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Oil projections in retrospect: Revisions, accuracy and current uncertainty

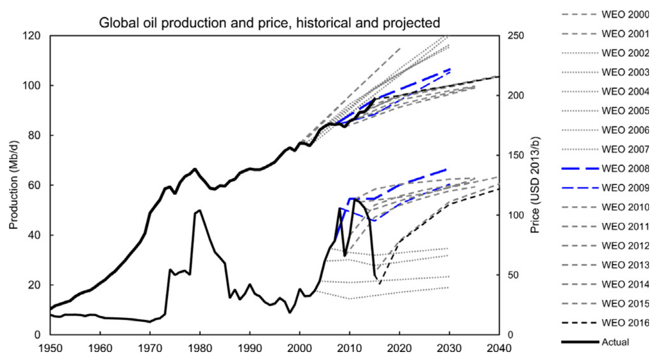
Henrik Wachtmeister*, Petter Henke, Mikael Höök

Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala, Sweden

HIGHLIGHTS

- Projections of oil production, price and investments in WEO 2000–2016 are evaluated.
- Revisions are largest for OPEC and unconventional and due to demand and supply factors.
- Accuracy is high for Non-OPEC conventional, and low for OPEC and unconventional oil.
- Empirical prediction intervals are derived to show uncertainty of current projections.
- Previous retrospective studies of IEA and EIA energy projections are reviewed.

GRAPHICAL ABSTRACT



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ABSTRACT

Scenarios and projections are important for decision and policy making. Accuracy of past projections can be useful for both scenario users and developers, for insight on current projection uncertainty, and for guiding improvement efforts. This paper compiles projections of oil production, oil prices and upstream investments from the years 2000 to 2016 from the annual World Energy Outlook by the International Energy Agency, and investigates revisions and accuracy of past projections and implied uncertainty of current ones. Revisions of world oil production, price and investments have been motivated by a combination of demand and supply factors. Downward revisions are mainly allocated to OPEC, while recent upward revisions are due to unconventional oil, in particular US tight oil. Non-OPEC conventional projections have been stable. Price and investments have been revised mostly upwards. Projection accuracy follows the size and directions of these revisions, with high accuracy for Non-OPEC (mean absolute percentage error of 4.8% on a 5 year horizon) and low for OPEC (8.9%) and unconventional (37%). Counteracting error directions contribute to accurate total World oil supply projections (4%) while price projections have low accuracy (37%). Scenario users should be aware of implied uncertainty of current oil projections. In planning and decision making, uncertainty ranges such as those presented here can be used as benchmarks. Scenario developers should focus improvements efforts on three areas in particular: tight oil, OPEC and new technology.

1. Introduction

Scenarios and projections play a key support role in decision and policy making. In the energy field much effort has been spent on deriving projections of future production and prices of oil. This interest can be justified since oil is still the world's largest energy source, providing 33 percent of global primary energy consumption [1], and arguably also the most important one due to its dominance in

* Corresponding author.
E-mail address: henrik.wachtmeister@geo.uu.se (H. Wachtmeister).

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transportation, where it stands for 94 percent of the energy used [2]. Furthermore, oil production and its price dictate magnitudes and directions of international trade flows as well as the profitability of some the world's largest companies. In the longer term, oil developments effect the security of nations as well as the global environment due to its non-renewable and fossil nature. Yet, less effort has been spent on evaluating these projections in systematic ways, although requests have been made [3,4] and important lessons learned from general energy retrospective studies [4–10].

According to O'Neill and Desai [11] analysis of performance of past projections can be useful for two main reasons: (i) to inform scenario users about implied uncertainty of current projections based on historical accuracy, and (ii) to identify accurate and inaccurate parts of projections to inform modelers and scenario developers where improvement efforts can be aimed, and to what extent accuracy increases can be expected in the future. The purpose of this paper is to shed light on these two points by a case study of annual oil projections published between the years 2000 to 2016 in the World Energy Outlook (WEO) by the International Energy Agency (IEA), a publication that is often regarded as the most authoritative source of energy analysis and long term scenarios [12].

Besides being directly relevant to oil scenario users and oil modelers this study should be useful for the wider energy modeling community concerned with incorporating uncertainty in the modeling practice [13], for example by the characterization of input uncertainty [14] of key parameters such as the oil price. The results can also contribute to the longstanding debate of potential future oil supply constraints [15] as well as the more recent peak demand prospect [16]. In particular, these results can be used to evaluate past questioning of IEA WEO oil projections [17,18].

The paper consists of four main parts. First, revisions of past projections of oil production, price and investments published in WEO 2000–2016 are quantified and, if available, stated motivations of these revisions are presented. Second, accuracy of past projections are calculated and whether accuracy has increased or not in recent projections is investigated. Third, implied uncertainty of current projections, based on the simple premise that future uncertainty is at least as large as historical projection errors, is illustrated by applying derived empirical prediction intervals to WEO 2016 projections. Finally, in the discussion, projection accuracy and uncertainty are discussed and recommendations for scenario users and scenario developers are made.

The paper contains a literature review and in line with previous studies [11,19–33] it adds empirical evidence in the form of detailed projection evaluation to the broader literature concerned with evaluation and improvement of energy models, projections and scenarios [4–10,34] and their use in policy and decision making, for example [35–37]. The present study fills two important gaps in the existing literature by providing (i) an in-depth oil sector specific retrospective and (ii) a unique examination of IEA WEO oil projections. Many previous retrospectives only look at projections of aggregate consumption of certain fuels or total energy use. This paper improves the focus on the oil sector by investigating projections of total use, production, price and investment, with further disaggregation of global production projections in the five categories: World oil supply, World conventional oil production, World unconventional oil production, OPEC conventional oil production and Non-OPEC conventional oil production. This detail makes it possible to reveal the source of underlying uncertainty by, for example, distinguishing between demand and supply driven errors. Besides calculation of historical accuracy of different disaggregations, this paper also investigates revisions of projections and their stated motivations as a further mean to better understand uncertainty and its sources.

Lastly, there is an important distinction between the exploratory and predictive use of energy scenarios and projections. Today most energy modelers promote published scenarios as possibilities of what might happen rather than predictions. This is arguably a necessary approach since making definite forecasts of such complex systems as the global energy system can be deemed impossible as it includes, among many things, assumptions on human behavior and innovation. Indeed, the WEO reports frequently stress that presented scenarios and projections are not forecasts, they are merely intended to demonstrate how markets could evolve under certain conditions [38]. How close these scenarios are to actual outcomes depends not only on how well underlying models and assumptions represent how energy systems and markets work, or on the occurrence of disruptive events, but also on users' reaction to these scenarios. This third point is highlighted in the foreword to the WEO 2015 report by Fatih Birol, chief executive of IEA: *"the reason that we look into the future is to trigger key policy changes in the present"* [38]. This statement echoes a key purpose of long term energy scenarios according to Craig, Gadgil and Koomey [10] who declared that scenarios, at their most successful, influence how people act by showing the consequence of not acting. These disclaimers aside, the central scenarios of the WEO reports are widely used as a baseline case for future energy planning, at least in the short to medium term, possibly in the absence of any better guidance. According to the organization itself, WEO scenarios are used by both the public and the private sector as framework for policy, planning and investment decision making [39]. For the case of this paper, the projections of the central scenarios presented in the WEO reports are treated and evaluated as forecasts, even though they are not strictly forecasts by definition or by intention of their developers. Yet, since they are often used as such in real world planning this kind of evaluation can still be relevant and informative. The analysis can be framed as an investigation of the uncertainty involved when using the central scenarios as predictions, and of possible ways to reduce it. To highlight this approach, the term forecast is avoided, instead scenario and projection are used, where a scenario refers to a consistent set of assumptions that can produce a range of different projections of specific parameters.

2. Literature review

2.1. Evaluation of forecasts and projections

This literature review first provides an overview of key theoretical and broader works in the field of evaluation of energy forecasts and projections. In the second part it provides a complete review of the existing literature performing detailed quantitative retrospective studies of IEA and US Energy Information Administration (EIA) energy projections.

A landmark work in forecast evaluation and accuracy is Ascher's 1978 book [5] that examines forecasts in areas of population, economics, energy, natural resources, transportation and technology from the 1930s until the 1980s, both quantitatively and qualitatively. Several important observations valid across different fields are found. For example, all trends examined, including technological and natural resource trends, are heavily dependent on socio-economic factors. Also the level of sophistication and complexity of methodology are found to have relatively little influence on accuracy, while core assumptions on the other hand have high impact. In fact, despite evolution of method sophistication, there is no clear evidence of forecast accuracy increasing over time. Instead assumptions is pointed out as the most important factor, highlighting the importance of qualitative factors and judgment. In particular Ascher points out *assumption drag*, the persistence of invalid assumptions already contradicted by data, as an area for improvement and the importance of the ability to quickly include new information and altered circumstances. Finally, Ascher makes an important methodological contribution for dealing with evaluation of current forecasts where the outcome exists in the future. He shows that the dispersion of forecasts reflects uncertainty and related minimum error.

Another famous retrospective was made by Landsberg [6] who revisited the comprehensive assessment of demand and supply of US resources from 1960 to 2000 conducted by a large team of experts, including Landsberg himself, published by *Resources For the Future* [40]. From evaluating his own work more than two decades later, Landsberg makes several observations, including the following. First, extrapolation of trends, if done thoughtfully, can be useful since momentum and capital stocks make trends somewhat projectable into the future. Second, many notable errors stemmed from changes in efficiencies, such as power plant heat rates, fuel efficiencies of automobiles etc. Sensitivity studies of such inputs can therefore be valuable. Third, aggregate projections can be quite accurate, but as a result of offsetting sub-errors. The need to disaggregate and look at subsectors are therefore necessary. Fourth, over longer timespans events occur that are simply unforeseeable or at least unpredictable with any certainty, for example the oil shocks, environmental concerns or opposition to nuclear power. Projecting the future 20, let alone 40 years, into the future is a far too long period for maintaining validity of many assumptions.

Broader retrospectives, with both qualitative and quantitative elements, have also been made by Smil [7,8]. The author focuses on and catalogues failures of long range energy forecasts. His conclusion is that long range point forecasts should be abandoned in favor of scenario and normative projections.

