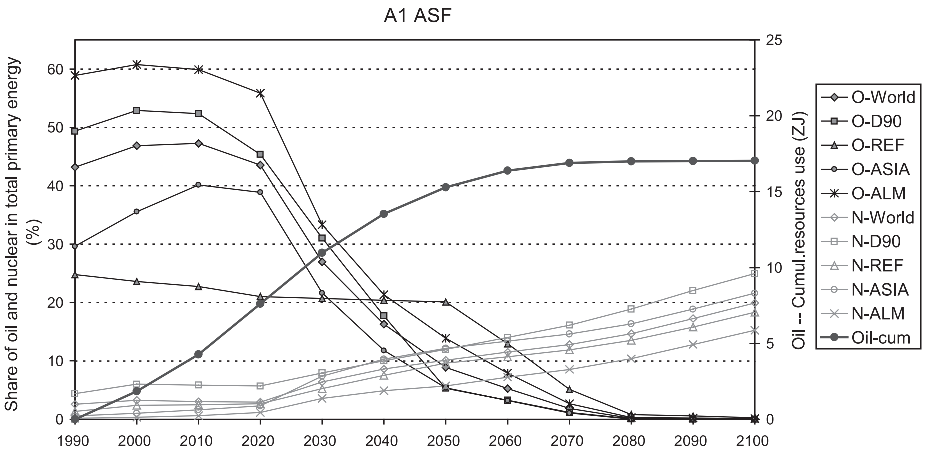
Oil shales, natural bitumen, tar sands, and heavy crude oil are together called unconventional oil resources, which have been defined as occurrences that cannot be tapped with conventional production methods for technical or economic reasons or both (Rogner, 1997). These resources form a large part of the vast store of hydrocarbons in the earth's crust, and have been the focus of interest for unconventional energy resource analysts. New technologies have been developed to extract some of these resources economically, and production has started in countries like Canada and Venezuela. The extent to which these unconventional occurrences, which exceed conventional oil several fold, might be defined as reserves in the future will depend on the continued development of technologies to extract them at acceptable economic and environmental costs (WEA, 2000). Hence, the role of oil in the scenarios discussed below depends to a large extent on the model- and scenario-specific assumptions about technology change in the oil exploration and up-stream sectors and the resulting quantities of oil availability.

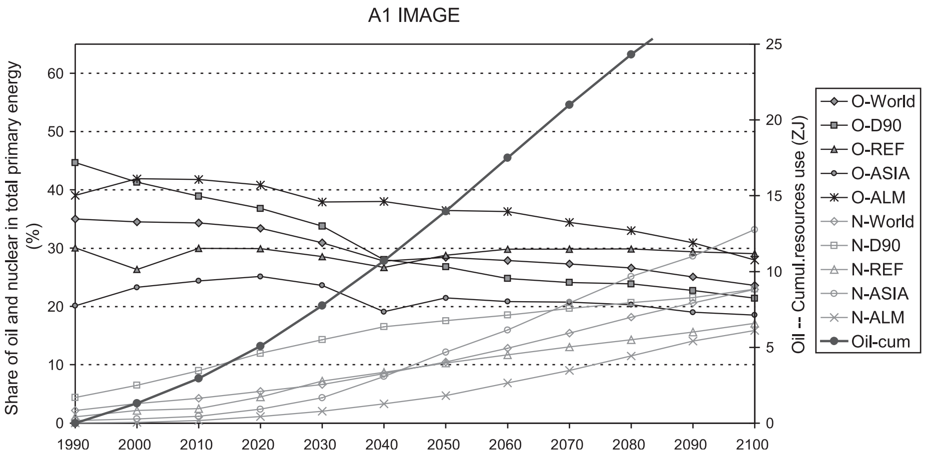
What do these scenarios tell us about the future role of oil and nuclear energy in the global energy system? We take the four storylines in turn and review the model results by following the same pattern: first we give a concise characterization of the economic development, energy efficiency improvement, and the electrification of final energy and then focus on their projections for the two energy sources of our interest here. We keep the textual summaries short and encourage the reader to study the figures for other interesting outcomes.

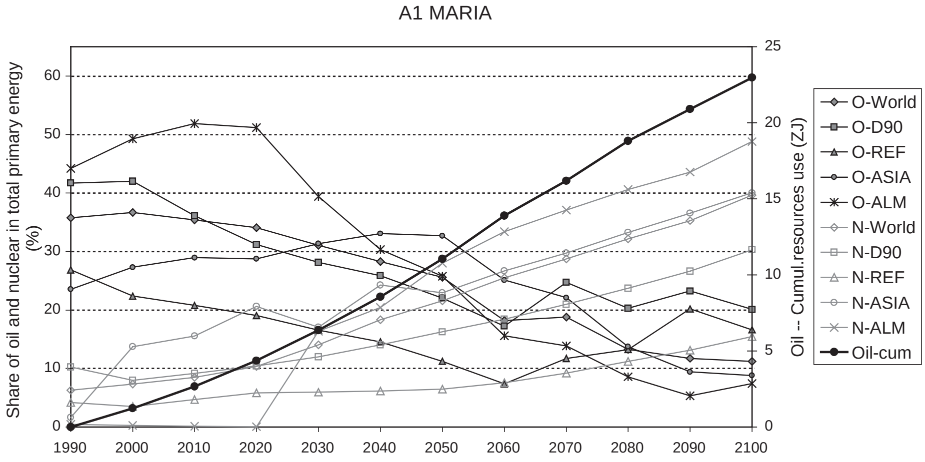
In the *globalizing, economic welfare-oriented world of A1*, incomes grow exponentially through the end of the 21st century. (In order to demonstrate the flexibility of the development of the energy system, several variants were developed under the A1 storyline. Our discussion here is based on the A1B scenarios depicting a balanced development of energy resources and technologies.) Per capita GDP reaches 60,000 dollars even in the least affluent regions of Africa and Latin America and exceed 110,000 dollars in the OECD90 region. This phenomenal economic growth is coupled with a persistent increase in energy efficiency: total primary energy per GDP falls to around 5 MJ/USD (Megajoule/US dollar) or below by the end of the century. The share of electricity in total final energy is also increasing. CO_2 emissions from fossil fuel use culminate at the level of about 18 GtC/year (IMAGE and MESSAGE) and 16 GtC/year (AIM) between 2050 and 2070 and then decline below 14 GtC by 2100.

This relatively uniform depiction of the 21st century turns into sometimes astonishing differences when we look into the details of energy use (see Fig. 1). *Oil* maintains a share in total primary energy between 18% and 30% in different world regions and about 25% in the world energy balance according to the results of the IMAGE model, drops to 20% or below according to the MARIA model and falls below 10% according to the MESSAGE and AIM models. The cumulative global oil use reaches 30 ZJ by 2100 in the IMAGE model, 25 ZJ in MESSAGE, and somewhat above 20 ZJ in the AIM and MARIA models. Meanwhile, the less than 5% share of *nuclear energy* in total primary energy at the


A1 AIM
Share of oil and nuclear in total primary energy (%)
Oil -- Cumul.resources use (ZJ)
O-World
O-D90
O-REF
O-ASIA
O-ALM
N-World
N-D90
N-REF
N-ASIA
N-ALM
Oil-cum


A1 ASF
Share of oil and nuclear in total primary energy (%)
Oil -- Cumul.resources use (ZJ)
O-World
O-D90
O-REF
O-ASIA
O-ALM
N-World
N-D90
N-REF
N-ASIA
N-ALM
Oil-cum


A1 IMAGE
Share of oil and nuclear in total primary energy (%)
Oil -- Cumul.resources use (ZJ)
O-World
O-D90
O-REF
O-ASIA
O-ALM
N-World
N-D90
N-REF
N-ASIA
N-ALM
Oil-cum



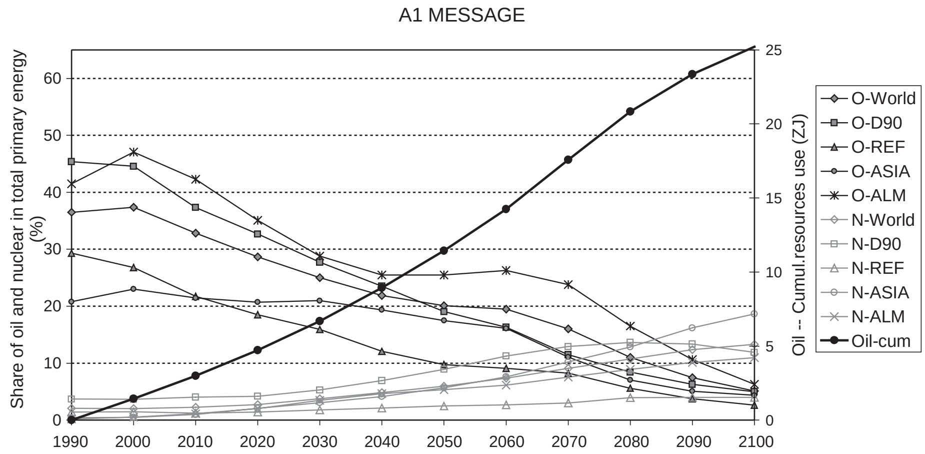


Fig. 1. Shares of oil and nuclear power in the total primary energy supply and cumulative oil consumption according to five models under the SRES A1 scenario. Source: after IPCC (2000). Notes: *Notation*: O* = oil, N* = nuclear, D90 = OECD1990, REF = reforming economies of eastern Europe and the former Soviet Union, ASIA = Asia, ALM = Africa and Latin America, Oil cum = cumulative global oil consumption, *Models*: AIM = Asia Pacific Integrated Model, ASF = Atmospheric Stabilization Framework Model, IMAGE = Integrated Model to Assess the Greenhouse Effect, MARIA = Multiregional Approach for Resource and Industry Allocation Model, MESSAGE = Model for Energy Supply Strategy Alternatives and their General Environmental Impact.