Similarly, Bezdek and Wendlig [9] systematically analyze 49 long range energy studies conducted from 1952 and onwards. They find that a large portion of the projections and associated policy recommendations turned out to be inaccurate, but also found elements that were correct. In particular they note that many forecasts consistently underestimated the size of world energy resources, in particular oil and gas, pointing out that world oil production has been predicted to peak within the next 10–15 years many times without coming true. Also, forecasts tend to underestimate the role of prices and adaptability of markets as well as improvements of existing technologies. They also identified how new technologies thought to be commercially viable in the near future, e.g. photovoltaics and wind power, rarely materialized as fast as expected. Quantitatively they find that most forecasts have overestimated US primary energy consumption. On the accurate side, they note the increasing import dependency of foreign oil and the increase of natural gas use. Finally, on the inaccurate side they point out the oil price.

An important contribution to the literature is provided by Craig, Gadgil and Koomey [10] who analyze long-term US energy forecasts, covering two or more decades, from 1960 to 2000 and discuss why and how such projections can be useful. It is observed that forecasters often underestimated the importance of unmodeled surprises (as the oil shock, and following efficiency response, etc.) and they recommend the use of scenarios and adoption of strategies designed for uncertainty. Also they stress the importance of data and assumptions over model sophistication, and the danger of assuming fixed laws of human behavior. Finally, they note that projections can be “successful” while still inaccurate, when they influence how people and decision makers act by showing the consequence of not acting, or acting in a certain way.

In [4] the same authors place more focus on retrospective analysis of past forecasts as a valuable tool to improve methodology of current and future forecasts as well as to uncover and explain uncertainty. The analysis draws on Landsberg [6] but gives new recommendations on how retrospectives should be done, including the following: disentangle input data issues from modeling issues (error in data vs. error in model specification), use decomposition techniques (explore sectoral detail to find underlying trends) and identify and assess impacts of discontinuities (oil shocks, etc.). The authors note that retrospectives are rarely conducted, in particular in comparison to the large amount of forecasts generated, and request more studies of this kind.

Fye et al. [34] conduct a broad study evaluating the accuracy of 300 technology forecasts, including 33 energy specific ones. They find that quantitative methods were better at predicting *when* an event will occur, while qualitative methods were better at predicting *if* an event will occur. Otherwise only forecast horizon had any explanatory power for accuracy.

2.2. Retrospectives of US EIA

To our knowledge, Shlyakthar et al. [19] provides the first detailed quantitative retrospective analysis of EIA Annual Energy Outlook (AEO) projections. They use projections from AEO 1983, 1985 and 1987 for the year 1990 for around 180 energy producing or consuming sectors of the US economy. Focus is on the distribution of errors, which are then used to construct empirical prediction intervals for current projections. They find their intervals to be broader than the presented high/low AEO scenarios. The paper is an important methodological contribution, introducing the idea of empirical prediction intervals applied to current projections, but it does not provide detailed insights on error specifics, such as size, cause, bias and relation to projection horizon.

Since 1996 the EIA has provided their own annual forecast evaluations of past AEOs, with the most recent being [41]. This is an appreciated initiative with calculation of ‘projected vs. actual’ from AEO 1994-2016 for many projection categories. Their derivations of mean absolute error (MAE) and mean absolute percentage error (MAPE), however, are averaged for each forecasted year and not by projection horizon, which would be more informative and comparable with other projections. Some qualitative reasons for errors and revisions are also given. They note that changes in energy polices have had major impacts on accuracy and that price forecasts are less accurate than forecasts for production and consumption.

O’Niell and Desai [11] assess the accuracy of US energy consumption and underlying projections of GDP and energy intensity in EIA AEO 1982-2000. They find that energy consumption projections have tended to underestimate future consumption. Energy consumption projections over 10–13 years have had MAPE of 4 percent, and about half for shorter time horizons. However, this high accuracy is the result of much larger offsetting errors in GDP and energy intensity projections, where GDP has been consistently too high and energy intensity too low, by more than 15 percent for a 10 year horizon. They find no evidence of improvement in accuracy of the three parameters over time.

Winebrake and Sakva [22] expand the analysis of O’Niell and Desai by assessing subsectors of energy consumption (commercial, industrial, residential and transportation) and by including additional AEO projections using the sample EIA AEO 1982-2003. They find that small errors for total energy consumption conceals much larger canceling sectoral errors. For example, total energy consumption MAPE on a 5 and 10 year horizon is only 3.2 and 4.9 percent, respectively, but is a result of the underestimation of transportation and overestimation of industry. They find increasing inaccuracy with projection time horizon, but they find no evidence of accuracy improvement over time.

Auffhammer [23] applies statistical methods to show empirically what type of implicit loss function EIA AEO forecasts have, where the loss function describes the relative cost of forecast errors, i.e. how costly the producer of the forecasts finds over predictions relative to under predictions of the variable of interest. Auffhammer examines 17 forecast categories of US energy consumption, production and price as wells GDP, energy intensity and CO_2 emissions from EIA AEO 1983-2003. However, only short term error analysis is done by calculating errors for same year and one year ahead forecast horizons. The study finds strong empirical evidence of asymmetric loss for oil, coal and electricity prices as well as for natural gas consumption, electricity sales, GDP and energy intensity.

Fischer, Herrnstadt, and Morgenstern [26] investigate potential for systematic errors in EIA AEO 1984-2004 forecasts by calculating errors for total energy demand and 14 fuel and consumption categories for the years 1985–2006, restricting the analysis to 1–5 year horizons. After controlling for projection errors in GDP, oil prices, and heating/cooling degree days, the study finds a remaining tendency to underestimate total energy demand by an average of 2 percent per year over the 1–5 year projection horizon. In the individual sectors directional consistency in error patterns is found with some sectors having significant biases.

Wara, Cullenward, and Teitelbaum [27] examine forecasted US electricity sales in EIA AEO 1997-2013 and find consistent over-projections, and discuss its relevance to policy including the EPA's Clean Power Plan.

Gilbert and Sovacool [28] examine renewable energy projections in EIA AEO 2004-2014 and find consistent under-projections for most renewable energy types in the medium and long-term. The authors investigate potential causes, including a dynamic policy environment.

Bernard et al. [31] focus solely on oil prices and investigate accuracy of EIA AEO 1995-2011 oil price projections in relation to simple econometric models and statistical forecasting methods. The authors find that AEO projections beat a random walk model around the two ends of the forecast horizon, in the short and very long term. For medium to long horizons a range of simple models often produces similar or better forecasts than the AEO.

Kaack et al. [32] evaluate projection errors for 18 energy production, consumption and price categories from EIA AEO 1982-2016. Based on an analysis of error distributions and out-of-sample tests of resulting error-based probabilistic forecasts, they apply derived empirical prediction intervals to AEO 2016 reference projections, and compare these to AEO high, low and others scenarios. The authors find that observed uncertainties (empirical prediction intervals) are larger than AEO scenario ranges. They confirm that Gaussian density, estimated on past performance, leads to accurate uncertainty estimates.

2.3. Retrospectives of IEA

The literature investigating IEA projections is limited in comparison to US EIA studies. To our knowledge, only three detailed retrospectives exist, and only two of these investigate projections from the IEA flagship publication World Energy Outlook (WEO).

Linderoth [21] examines projections from the IEA publication series *Energy Policies of IEA Countries* covering total primary energy supply, oil consumption and final consumption by sector (industry, transportation and other) for all IEA member countries as of 1978. These projections are submitted by member countries and are not based on IEA's own analysis. Projections published from 1978 to 1994 are investigated and accuracy calculated for the years 1985, 1990 and 1995. The study finds large positive forecast errors as a result of the second oil crisis. Moderate error in total energy consumption is a result of larger offsetting errors in industry (overestimated) and transportation (underestimated).

Liao et al. [29] examine energy demand projections for the year 2010 from IEA WEO 1993-1996, 1998, 2000, 2002 and 2004. They calculate forecast errors for total energy demand, as well as oil, gas and coal demand for 4 countries and 7 regions including the world total. They also calculate errors in underlying assumptions of GDP, population and oil price and apply econometric tools in an attempt to connect these errors to the aggregate projection errors of the various categories of demand. They find GDP to be the leading error source but note that their econometric set up only accounts for around 20 percent of the total demand error. Correspondingly, 80 percent of the error originates from other sources not included in their model. The study finds IEA WEO having high accuracy for total energy demand for the world as a whole and for OECD with percentage errors lower than 2 percent. However, individual countries vary, with projections for China being the most inaccurate, followed by India, Brazil and Russia.

Cabeza et al. [33] examine accuracy of IEA WEO 1977, 1982, 1994, 1998 and 2004 projections of energy supply and consumption, GDP and population growth for OECD countries up until 2013. They find that WEO 1977 substantially overestimated energy demand, while later projections were quite accurate, although slightly underestimating demand.

2.4. Other retrospectives

Besides the above studies investigating EIA and IEA projections there exist some other quantitative retrospectives investigating other projections, including work by Huntington [20], Sohn, Binaghi, and Gungor [24], Pilavachi et al. [25] and Trutnevyte et al. [30].

Huntington [20] has an oil sector focus and is therefore treated in more detail here. The paper reviews forecasts of production, consumption and the price of oil published in Stanford's Energy Modeling Forum's 1980 study *World Oil*. The study applied 10 existing global oil models and consisted of over 40 leading analysts. Huntington calculated accuracy of these projections for the year 1990 and found that the average of all 10 models for oil consumption was relatively accurate −2.1 percent for the world, with OCED even higher (−1.5 percent) but less for Non-OECD (−10 percent) on a ten year horizon. On the production side errors are larger, with average 18 percent for OPEC and −21.7 for Non-OPEC production, illustrating once again that accurate aggregate demand can appear together with inaccurate canceling subsectors. Oil price projections were very inaccurate, on average overestimated with 222 percent. Huntington also applies a simple model similar to the World Oil models, which through backcasting is used to investigate the effect of faulty input assumptions on output errors (i.e. disentangle input error from model misspecification).

3. Methods and data

3.1. Methodology of World Energy Outlooks

This paper compiles projections from WEO 2000 to 2016 (17 publications). Each WEO includes a few different scenarios, both for global energy as well as for the oil sector. Only one, however, is referred to as the central scenario and this scenario is presented in greater detail. This paper is limited to these annual central scenarios, referred to as the Reference Scenario in WEO 2000-2009 and the New-Policies Scenario (NPS) in later reports. These central scenarios might be seen as more probable than the more goal oriented climate scenario 450 Scenario, or the no change Current Policies Scenario.

Oil supply projections presented in the WEO are derived using the IEA World Energy Model (WEM). The WEM has been developed by the IEA since 1993 and is a partial equilibrium simulation model covering global energy supply, energy transformation and energy demand [42]. Key exogenous assumptions driving the model are economic growth, demographics and technological development. Also specific costs and polices are determinant inputs. Oil supply level, oil price and related oil sector investments necessary to meet projected demand are estimated by a regional bottom-up oil supply module. This module has seen some major developments during the years. The base of the current module framework was implemented in WEO 2008 when two major changes were made. First, an industry replicating decision algorithm for development of new fields was introduced based on net present value criteria of new projects. Second, based on a detailed empirical field decline rate study, new estimates of decline rates of producing fields as well as new standard production profiles for future fields were introduced. For this reason, and since it is in the middle of the investigated time period, the WEO 2008 is used as a divider between "old" and "new" projections in the accuracy analysis, where old is WEO 2000-2007 and new is WEO 2008-2015 (WEO 2016 errors cannot yet be evaluated).

In its current form, the oil supply module can be described as a bottom-up field-by-field model where demand is exogenous (but price sensitive) and future oil production, price and investments are endogenously derived by net present value of new supply projects and decline in existing production [42]. For a detailed review of the IEA model and comparison to other similar models see [43], for a broader background on bottom-up oil production models see for example [44,45]. The IEA oil supply module was also reviewed in a technical

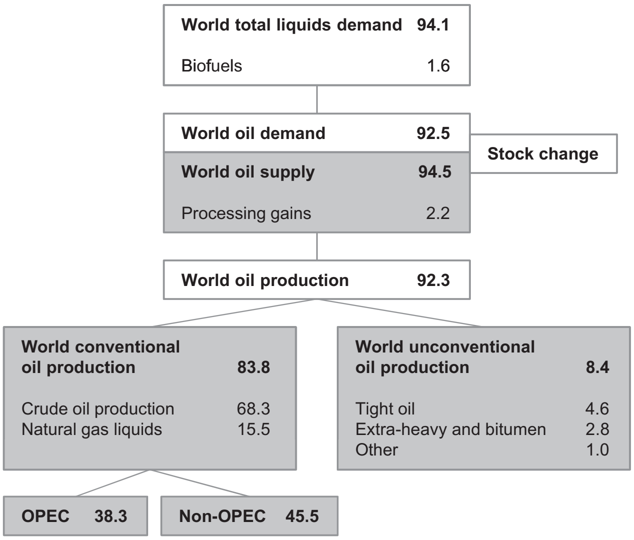

Fig. 1. Hierarchical structure of key WEO definitions and categories of oil and corresponding amount of production in year 2015 (Mb/d). Categories investigated in this paper are marked with grey boxes.

report [46] as part of the comprehensive assessment of global oil depletion by UK Energy Research Centre [15].

The supply module aggregates field-by-field production to country, regional and global level. Also it derives production by production technology and source in conventional and unconventional production, as well as crude oil, natural gas liquids (NGL) production and refining gains. The top production aggregate is called World oil supply and consists of all liquid petroleum production sources and equals World oil demand. Oil production includes both crude oil and NGL, but not refining gains. Conventional and unconventional production depend on production technology and the unconventional category has changed somewhat with time. This paper uses these same definitions and categories. See Fig. 1 for schematic overview of WEO supply categories, where aggregates studied in this paper are highlighted.

3.2. Data

Where possible, all data used in the analysis are taken from the WEO reports, both actual and projected. Since projected values are not given for every year (usually data every five years are given) linear interpolation is used between provided data points for projection presentation and accuracy calculation. Usually every WEO presents an actual value for the year prior to the WEO release year. This value is used as starting point for the linear interpolation to the first projection value. This means that, for example, WEO 2008 (released in year 2008) contain an actual historical value for 2007 and a projected value for 2008. In other words, for WEO 2008, a projection of the time horizon one year projects a value for the calendar year 2008, and a projection of the time horizon five years projects a value for year 2012. For some categories in older reports, actual values lag two or sometimes three years behind the release year. In these cases and when actual values are missing for other reasons (for example changing definitions of unconventional oil), compatible data from Rystad Energy UCube database are used as actual values. All price and investment figures are converted and presented in year 2013 US dollars (USD 2013).

3.3. Revisions of projections

To complement the quantitative compilation of projection revisions, all WEO reports are reviewed for motivations of major projection revisions. This review focuses on the oil scenarios and the changes within these (i.e. only the oil chapters are reviewed in detail) and omits a detailed analysis of substitution and dynamics with other energy sources. However, it is important to remember that the WEO reports model all energy sources, and for example, substitution might not only depend on higher oil prices, but also on lower prices of alternative energy sources driven by factors outside the oil system.

3.4. Accuracy of projections

There are several different measures of forecast accuracy, when accuracy is defined as the error size of forecasted value and actual value. Hyndman and Koehler [47] recommend scaled errors such as the mean absolute scale error for detailed measurement. However, when all data are positive and greater than zero, as is the case with the WEO projections, the mean absolute percentage error (MAPE) may still be preferred for reasons of simplicity. Also, in previous similar studies percentage error and MAPE appears to be the measures of choice.

This study uses the projection error (E), percentage error (PE), mean absolute error (MAE), and mean absolute percentage error (MAPE) as defined as

$$E_{t,\tau} = F_{t,\tau} - Y_{t,\tau} \tag{1}$$

$$PE_{t,\tau} = \frac{F_{t,\tau} - Y_{t,\tau}}{Y_{t,\tau}} \tag{2}$$

$$MAE_{\tau} = \frac{1}{n_{\tau}} \sum_{t} |E_{t,\tau}| \tag{3}$$

and

$$MAPE_{\tau} = \frac{1}{n_{\tau}} \sum_{t} |PE_{t,\tau}| \tag{4}$$

where F_t is the forecasted value (projection value) and Y_t the actual value for year t, and where n_τ is the number or projections (sample size) with equal projection time horizon τ (1 year, 2 years,..., 16 years). Accordingly, a positive percentage error corresponds to a projection overestimation, and a negative one to an underestimation.

For each projection category and each WEO annual E, PE and error direction are calculated. From these values MAPE and MAE are derived according to projection time horizons (1–16 years). Furthermore, MAPE, MAE and error direction are calculated for three different groups of WEO reports: All, WEO 2000–2007 and WEO 2008–2015 (also referred to as all, old and new). The direction of annual PE is given according to underestimation, neutral or overestimation with neutral defined as PE $< \pm 0.5$ percent of actual value. The purpose of the neutral interval is to allow a classification for accurate projections.

3.5. Empirical prediction intervals

Prediction intervals are complements to point forecasts that indicate the precision of the forecasts. Theoretically, actual outcome will fall within the prediction interval with a certain probability. The intervals are usually presented as fan charts around the point forecast and are used today by many forecasting institutions such as the Federal Reserve, the European Central Bank and the International Monetary Fund. For a recent overview of the properties and usage of empirical prediction intervals in forecasting see [48]. In short, prediction intervals can be derived in two ways. Either theoretically, based on the model and uncertainty in its parameters, or empirically, based on the accuracy of previous forecasts. Empirical prediction intervals has the advantage that they can be constructed only from past forecasts and actual outcomes and do not require any detailed knowledge or access to the model producing the forecasts. They are based on the simple but intuitive premise that the likely margin of future error is provided by past forecast errors. The concept was introduced in the 70 s and is increasingly applied in real forecasting exercises [48] including by many of the central banks [49].

In this paper empirical prediction intervals are constructed with the same confidence interval as used by the European Central Bank [50]. To the point forecast, one mean absolute error (MAE) for the particular time horizon is added on each side resulting in a range of width two MAEs consistent with a 57.5 percent confidence interval, if a Gaussian error distribution is assumed, which according to [32] is a valid assumption. Furthermore, a wider interval constructed from two MAEs on each side is presented, with a width of four MAEs consistent with a confidence level of 88.9 percent. These two empirical prediction intervals are calculated based on the MAEs for all WEOs and for the new WEOs, resulting in four fans.

4. Results

4.1. Revisions of oil projections

4.1.1. Historical production and price development: 1950–2015

The global oil market is a complex system driven and constrained by geology, technology, economics and politics. During its history these factors have had various impacts. This section gives a short overview of key historical developments followed by an initial survey of main WEO projection revisions.

Fig. 2 shows historical global production and price of oil from 1950 to 2015 together with future projections of the WEO top production aggregate World oil supply and oil price in central scenarios published in WEO 2000 to 2016. Looking at the historical production and price data, four broad regimes can be identified since the Second World War (similar to [51]). First, the period prior to 1973, characterized by exponential growth of production and declining prices due to global oversupply from large annual discoveries of conventional oil, with most of demand coming from OECD countries, establishing the main part of their current oil dependency. Second, the volatile period 1973–1985 that followed decreasing US production and OPEC's increasing market control, which culminated in the first and second oil crisis 1973 and 1979 with oil prices reaching record levels. Third, the period 1986–2002, with decreasing OPEC control, increasing production (although at a slower pace) in part from new Non-OPEC provinces, and with oil prices at a new long term average around 30 USD/b, a doubling compared to the first period. Fourth, the period 2003–2014, with rapidly increasing non-OECD demand, stagnating global conventional oil production, rising prices and increasing unconventional production. To this list a fifth period might be added starting with the price fall of 2014, stemming from increasing US tight oil production, OPEC market share strategy and weaker global demand growth. Table 1 summarizes production growth rates, in compound annual growth rate (CAGR), and average prices during the four periods.

Table 1
Historical production growth rate (compound annual growth rate) and mean price during different time periods.

Historical period	Production CAGR (%)	Mean price (USD 2013/b)
1950–1972	7.8	14
1973–1985	0.1	65
1986–2002	1.3	31
2003–2014	1.4	81

4.1.2. Revisions of global production, price and investment projections: 2000-2030

Moving on to projected future production in Fig. 2, four categories of projections with similar trajectory and endpoint range can be distinguished for World oil supply: (i) WEO 2000 and 2001, (ii) WEO 2002-2007, (iii) WEO 2008 and 2009 and (iv) WEO 2010-2016. These four groups are separated by three major step wise downward revisions (between WEO 2001 and 2002, WEO 2007 and 2008 and WEO 2009 and 2010) and with the most recent group being characterized by annual gradual upward revisions. These major revisions and their motivations will be investigated in more detail in Section 4.1.4.