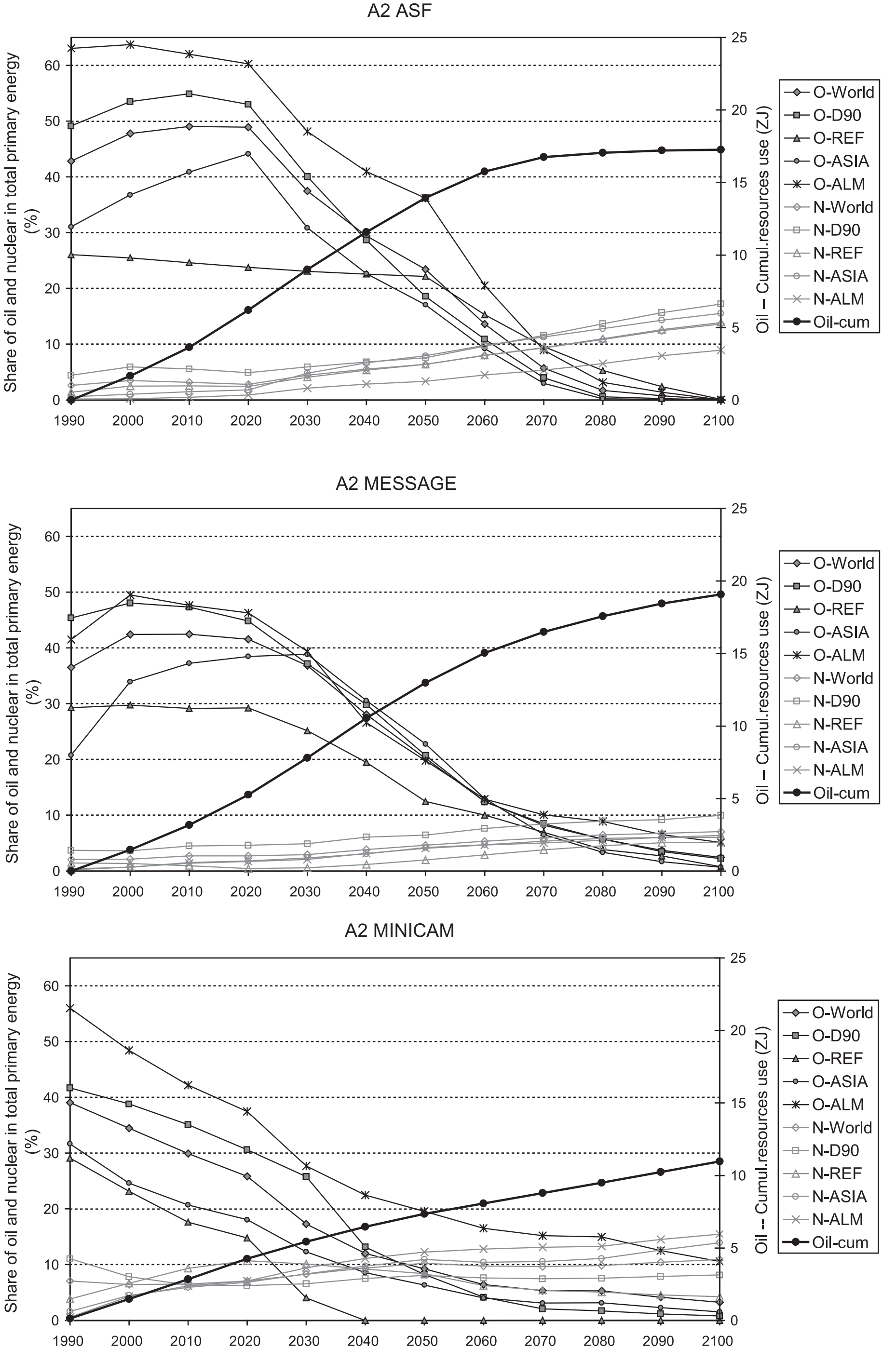
beginning of the century increases to between 15% and 35% in different regions, and to 22% worldwide in the IMAGE model, to the range of 15% to almost 50% in different regions, and to 40% globally according to the MARIA model (Fig. 1). In contrast, the nuclear shares are more modest in the MESSAGE model reaching between 5% and 18% in the regions, 13% in the global primary energy use.

The regional increases in per capita GDP are rather modest in the equally *economic welfare-oriented but more fragmented world of the A2 scenario*. With the exception of the OECD90 region (close to 60,000 USD per capita annual GDP in 2100), per capita incomes remain well below the 10,000 USD level even in the middle of the century. Energy efficiency increases steadily in all regions and the energy intensity of GDP declines below 15 MJ/USD by 2100 everywhere. The spread of electrification differs across the models also in this scenario. The share of electricity in the total final energy reaches 15% to 70%, depending on the region, in the MiniCAM model, but remains far below in the MESSAGE results (30% to 50%) and even lower in the ASF model (between 25% and 38%). The modest rate of economic development, together with the underlying slower rate of technological change and longer capital renewal cycles, leads to high levels and steadily increasing CO_2 emissions from fossil use. Global CO_2 emissions approach 30 GtC annually by the year 2100.

The *contribution of oil* to the world's primary energy supply reveals three distinctively different paths under the three selected models (Fig. 2). The share of oil in total primary energy remains high in most world regions according to the MESSAGE model (40% of the total global primary energy supply) but this is followed by a fast decline and the share of oil dips below 5% in the energy balances of all regions by the end of the century. The decline of oil's share starts earlier according to the ASF model, drops below 10% in all world regions by 2070. In contrast, in the depiction of the MiniCAM model oil's share declines fast from the beginning of this century, but provides a notable contribution even in later decades. The cumulative global oil consumption differs widely across the models as well. It reaches only about 11 ZJ according to MiniCAM, over 17 ZJ under ASF and about 19 ZJ in the MESSAGE model. The *contribution of nuclear energy* to the global primary energy balance also varies in the three models (Fig. 2). It increases to between 5% and 10% in the second half of the century according to MESSAGE. The MiniCAM model shows an increase in the first half of the century in the reforming economies of the former Soviet Union and Eastern Europe, but a decline in the second half, while nuclear remains stable at about 8% in the primary energy supply of the OECD90 region. Only Asia and the Africa–Latin America region show steady albeit modest rates of increase in the share of nuclear energy to around 15% by 2100. The ASF model, in contrast, shows a permanent increase of the nuclear share in all regions through the whole century to levels between 9% and 18% across the world regions.