For projections of oil prices, two groups of projections with similar trajectory and endpoint range can been seen: the WEO 2004-2007 and WEO 2008-2016. The first group has almost flat projections while the second has increasing trajectories with similar end point range averaging at 123 USD/b in 2030, which can also been seen more clearly in Fig. 3 (left). To the right in Fig. 3 average annual upstream investment in the oil sector, necessary to fulfill production and price projections, is presented. Since WEO 2005 projected annual investment has increased from 106 to 513 billion USD per year in WEO 2014, an increase of 384 percent. However, downward revisions occurred in WEO 2015 and WEO 2016, with the latest report estimating 438 billion USD per year, a 313 percent increase from WEO 2005.

Table 2 summarizes averages of production growth rates for the

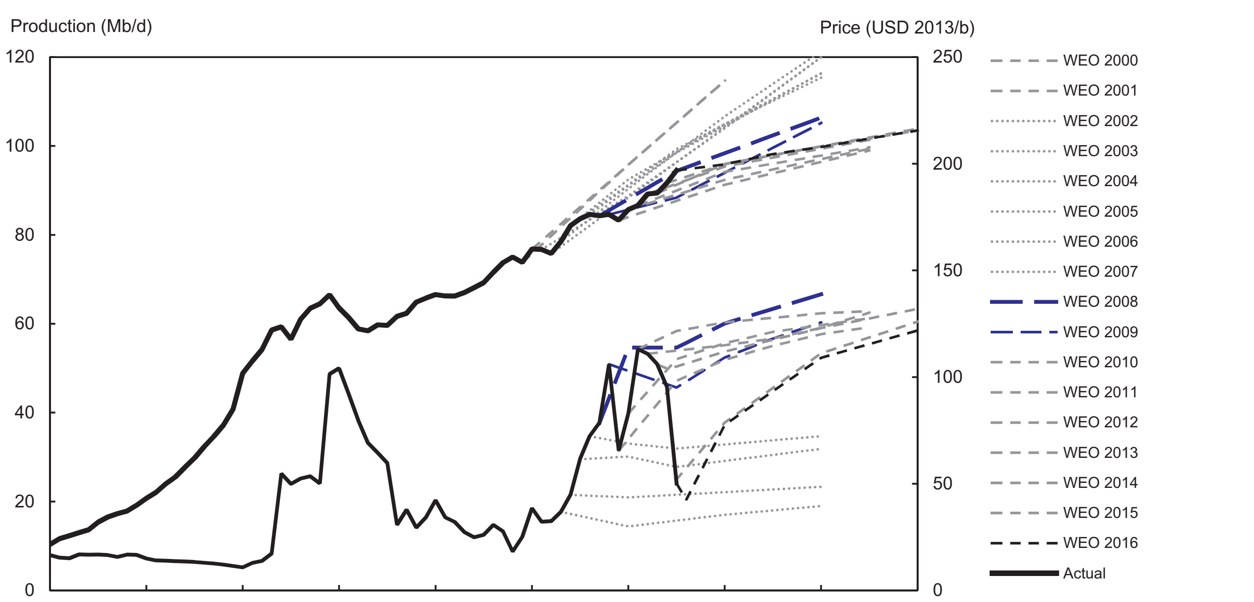

Fig. 2. Historical world oil production and price from 1950 to 2015 and projections for World oil supply and oil prices from central scenarios of WEO 2000–2016.

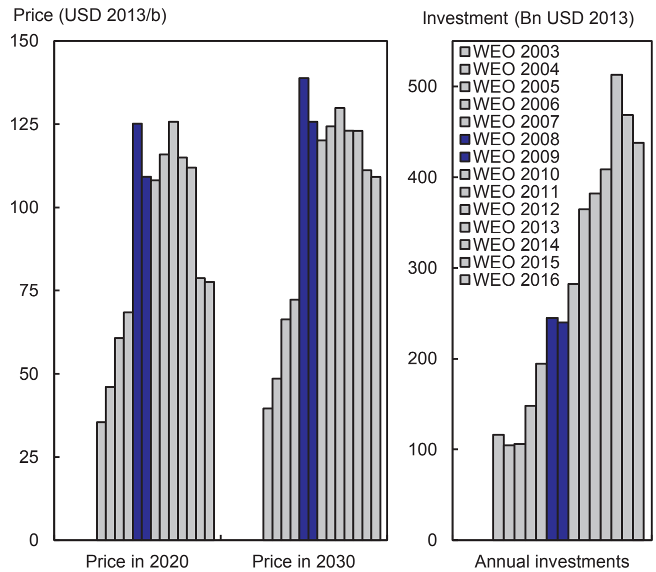

Fig. 3. Projections of oil prices in year 2020 and 2030 (left) and projected average annual upstream oil investments during scenario period (right). Price projections starts with WEO 2004.

Table 2
Average production growth rate, mean price in year 2030 and average annual investments of four groups of projections.

Projections	Production CAGR (%)	Mean price in 2030 (USD 2013/b)	Annual investment (Bn USD 2013)
WEO 2000-2001	2.1	n/a	n/a
WEO 2002-2007	1.5	57	134
WEO 2008-2009	1.0	132	242
WEO 2010-2016	0.5	120	408

whole projection time horizon, price in 2030 and annual investments for the four groups of projections. Based on this initial grouping, and compared to historical developments, World oil supply projections have been revised downwards with time, while price and necessary investments have been revised mostly upwards.

4.1.3. Breakdown of production revisions

The top WEO production aggregate World oil supply consists of conventional and unconventional oil production, as well as OPEC and Non-OPEC production. In Figs. 4 and 5 production projections for year 2020 and 2030 are presented for World oil supply and its constituent parts World conventional oil production and World unconventional oil production. World conventional production is further divided into OPEC and Non-OPEC conventional oil production. The WEO 2000 and WEO 2001 scenarios run only until 2020 and are therefore missing in Fig. 5.

As seen in Fig. 4, and as noted already in Fig. 2, World oil supply has been revised down significantly in three steps: between WEO 2001 and 2002, between WEO 2007 and WEO 2008 and between WEO 2009 and 2010. Also, the gradual increase starting from WEO 2010 can be seen. A similar pattern is visible in Fig. 5 for year 2030, however at a somewhat larger scale, in particular the significant revision between WEO 2009 and WEO 2010.

By looking at the break up of World oil supply in conventional and unconventional oil production, the downward revisions can be traced to the conventional part while the more recent upward revisions are associated with the unconventional part. Further break up of World conventional oil into OPEC and Non-OPEC conventional production reveals that almost all downwards revisions are to be found in the OPEC category while the Non-OPEC projections have been relatively stable.

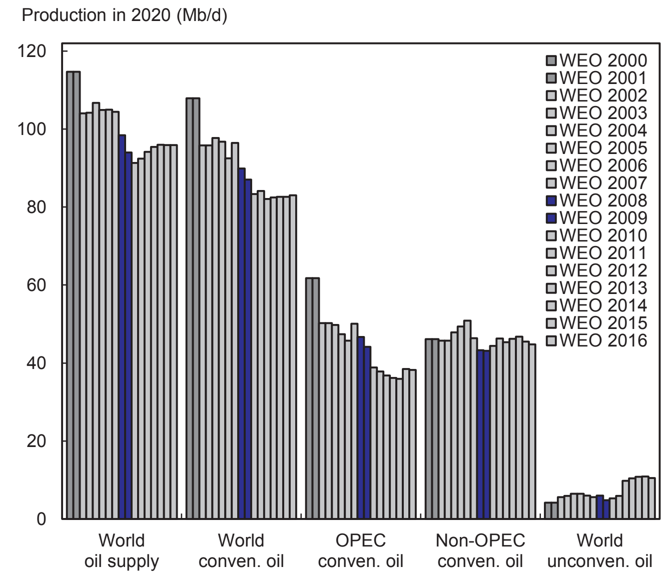

Fig. 4. Projected production in 2020.

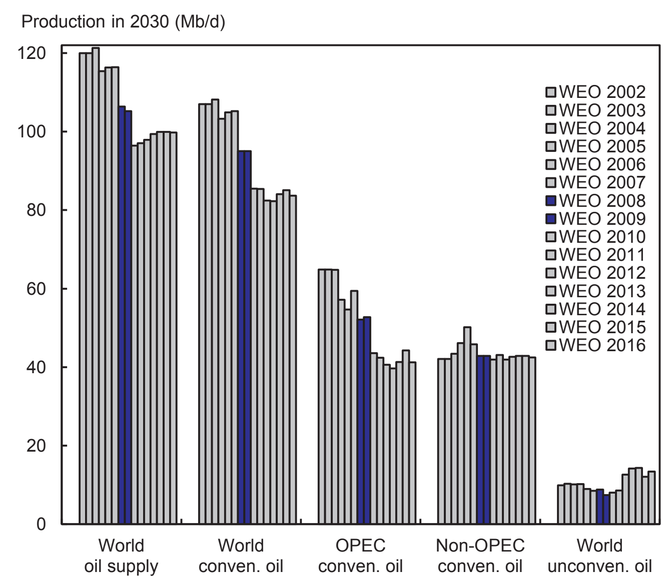

Fig. 5. Projected production in 2030.

In summary, the major part of World oil supply revisions can be traced to downward revisions of OPEC conventional oil production and upward revisions of World unconventional oil production.

4.1.4. Stated reasons for revisions

As described in for example WEO 2008 Chapter 1, all WEO energy scenarios, not only the oil scenarios but also for other sectors and total energy use, are dependent on five principal mechanisms: population, economic growth, energy prices, technology and government policies. Changes in assumptions of future development of these mechanisms will have large impacts on projections. Assumptions for population and global economic growth have been relatively stable in the WEO 2000-2016 scenarios, and so has the interlinked assumption on global primary energy demand. However, assumptions of the share of oil in global primary energy demand have seen relatively larger changes as oil competes against other energy sources and efficiency measures in the energy system. This wider context is important to remember, and constitutes an interesting area for further research. However, further detailed analysis of this wider dynamic is outside the scope of this paper.

The quantity of the top WEO aggregate World oil supply represents both the total sum of different supply sources as well as the total global demand for oil. Some motivations of projection revisions presented in the reports are found on country or production type level. Such revisions can be based on changed political assumptions, specific technological developments or new geological information. The three large revisions identified in Sections 4.1.2 and 4.1.3, however, are found under descriptions of global oil demand.

The first major downward revision between WEO 2001 and 2002, with the magnitude −10.7 Mb/d in World oil supply and −11.6 Mb/d in OPEC conventional production for year 2020, is described in WEO 2002, p. 91:

"This year's WEO projects a lower growth rate in world oil demand over the next twenty years than was anticipated in WEO 2000. This difference is mainly due to downward revisions to historical data and slower growth than expected in recent years", and

"The share of OPEC countries in world oil supply in this Outlook differs markedly from that in WEO 2000. Projected OPEC production is now 11.6 mb/d lower in 2020. This is partly because of lower expectations for growth in world oil demand, as discussed above. An even greater portion of the difference in projections can be explained by stronger expected growth in non-OPEC and nonconventional oil production. These increases are explained primarily by technological factors. Because OPEC production plays the role of the swing producer in the World Energy Model, the projected share of its production in world oil supply is lower than in WEO 2000."

According to the report, this revision stems from reduced expectation of future demand based on analysis of current trends, and since the WEM model assumes OPEC production on the margin, the entire revision is allocated to this category. From Fig. 4 no significant changes in Non-OPEC or unconventional production can be seen between WEO 2000 and WEO 2002, which makes the second motivation difficult to interpret. It can be added that WEO 2000 included new resource figures from the new USGS assessment [52] released that same year [53]. These new resource estimates were higher than previous ones, relaxing long term constraints, and possibly explaining why WEO 2000 projections were higher than WEO 1998. However, it is beyond the scope of this study to pursue further.

The second major downward revision between WEO 2007 and 2008, of the magnitude −6 Mb/d in World oil supply for year 2020, and −10 Mb/d for 2030, is described in WEO 2008, p. 94:

"The share of oil in global primary energy demand drops from 34% in 2006 to 30% in 2030. This is a significant, 10-mb/d downward revision from last year's Outlook, reflecting the impact of much higher prices and slightly slower GDP growth. A number of new government policies introduced in the past year — notably moves in the United States and Europe to promote more fuel-efficient vehicles and encourage biofuels supply — also contribute to the reduction."

Also in WEO 2008, p. 253, reduced OPEC production of −3.4 Mb/d in 2020, −7.3 in 2030, is commented:

"It now looks much less likely that the key producing countries, in particular, will be willing and able to expand capacity as much and as quickly as previously assumed."

Furthermore, adding to the reduction is decreased projections of Non-OPEC, −3.1 in 2020 and −2.9 in 2030 stemming from the detailed update of the field-by-field supply module. In summary, the WEO 2007-2008 revision is mainly allocated to OPEC, but this time due to a combination of factors including actual lower expectations of OPEC production due to political or strategic assumptions and lower estimated Non-OPEC production, derived from the new decline rate and field-by-field study. All of this in a higher oil price environment, estimated with the improved supply module, leading to lower estimated total demand for oil.

The third major downward revision, between WEO 2009 and 2010, of the magnitude −2.7 Mb/d in 2020 and −8.8 in 2030 of World oil supply, and −5.3 and −9.1 in OPEC respectively is mainly due to a new central scenario. In WEO 2010 a new set consisting of three scenarios is presented: New Policies Scenario (NPS), Current Policies Scenario and 450 Scenario. These three base scenarios are still being used. The NPS is the new central scenario and differs from the old central scenario (the Reference Scenario) in extent of implemented polices in the future. The Reference Scenario included only policies actually implemented to publication date, while the NPS includes policy commitments by governments that have been announced but not yet implemented. The Current Policies scenario is similar to the old Reference Scenario, with only current policies in place, while the 450 Scenario is based on radical policy implementation limiting CO_2 emissions to a global temperature increase of 2 °C.

For oil, a combination of policy actions in the NPS reduce projected demand: promotion of efficient oil use, switching to other fuels, reduced fuel subsides in consuming countries and increased taxes on oil products. Reduced demand is partially offset by rising production costs (WEO 2010 p. 59) and the projected price in NPS is similar to previous projections of the Reference Scenario in WEO 2009. Increasing production costs are also reflected in the continued upward revision of investments, until WEO 2015.

The fourth gradual upward revision of global oil supply starting with WEO 2010 is a result of annual gradual upward revisions of unconventional oil production, most importantly due to the entrance of US tight oil production projections in WEO 2012 (a preliminary projection was included in WEO 2011). The tight oil projections have underestimated actual production every year since inclusion and the projections have consequently been revised gradually upwards. The WEO 2015 breaks this trend with a downward revision of post 2020 tight oil production and Canadian oil sands production, and upward revision of long term OPEC production following the price collapse in 2014. According to WEO 2015 the price collapse was driven by a slowdown in demand growth and record increases in supply, particularly tight oil from North America, as well as a decision by OPEC countries not to try to (immediately) rebalance the market through cuts in output. In WEO 2016 tight oil is revised up, and OPEC down, compared to WEO 2015.

4.2. Accuracy of oil projections

4.2.1. Production projections

Fig. 6 presents historical and projected production for the five categories World oil supply, World conventional and World unconventional production as well as OPEC and Non-OPEC conventional oil production. Fig. 9 presents calculated accuracy in terms of mean absolute percentage error (MAPE) of projections by projection time horizon. Table 3 compiles MAPE and MAE on a five and ten year horizon as well as error direction of the projections. As a compliment Fig. A1 in the appendix shows projections of the different categories together in the same figure with both linear and logarithmic scales to further facilitate interpretation.

From an initial overview of the first set of figures (Fig. 6), some observations already made in the previous revision section are clear. The top aggregate World oil supply has been revised downwards in three distinctive steps and then, more recently, gradually revised back up. A look at the projections of World conventional and unconventional oil production shows that the downward revisions stem from the conventional part while the recent upward revisions stem, to a high degree, from the unconventional one. A further look at the breakdown of conventional oil in OPEC and Non-OPEC shows that the downward revisions stems from OPEC while Non-OPEC projections have been relatively stable.

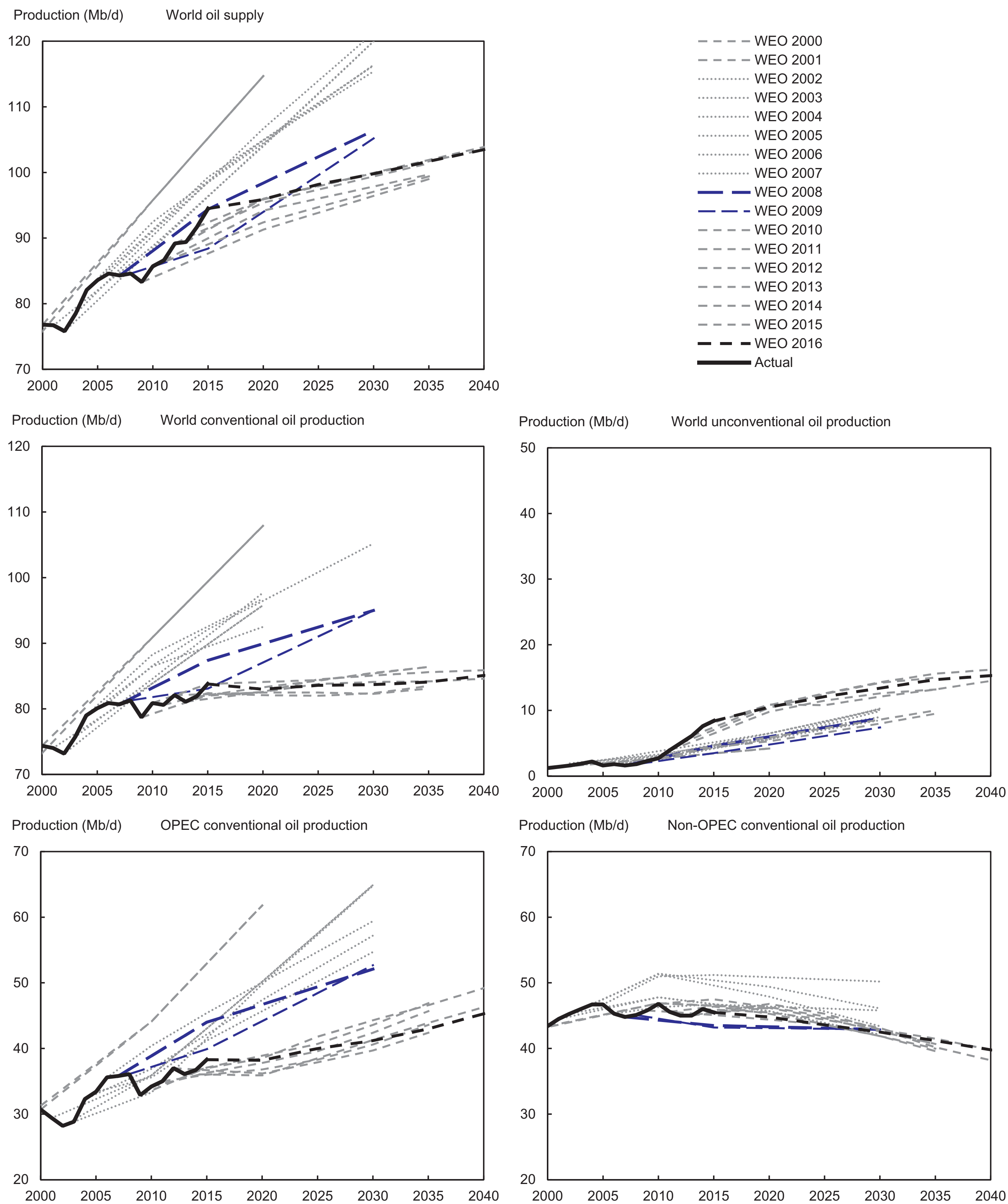

Fig. 6. Actual (2000–2015) and projected production for World oil supply, World conventional oil production, World unconventional oil production, OPEC conventional oil production and Non-OPEC conventional oil production.