In the *globalizing but more environmentally oriented B1 scenario*, per capita incomes grow exponentially in all world regions but at a slower rate than in the A1 world. There is also more diversity in the income paths across the models under this scenario compared to the two others evaluated above. Energy efficiency improvements are fast throughout the century and converge to values below 5 MJ/USD GDP energy intensities in all regions by 2080. The models are also similar in predicting steady increases in the share of electricity in total final energy in all regions to reach levels of about 38% to 58% depending on the region. However, there is a surprising diversity of carbon emission paths across the models under this scenario.

According to the MiniCAM model, the *share of oil* in the total primary energy supply decreases over the next few decades but remains stable after 2040 in all world regions between 15% and 32% (Fig. 3). The IMAGE model is similarly optimistic about the contribution of oil to the total primary energy balance but the MESSAGE model computes steadily declining shares of oil in all world regions, except Asia, from 2000 on down to levels between 5% and 8% by 2100. The cumulative resource use of oil between 1990 and 2100


A2 ASF
Share of oil and nuclear in total primary energy (%)
Oil -- Cumul.resources use (ZJ)
O-World
O-D90
O-REF
O-ASIA
O-ALM
N-World
N-D90
N-REF
N-ASIA
N-ALM
Oil-cum
A2 MESSAGE
A2 MINICAM
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100

stays in a remarkably small range: between 16 ZJ (MiniCAM) and 20 ZJ (IMAGE) but the dynamics are markedly different in the models. Regional *shares of nuclear* energy under this scenario show marginal increases in AIM to between 5% and 8% in world regions by 2100, modest increases in MESSAGE (to 8–13%), and significant increases, especially in the second half of the century, in MARIA to levels of 20–28% around 2100 (Fig. 3).

The *combination of regionalism and environmental orientation* leads to a world *in the B2 scenario* with more unequal income distribution across the regions than in any other scenario. While GDP per capita in the OECD90 region increases to about 60,000 dollars, the African–Latin American region remains below 15,000 USD per capita even hundred years from now. Although the rates of energy efficiency improvement are modest, the amount of total primary energy per unit of GDP gets below 5 MJ/USD by 2100 in all regions. Here again, there is a large degree of divergence in the share of electricity in total final energy across the models. While the electricity shares reach 40% to 50% in all regions in the MESSAGE model, it stays below 25% even in the OECD90 region and below the 15% mark in the reforming economies and Asia according to the MARIA model. CO_2 emissions from fossil fuel use increase uniformly in all models to above 14 GtC.

The *share of oil* in total primary energy declines also under this scenario through the whole century in AIM and MESSAGE but shows a somewhat surprising revival in the last two decades in the MARIA model (Fig. 4). AIM and MESSAGE are similar in their expectations concerning the *role of nuclear energy* (Fig. 4). Following a very modest growth through the whole century, the share of nuclear is between 5% and 8% in 2100 according to AIM and between 8% and 12% in MESSAGE. The MARIA model indicates a fast growth of nuclear energy share after 2040, reaching shares between 20% and 25% in the primary energy supply in all regions by 2100.

What are the main conclusions we can draw from this diverse mosaic of scenarios and models? All models under all scenarios show *persistent declining trends in the share of oil* in total primary energy use in this century with two exceptions. The first is the MiniCAM model under the B1 scenario according to which the decline in oil shares during the first four decades fades away and oil remains a significant constituent of the energy portfolio with shares between 12% and 30% in regional primary energy balances in 2050 and even slightly increasing thereafter. A somewhat similar revival of the share of oil can be observed in the MARIA model under the B2 scenario, but much later in the century (around 2080) and at a much lower level (around 15%). Yet there is considerable degree of variety behind this general pattern. Oil seems to face the bleakest future in the economically oriented but regionally fragmented world of the A2 scenario: all three models (MiniCAM, MESSAGE, ASF) indicate a phase-out to shares in the total primary energy use below 5% by 2100. The models are divided in their depictions of the globalization scenarios. MARIA and IMAGE project significant shares of oil in regional energy balances between 10% and 30% under the A1 scenario, and similarly do MiniCAM and IMAGE (15–30%) in the B1 scenario. In

Fig. 2. Shares of oil and nuclear power in the total primary energy supply and cumulative oil consumption according to three models under the SRES A2 Scenario. Source: after IPCC (2000). Notes: *Notation*: O* = oil, N* = nuclear, D90 = OECD1990, REF = reforming economies of eastern Europe and the former Soviet Union, ASIA = Asia, ALM = Africa and Latin America, Oil cum = cumulative global oil consumption, *Models*: ASF = Atmospheric Stabilization Framework Model, MESSAGE = Model for Energy Supply Strategy Alternatives and their General Environmental Impact, MiniCAM = Mini Climate Assessment Model.

contrast, under the same patterns of socioeconomic development, the share of oil is expected to decline well below 10% by both MESSAGE and AIM (A1 scenario) and MESSAGE and ASF (B1 scenario).