Furthermore, the actual historical production data for the different categories gives a good picture of the developments from year 2000 to today: the rapid increase in OPEC production during the price hike starting in 2002, the following stagnation of World conventional production around 2005, in turn leading to overall stagnation of World oil supply, the OPEC production cuts following 2008 economic crisis, and finally, the surge of US tight oil production increasing World unconventional oil production and World oil supply significantly.

Moving on to the second set of figures (Fig. 9) presenting the accuracy of projections compared to actual outcome, it is seen that the

Table 3
Mean absolute percentage error (MAPE) and mean absolute error (MAE) on five and ten year horizons as well as error direction of different groups of projections.

Projections	MAPE (%) 5	MAPE (%) 10	MAE (Mb/d) 5	MAE (Mb/d) 10	Error direction (%) Under	Neutral	Over
World oil supply							
All	4.0	7.0	3.4	6.2	26	4	71
WEO 2000-2007	4.1	7.0	3.5	6.2	12	1	87
WEO 2008-2015	3.7		3.4		64	11	25
World conv. oil prod.							
All	3.3	9.2	2.7	7.4	17	9	74
WEO 2000-2007	4.3	9.2	3.4	7.4	12	3	85
WEO 2008-2015	1.4		1.2		31	25	44
OPEC conv. oil prod.							
All	8.9	13.7	3.1	4.8	32	1	66
WEO 2000-2007	10.4	13.7	3.6	4.8	25	1	74
WEO 2008-2015	6.0		2.2		53	3	44
Non-OPEC conv. oil prod.							
All	4.8	6.5	2.2	3.0	28	8	64
WEO 2000-2007	5.8	6.5	2.6	3.0	18	6	76
WEO 2008-2015	2.8		1.3		56	14	31
World unconv. oil prod.							
All	37.2	23.4	1.5	1.5	61	1	38
WEO 2000-2007	34.4	23.4	0.7	1.5	50	2	48
WEO 2008-2015	43.0		3.0		92	0	8
Oil price	MAPE (%)		MAE (USD/b)				
All	37.0	46.3	29.1	44.4	65	0	35
WEO 2000-2007	41.7	46.3	40.2	44.4	93	0	7
WEO 2008-2015	32.3		17.9		33	0	67

mean absolute percentage error (MAPE) is typically increasing with projection horizon, and also that the more recent scenarios, from WEO 2008-2015, are generally more accurate than older ones from WEO 2000-2007 on the same time horizon. It is also clear that projections for conventional oil have been significantly more accurate than for unconventional oil (note the different axis scale for unconventional). Within conventional, it is also clear that the accuracy of Non-OPEC projections is significantly higher than for OPEC.

A look at the top aggregate World oil supply reveals that the MAPE on a five year horizon for all projections is 4.0 percent, and on a ten year horizon 7.0 percent (see also Table 3). Evaluating only recent scenarios, from WEO 2008-2015, the MAPE is 3.7 percent on five year basis. The error direction, in terms of underestimation, neutral or overestimation, has also become more even compared to older projections from WEO 2000-2007, where the older ones consisted of 12 percent underestimations, 1 percent neutral, and 87 percent overestimations. The errors of the recent scenarios consist of 64 percent underestimations, 11 percent neutral and 25 percent overestimations. In summary, in terms of accuracy and error symmetry, there has been an improvement between older and newer WEO World oil supply projections, and a shift from mostly overestimations to mostly underestimations.

The track record for World conventional oil production projections is similar to World oil supply. This is natural since conventional production constitutes the dominant part in overall supply. The MAPEs are 3.3 and 9.2 percent on a five and ten year horizon, respectively. For the recent WEOs the errors are remarkably small during the first five years. Also, the error direction has gone from mostly overestimations in older reports to a quite even distribution in recent ones.

Looking at the two parts of World conventional production, OPEC and Non-OPEC conventional, reveals a significant divergence in accuracy. The MAPEs for OPEC on five and ten year horizon are 8.9 and 13.7 percent. For Non-OPEC the result is 4.8 and 6.5 percent. Even Non-OPEC projections longer than ten years show very high accuracy, all being below 6.5 percent. For OPEC, projections longer than ten years

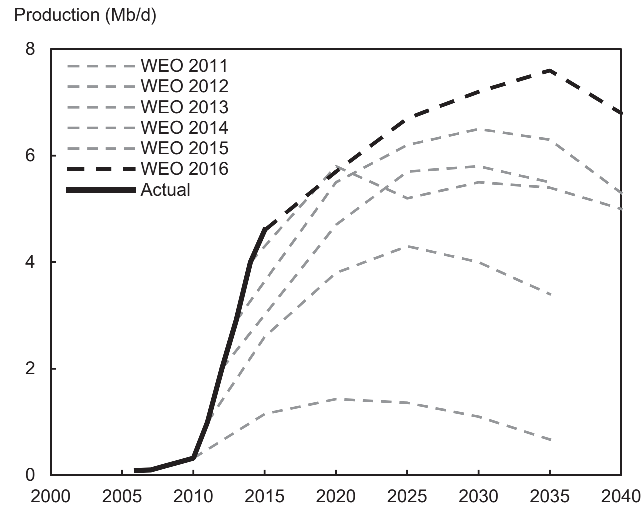

Fig. 7. Actual (2006–2015) and projected tight oil production.

deteriorate significantly with MAPEs surpassing 30 percent. Improvements in accuracy and error direction have occurred for both groups, with recent Non-OPEC projections showing particularly high accuracy, a five year MAPE of 2.8 percent, and a relatively even distribution of error direction.

The final supply source, World unconventional production, has MAPEs of a different magnitude, reaching in some cases over 50 percent. This large error is not only because unconventional production is arguably the most difficult category to project, since it consist of new or even unknown technology, it is also partly due to the low base of production in this category making smaller absolute differences larger in relative terms. Also, as mentioned in the methods section the definition of unconventional oil production has shifted, which makes the underlying data more uncertain with possible discrepancies. A further breakdown of the unconventional category reveals that the total track record is a combination of initial overestimation of Canadian oil sands production and more recently, continuous underestimation of US tight oil production, as seen in Figs. 7 and 8.

4.2.2. Price and investment projections

Projections of oil prices are available from WEO 2004 and onwards and are presented in Fig. 10. As seen in Fig. 11, the MAPE on a five year horizon for all projections is 37 percent, and reaches 67 percent on an eight year horizon. This high inaccuracy, compared to production

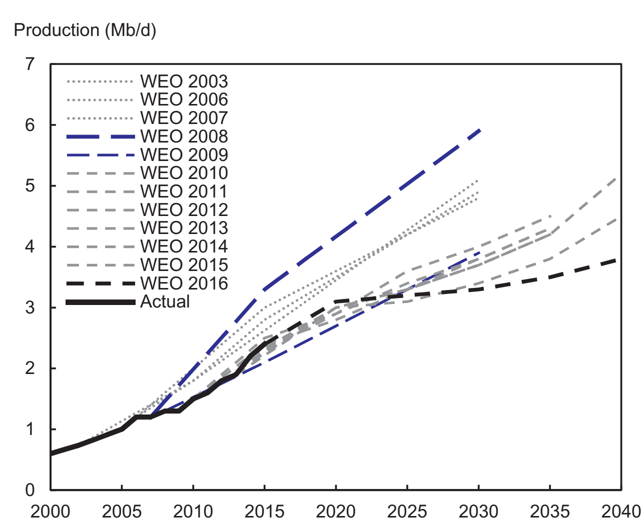

Fig. 8. Actual (2000–2015) and projected Canadian oil sands production.

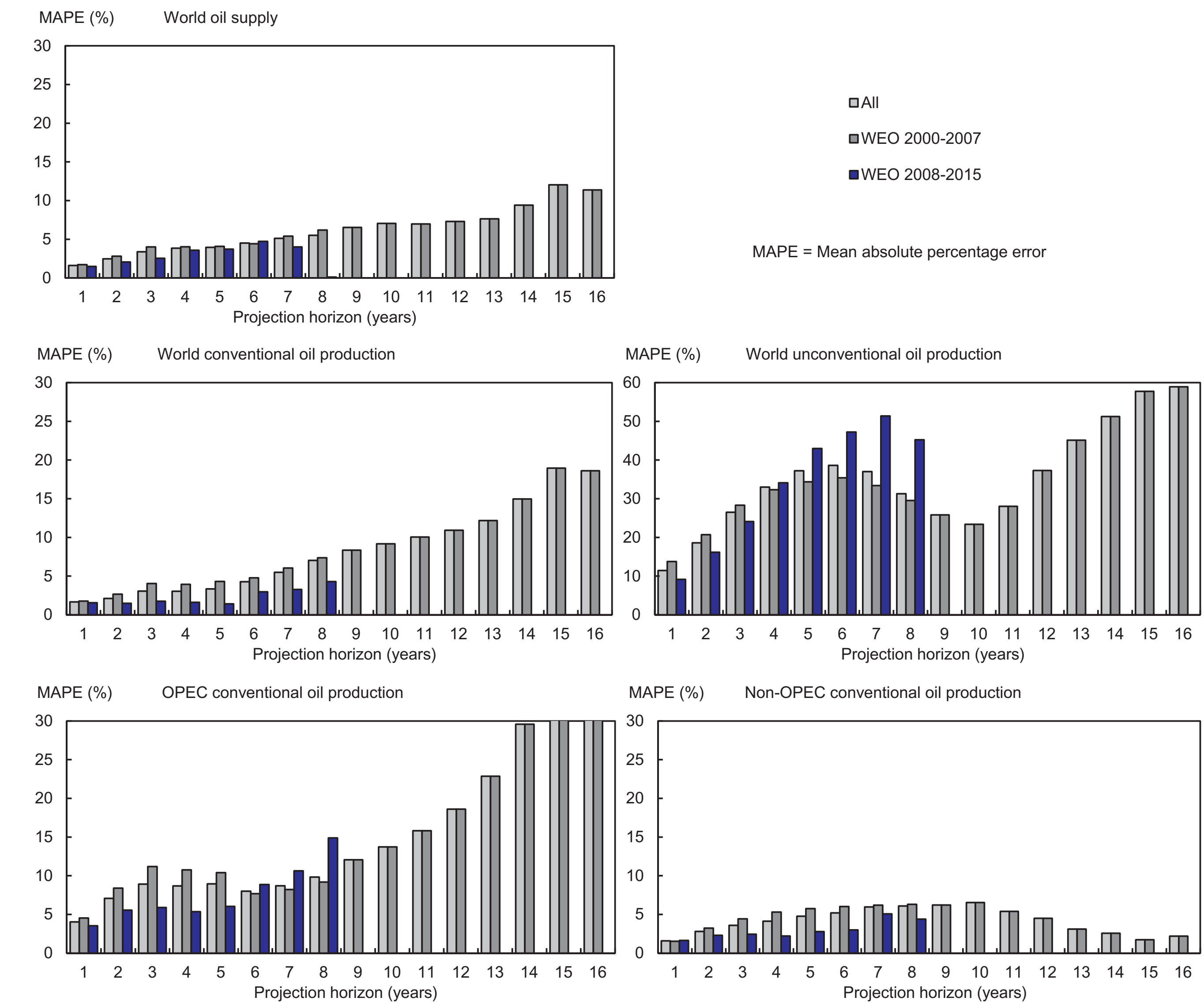

Fig. 9. Mean absolute percentage error (MAPE) by projection horizon (years) for World oil supply, World conventional oil production, World unconventional oil production, OPEC conventional oil production and Non-OPEC conventional oil production. Note the different axis scale for World unconventional.