There is even more *diversity across storylines and models in the projections of the* potential *role of nuclear energy* in this century. The most homogenous expectations are associated with the A2 scenario: the share of nuclear is expected to be in the range of 5–18% in all regions according to the three models investigated. The regionally fragmented and environmentally oriented B2 scenario involves modest but slowly increasing nuclear shares

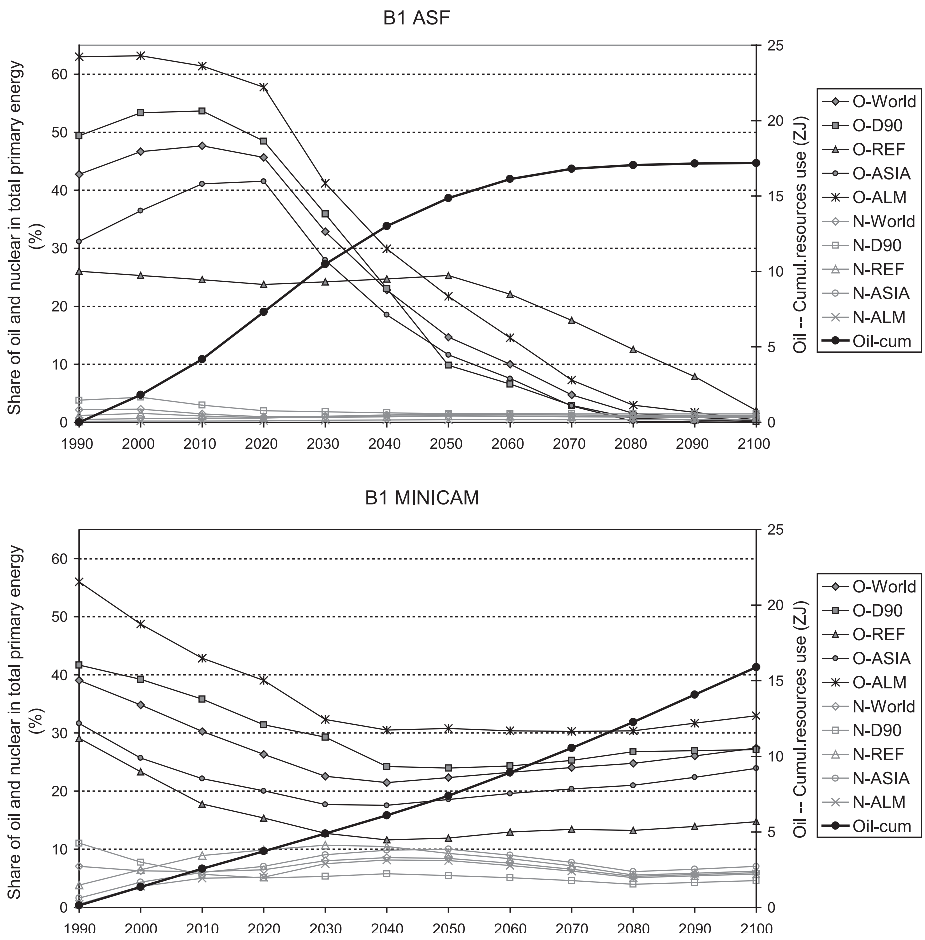
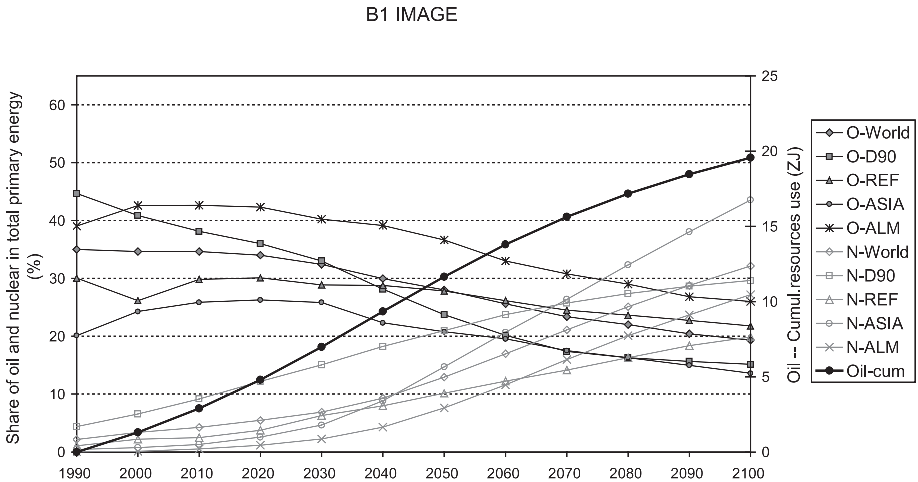


Fig. 3. Shares of oil and nuclear power in the total primary energy supply and cumulative oil consumption according to four models under the SRES B1 scenario. Source: after IPCC (2000). Notes: *Notation*: O* = oil, N* = nuclear, D90 = OECD1990, REF = reforming economies of eastern Europe and the former Soviet Union, ASIA = Asia, ALM = Africa and Latin America, Oil cum = cumulative global oil consumption, *Models*: ASF = Atmospheric Stabilization Framework Model, MiniCAM = Mini Climate Assessment Model, IMAGE = Integrated Model to Assess the Greenhouse Effect, MESSAGE = Model for Energy Supply Strategy Alternatives and their General Environmental Impact.



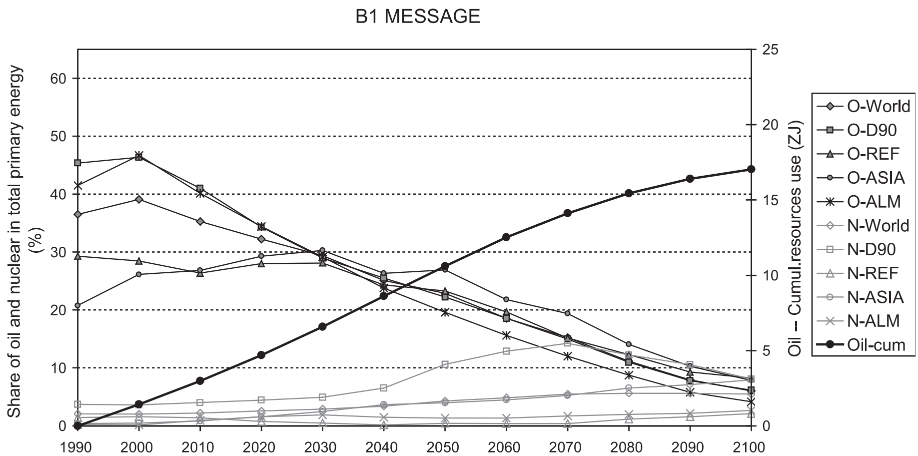
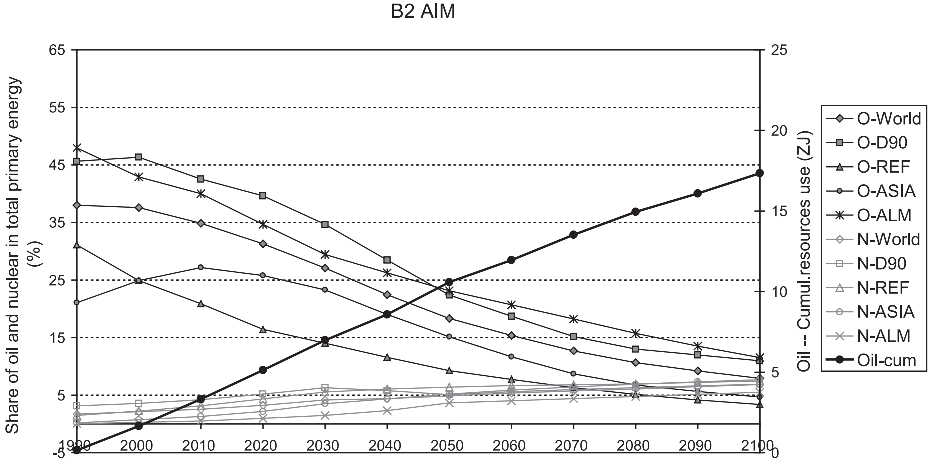
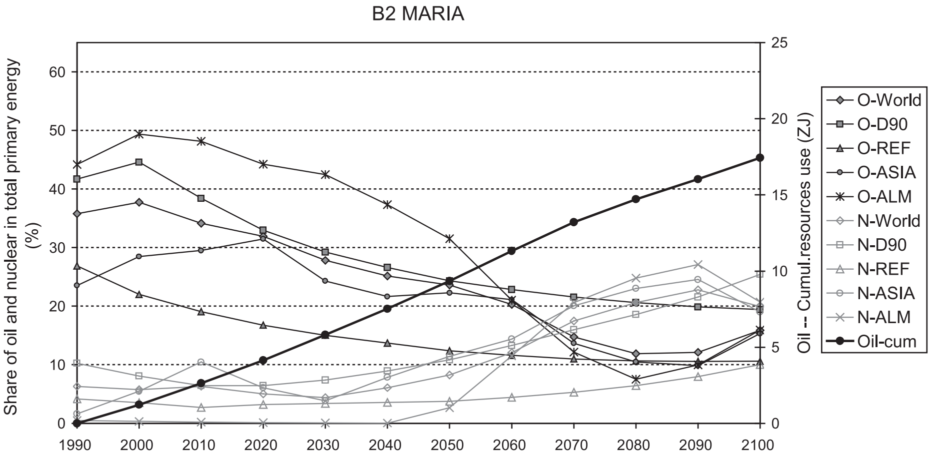