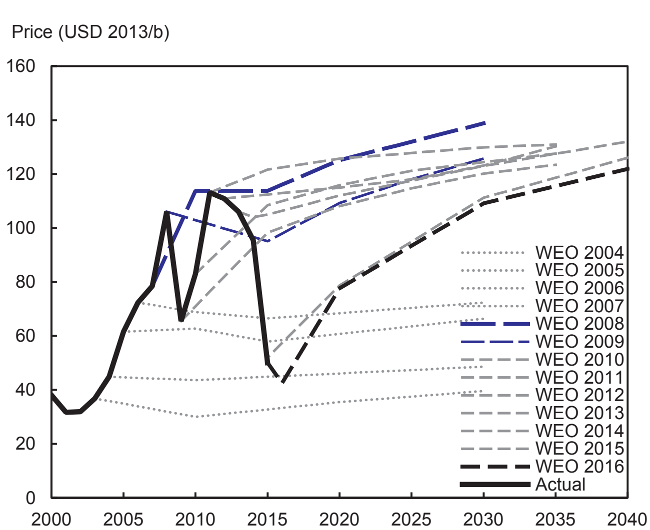

Fig. 10. Actual (2000–2015) and projected oil prices.

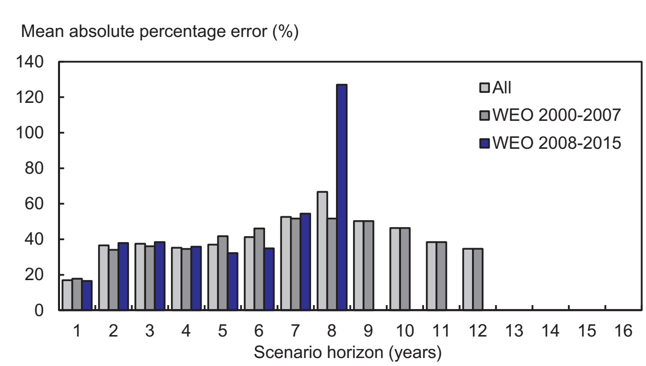

Fig. 11. Mean absolute percentage error (MAPE) by projection horizon (years) for oil prices.

projections, can be expected since oil prices have been more volatile than production historically. As noted in Section 4.2, two groups of projections can be distinguished. The WEO 2004-2007 projecting almost flat prices and the WEO 2008-2015 projecting prices reverting to around 120 USD per barrel in the long term, with the two most recent

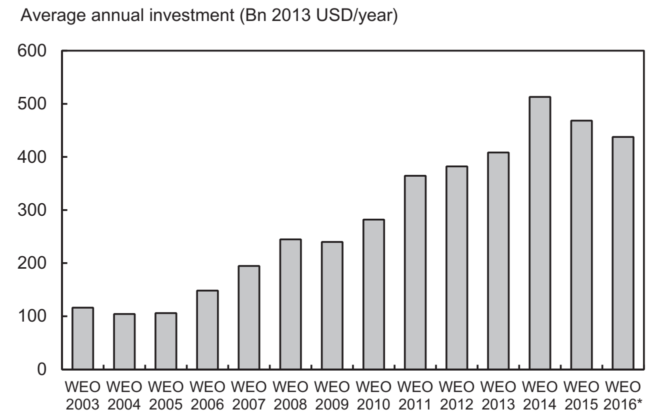

Fig. 12. Average annual upstream oil investments during projection period. * = WEO 2016 figure based on assumption since upstream oil is not reported separately from gas in WEO 2016. Assumption based on same decline as in total upstream oil *and* gas expenditure between WEO 2015 and WEO 2016.

projections doing so at a much slower pace. No trend of accuracy improvement can be distinguished. The error for only one year forward is around 17 percent for both new and old groups, illustrating the difficulty and uncertainty in price projection. As reported in Table 3, error directions have gone from mostly underestimations (93 percent) to a majority of overestimations (67 percent) in new projections. The WEO 2008 price projection for year 2015 was off by 127 percent, explaining the deterioration of the WEO 2008-2015 category for projection horizon 8 years.

Estimates of necessary upstream oil sector investment accompanying production and price projections are available since WEO 2003. In the reports, these are presented in cumulative amounts during the projection period. The corresponding average annual amount for each projection is presented in Fig. 12 (also previously in Fig. 3). As noted earlier, projected investments have been increasing gradually since WEO 2005, with a drop in the two most recent reports. Since only annual averages derived from cumulative amounts are available, no formal calculation of accuracy is made. However, historical annual global upstream oil and gas investment data for 2000–2015 published in WEO 2015 (Fig. 3.4, p. 117) show that these have increased each year in a similar way as projections have. This suggests a low accuracy consisting of almost only underestimations.

4.3. Uncertainty of current projections

Fig. 13 shows the production projections of WEO 2016 together with derived empirical prediction intervals. The grey areas represent prediction intervals based on all historical projections consistent with a 57.5 and 88.9 percent confidence level respectively (equal to ± 1 MAE and ± 2 MAE). The dashed lines represent prediction intervals based on only new projections (WEO 2008-2015) with the same two confidence levels. Since the prediction intervals are based on mean absolute errors per projection horizon, the sample underlying the mean decreases with the projection length. Specifically, the intervals for the longest horizon are only based on one projection and the far end of the prediction intervals should be treated with caution.

The general patterns from the previous accuracy analysis are also visible in this set of figures (Fig. 13). Prediction intervals for Non-OPEC production are significantly narrower than for OPEC. Also, intervals are tighter for conventional than unconventional oil production, at least in the near term. For most categories intervals based on only new projections are tighter. Except for the Non-OPEC category, the general trend of increasing uncertainty with projection horizon is obvious. The prediction intervals for oil prices are wide, illustrating the high uncertainty of these projections (Fig. 14).

5. Discussion

5.1. Comparison of results

The analysis show that WEO projections of the top production aggregate World oil supply have been revised downwards in three distinctive steps and recently, gradually upwards. Projections of oil price have been revised upwards until 2008 and stayed relatively stable since then. Upstream investments have been continually revised upwards between WEO 2005-2014. The downward production revisions are mainly allocated to OPEC conventional oil production while the Non-OPEC part has been relatively stable. The recent upward revisions are allocated to unconventional oil developments, in particular due to US tight oil.

The accuracy of projections between year 2000 and 2015 reflects the size and directions of revisions. The moderate accuracy of World oil supply is a combination of relatively high accuracy of conventional oil and low accuracy of unconventional oil. The relatively accurate conventional oil is a combination of high accuracy of Non-OPEC production and low accuracy of OPEC production. The inaccuracy of oil prices illustrates their high volatility and the common knowledge of the difficulties to predict oil prices with any certainty. In terms of accuracy and error symmetry, there has been an improvement between older and newer WEO production projections in most categories (unconventional oil being the most significant exception). Interestingly, this finding is contrary to Ascher's [5] broad study and O'Neill and Desai's [11] and Winebrake and Sakva's [22] specific EIA studies where all three found no evidence of accuracy improvement over time. Future updated studies, with larger samples of projections will determine if this part of our result will hold.

Main stated motivations of projection revisions include both demand and supply factors. On the demand side, revisions are made in accordance to lower than expected trends in oil demand, higher oil prices and stronger climate policies. On the supply side revisions stem from lower than expected willingness and ability to produce in OPEC countries, and reduced conventional production estimations in Non-OPEC countries due to more detailed modeling, and increased unconventional production due to US tight oil. Increases in oil price projections and necessary investments are a function of this changing supply-demand balance, and are also coupled to rising production costs.

These other findings are mostly in line with existing relatable retrospective energy studies. For example, [6,11,21,22,29] all find that small aggregate errors can conceal large sectoral errors, since counteracting errors can cancel each other out when aggregated. This motivates the more detailed and disaggregated approach as applied in this study. High accuracy of Non-OPEC projections is also illustrated in the case of Norway and Denmark [54], however this study only covers a single region of offshore production, with somewhat different dynamics compared to onshore production [55]. Issues with OPEC and difficulties with its projection have been noted many times [56,57], as well as the volatility and difficulty of projecting oil prices [58,59].

5.2. Robustness of results

The sample size is relatively small, with the revision analysis based on 17 projections and the accuracy analysis on 16. This small sample affects the robustness of the results, in particular as a function of horizon length, since sample size decrease by one for each time step. Combined with the tendency of increased uncertainty with projection length, the smaller sample size decreases the robustness of our longer term results significantly. The 5 and 10 year error averages often presented are based on 12 and 7 projections respectively, and should be fairly robust, or at least indicative.