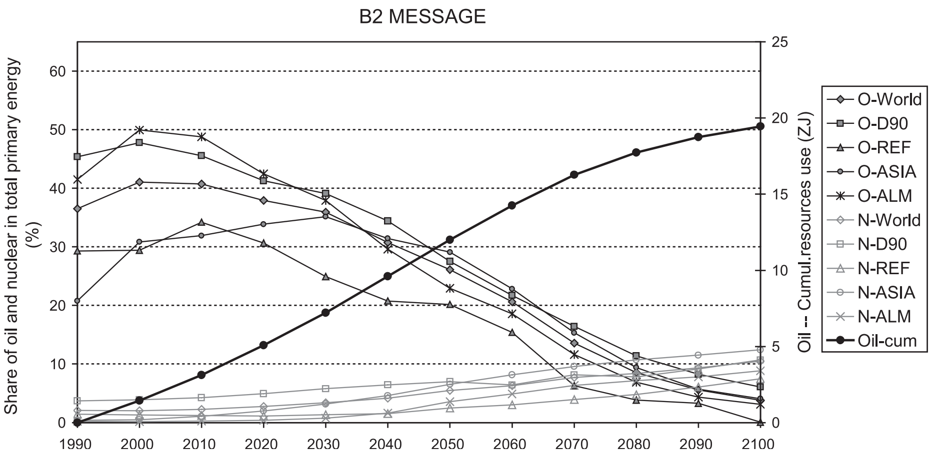
Fig. 3 (*continued*).

reaching about 5% (AIM), 10% (MESSAGE), and 20% (MARIA) by 2100. The largest spread of model results concerning the role of nuclear energy can be observed under the economically oriented globalization scenario of A1: the regional shares of nuclear energy never reach 10% according to AIM, stabilize between 8% and 18% in MESSAGE, climb to 18–33% in IMAGE, and surge to the range of 15% to 50% in the MARIA model.

It is important to point out that some *model rigidities* can be observed as well. Under the markedly different scenarios of A2 and B1, for example, ASF projects the same pattern of oil phase-out for all regions with the same cumulative resources use of 17 ZJ. A similar pattern of oil use, albeit with a lot more temporal and regional variations can be observed in MESSAGE. The modest role of nuclear energy is also persistent across the four scenarios in these two models. The nuclear shares in regional primary energy balances never exceed 15% in any region under any of these profoundly different global futures. In contrast, the models


B2 AIM
Share of oil and nuclear in total primary energy (%)
Oil -- Cumul.resources use (ZJ)
65
55
45
35
25
15
5
-5
25
20
15
10
5
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
O-World
O-D90
O-REF
O-ASIA
O-ALM
N-World
N-D90
N-REF
N-ASIA
N-ALM
Oil-cum


B2 MARIA
Share of oil and nuclear in total primary energy (%)
Oil -- Cumul.resources use (ZJ)
60
50
40
30
20
10
0
25
20
15
10
5
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
O-World
O-D90
O-REF
O-ASIA
O-ALM
N-World
N-D90
N-REF
N-ASIA
N-ALM
Oil-cum


B2 MESSAGE
Share of oil and nuclear in total primary energy (%)
Oil -- Cumul.resources use (ZJ)
60
50
40
30
20
10
0
25
20
15
10
5
0
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
O-World
O-D90
O-REF
O-ASIA
O-ALM
N-World
N-D90
N-REF
N-ASIA
N-ALM
Oil-cum

MARIA and IMAGE are more confident about the role of nuclear energy in this century. They project nuclear shares to increase to 30–40% in several scenarios, especially A1 and B1. Moreover, the role of nuclear energy is more responsive to the general characteristics of the scenarios in these models as it is apparent from the diversity of regional nuclear shares and their dynamics calculated under the conditions of different scenarios.

Stepping back from the century-scale, what can we expect in the medium term, over the next two decades? The share of electricity in total final energy and the associated demand for electric power is largely determined by grid connections. Future grid connection of so far unserviced areas depends on the economics and environmental performance of distributed generation versus the costs of central generation plus transmission costs. Electricity demand will also skyrocket in metropolitan areas requiring enormous investments in incremental generating capacity (more than 1560 GW until 2020). All technologies and fuels will be needed, including nuclear power and oil. Oil-based electricity has the benefit of low capital costs and its competitiveness depends very much on the oil product acquisition costs. At current market prices, oil is unlikely the least-cost alternative as long as there exist alternative fuel supply infrastructures. This is not the case everywhere. Taken altogether, growth in oil for power generation can still be expected in many developing countries.

The updated IEA (2004) World Energy Outlook-2004 projects that oil use for power generation is continuing its decline in the OECD to 3.5% by 2020 or the equivalent of 97 Mtoe of oil product use. The projected increase in developing countries to 177 Mtoe or 7.1% market share in electricity generation does not compensate the decline in the OECD and oil use decreases globally to just about 5% by 2020. In absolute terms, some 305 Mtoe of oil products will be combusted in power generation in 2020 (slightly up from the present 288 Mtoe). Nevertheless, nuclear power, and also hydropower, are projected to lose market shares as well: 11.6% and 14.5% by 2020, respectively. Coal almost preserves its 25-year-old share of 39% and decreases to 37.9%. Natural gas appears to be the real winner: 26.5% market share by 2020 with renewables other than hydro accounting for some 4.5%.

5. Summary and conclusions

A few decades ago, the competition between oil and nuclear energy took place directly in power generation and indirectly in end-use markets between electricity and oil products. The direct competition in the power sector has quickly faded away after the oil price shocks of the 1970s due to several reasons. The first one was the policy response in most oil importing countries to reduce their dependence on this resource with unreliable supply. The second reason was the advent of combined cycle technology that, together with air pollution concerns, paved the way for natural gas. Finally, maturing nuclear technology was also getting ready to take its share in power generation. There is also some positive feedback in

Fig. 4. Shares of oil and nuclear power in the total primary energy supply and cumulative oil consumption according to three models under the SRES B2 scenario. Source: after IPCC (2000). Notes: *Notation*: O* = oil, N* = nuclear, D90 = OECD1990, REF = reforming economies of Eastern Europe and the former Soviet Union, ASIA = Asia, ALM = Africa and Latin America, Oil cum = cumulative global oil consumption, *Models*: AIM = Asia Pacific Integrated Model, MARIA = Multiregional Approach for Resource and Industry Allocation Model, MESSAGE = Model for Energy Supply Strategy Alternatives and their General Environmental Impact.

this process. As oil has become the slack source in the total primary energy balance, this gave rise to price volatility, a rather uncomfortable attribute for electric utility operators. This gave additional support to nuclear energy emerging as a mature, commercially viable, and economically competitive item in the energy portfolio.

The issue of indirect competition is more complex because it involves many factors shaping the choice of end-use fuels in different sectors ranging from individual tastes to environmental regulations, from geographical conditions to technology availability. Not surprisingly, there is no detectable relationship between the share of nuclear energy in power generation and the share of electricity in final energy in different countries that might indicate an indirect form of oil–nuclear competition.

While the past expansion of nuclear energy occurred to the detriment of oil in the power sector, this is no longer the case today and highly unlikely to reoccur in the future. The respective market structures in which nuclear and oil operate now display little overlap and an expansion of nuclear power would not impinge on oil sales to power generation. Nuclear supplies base load to large grid-integrated markets where oil provides some peak supply, back-up capacity, small-scale and non-grid applications. Oil's main markets are the low energy demand intensity rural and remote areas usually with little or no grid integration. In an environmentally unconstrained future, nuclear power competes primarily against coal and possibly natural gas, depending on how closely natural gas prices track oil market prices and whether or not gas infrastructures are in place. However, current trends towards electricity market liberalization relying more on private sector shareholder value maximization create economic barriers to the expansion of present-day nuclear plants because of their high up-front capital costs and long amortization periods. In the absence of public policy support and/or the emergence of innovative reactor designs that lower the costs and further improve operating safety, nuclear power's market share might indeed follow a downward trajectory. Yet there is some evidence to the contrary. The order of the new Olkiluoto reactor in Finland is based on several studies, each confirming that nuclear generation is the best economic option to satisfy increasing demand for electricity (WNA, 2004).

Although direct competition between oil and nuclear energy has largely disappeared, a whole array of concerns has emerged about both energy sources and the associated technologies by the turn of the century. They include the specter of depletion, supply insecurity, and price volatility in the case of oil while operational safety, radioactive waste storage and disposal, and proliferation are the main causes of anxiety about nuclear energy. Nuclear power has many, especially environmental, benefits but encounters political and public resistance to its use in some countries while there is political support and at least public acceptance in others. So far, there is no consensus on the future role of nuclear power even in the short to medium run. Plausible long-term energy demand and supply analyses consistently foresee a growing role for nuclear power. A normative "sustainable development vision scenario" was developed by OECD's International Energy Agency (IEA, 2003) largely based on the high-technology variant of the SRES A1 storyline. This scenario projects very high annual growth rates for nuclear power, especially between 2020 and 2040, implying a 14-fold increase in global nuclear energy production between 2000 and 2050.

The paper has presented the first in-depth comparative analysis of the projected role of oil and nuclear energy in the 21st century based on a large number of global scenarios. It reveals some robust trends that seem to persist across a broad range of socioeconomic scenarios and a diverse set of global energy–economy models: steady growth and regional convergence (albeit at different rates) of incomes, enduring improvement of energy efficiency, and persistent increase in primary energy use. However, the global models differ, sometime widely, in regional details and the dynamics of energy sources in the global energy balance. It is important to bear in mind that all these IPCC scenarios are strictly non-intervention scenarios in the sense that no climate policy intervention is assumed beyond those that were already in place in 2000. In climate policy scenarios that seek broad mitigation options or specific cost-efficient CO_2 reductions, shares of oil and nuclear power are likely to shift but the projected mechanisms and timing of such changes should be subject of a separate analysis.

In an environmentally conscious future, nuclear power fares best against coal and, depending on the degree of environmental regulation, also against gas. Policies protecting global climate will certainly affect oil production and use as well but primarily with regard to oil substitutes in end-use markets, and, depending on the future techno-economic performance of renewables, also in the non-grid electricity markets. Nuclear generated electricity may indirectly challenge some oil use in the residential, commercial, and industrial sectors. However, electricity–no matter how generated–is expected to expand its market share because of its intrinsic features to improve productivity, cleanliness, and convenience. Policies enforcing an internalization of the externalities associated with the production and use of energy services will eventually improve the competitiveness of clean technologies such as nuclear power. In the global warming context, the key questions are how fast the world society decides to reduce CO_2 emissions, how high will be the costs of other mitigation options, and how the public acceptance of nuclear energy will change in some countries. Depending on the resolution of these questions and the concerns summarized above, the outcome could entail a new boost to nuclear energy or could lead towards the beginning of the end for this energy source.

Nevertheless, the unfolding of the nuclear trends will only modestly affect the prospects for oil in the global energy supply in this century. It will be the outcome of how today's oil-related concerns will be resolved and how the new competitors of oil (gas, renewables, synfuels, hydrogen from a diversity of possible sources) will fare in terms of costs, convenience, safety, cleanness, and dependability in the evaluation of future energy users.

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