The finding of improved accuracy is also sample dependent. We use WEO 2000-2016 and divide the sample in half for new and old averages. With different sample size or different comparisons it is

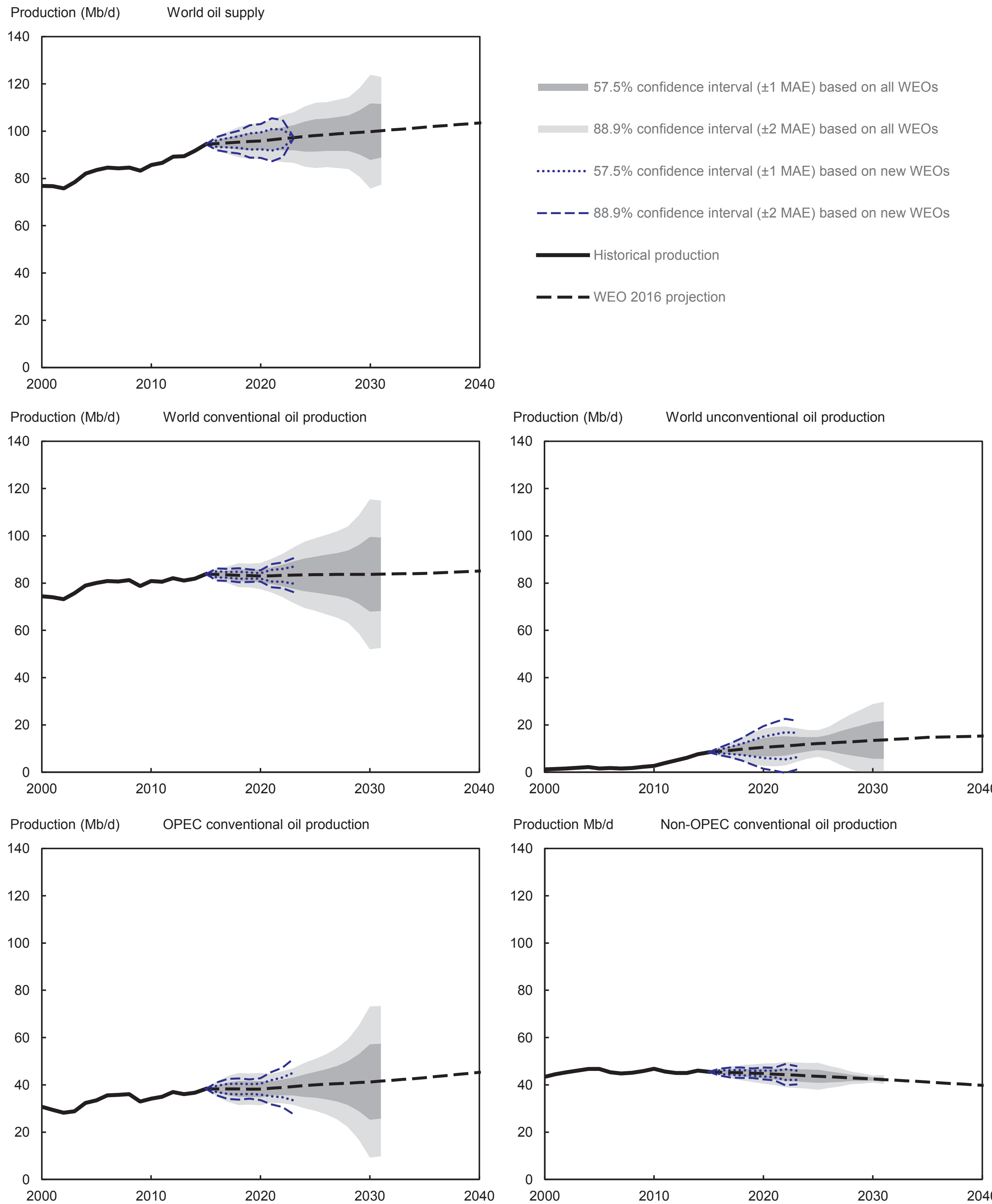

Fig. 13. Historical (2000–2015) and projected production of WEO 2016 with different empirical prediction intervals for World oil supply, World conventional oil production, World unconventional oil production, OPEC conventional oil production and Non-OPEC conventional oil production.

possible this result does not hold. Further studies can investigate this.

Besides these sample concerns the fundamental uncertainty of the future remains. There is no guarantee that past performance will inform future performance, although based on past experience it can be deemed likely. However, this opens up another layer of examination and is an interesting area for future research, for example the validation of derived empirical prediction intervals. A pioneering work in this area is [32] who show by out-of-sample investigations that the assumption of Gaussian error distributions is accurate, which we used in our study for the confidence level interpretations.

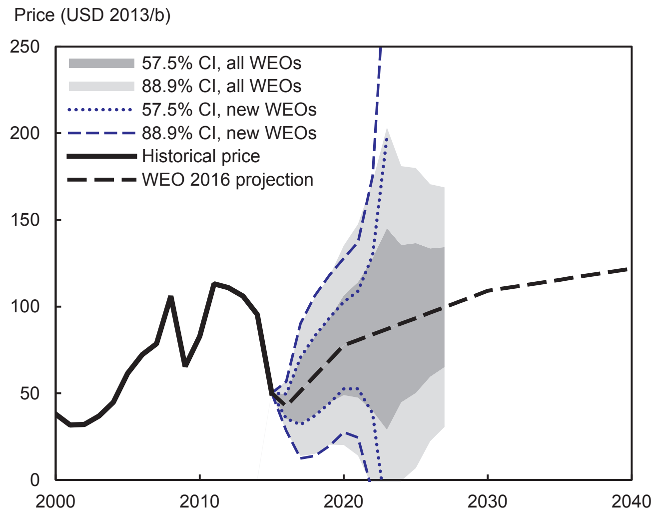

Fig. 14. Historical (2000–2015) and projected price of WEO 2016 with different empirical prediction intervals. Dark grey: ± 1 MAE of all WEOs, consistent with a 57.5% confidence interval, light grey: ± 2 MAE of all WEOs, consistent with an 88.9% interval, dotted blue line: ± 1 MAE of new WEOs (57.5%) and dashed blue line: ± 2 MAE of new WEOs (88.9%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.3. Implications for users and modelers

Returning to our two starting points, what can be said about current projections and future modeling efforts by looking at past oil projections?

When using scenarios, it is important to be aware of the inherent uncertainty in projections of oil production and price. In planning and decision making a thorough investigation of uncertainty and risks should be made, and a range of possible outcomes should be considered, and preferable a robust strategy capable of handling such a range should be adopted. Empirical prediction intervals as presented in this study can be used as benchmarks for such assessments. These results can also be used as quantifications of input uncertainty in larger energy models, for example future oil price assumptions.

Scenario developers should continue to develop models according to changing circumstances and new information. Continuous evaluation of past projections can aid in this effort. Revision logs, accuracy analysis and empirical prediction intervals can give methodological insight and assist in communicating uncertainty to users. Projection evaluation also allows comparisons between scenario making institutions and could strengthen the authority of the most useful ones.

As indicated in this study, accuracy has increased in recent projections. Continued or increased modeling efforts have the potential to further increase accuracy. Based on past performance, three areas in particular need special attention: tight oil, OPEC and new technology. The high accuracy of Non-OPEC conventional oil production projections indicates the effectiveness of the WEO modeling methodology when applied to well-known resources, technology and economical and political frameworks. In other words, a bottom-up, field-by-field, agent-based approach has predictive power in regions with market based economic systems and with functioning and transparent institutions. Increasing geological knowledge and cost estimations can potentially improve accuracy further. Since tight oil is currently only produced in the US, it is possibly to assume that this production, although with a different dynamic [60–62], can be modeled in a similar accurate way based on geological and technical information and market dynamics. Increased understanding and precise modeling of tight oil has the potential to lead to higher accuracy in total world oil production projections because tight oil might in the future function as a relatively fast balancer of global supply and demand, operating on market principles rather than political ones.

For OPEC production, or production from countries where production is strongly political or at risk for other reasons such as armed conflict or terrorism, projection will remain challenging. Here, an expanded exploratory scenario approach can be motivated. Possibly in combination with scenario probabilities to facilitate planning and decision making. Also, OPEC actions as reaction to tight oil developments will be an important area of further study [63].

New technology, in particular in form of innovation and technological development in the oil sector and in substitute technologies, is unlikely to become accurately predictable as no systematic approach except perhaps increased awareness of potential disruptive technologies is likely to reduce uncertainty. Yet, a disruptive technological event is, arguably, more likely to happen in times of change, for example after a price increase. Consequently, efforts to scan for potential disruptions could be increased during periods of turbulence.

Finally, the successful and constructive use of scenarios spring from the relationship between the developers and the users, and therefore communication is important. Developers can increase transparency in assumptions and methods, provide more scenarios with ranges of projections and highlight uncertainty. Users, on their side, have responsibility not to distort scenario results, or cherry pick certain projections, and always stress the uncertainty reported by developers.

5.4. Future work

Some areas of further research have already been mentioned, including continuous updating by inclusion of new projections and historical data. Ideally, the IEA itself could regularly provide such examinations, which the US EIA already does. Such an effort could be more sophisticated and insightful since it will have full access to the model and its assumptions. Another area is projection comparisons, for example between EIA and IEA in terms of methodology and performance. An interesting methodological extension would be to use the quantifications of revisions to construct confidence intervals for comparison with the intervals based on past errors. This method is in line with Ascher's [5] observation that dispersion of projections reflects uncertainty and related errors.

6. Conclusions

This paper sat out to quantify revisions and accuracy of projections of central IEA WEO oil scenarios in order to inform scenarios users about indicated uncertainty of current projections and to inform scenario developers and modelers on where improvement efforts can be aimed.

Based on past performance, the uncertainty of current oil price projections is high. The mean absolute percentage error for oil prices is 17, 37 and 67 percent on 1, 5 and 8 year horizons, respectively. From a probabilistic view, taking the five year horizon as an example, this result implies that the WEO 2016 five year ahead point projection for year 2020 of 78 USD/b has at best a 58 percent chance of being within 49–107 USD/b, or a 89 percent chance of being within 20–135 USD/b. Empirical prediction intervals as derived here can help in communicating such uncertainty and assist in planning and decision making as useful benchmarks, or as input uncertainty in other models. Uncertainty of production projections is lower, with mean absolute percentage error for World oil supply of 4 and 7 percent on a 5 and 10 year horizon. However, important differences in underlying categories exist, with low accuracy of OPEC (8.9 and 13.7 percent, on 5 and 10 year horizons, respectively) and unconventional production (37 and 46 percent) while Non-OPEC production has high accuracy (4.8 and 6.5 percent).

Four major and mostly downwards production projection revisions were identified, motivated by both supply and demand factors that included policy reduced demand, OPEC strategic behavior and new

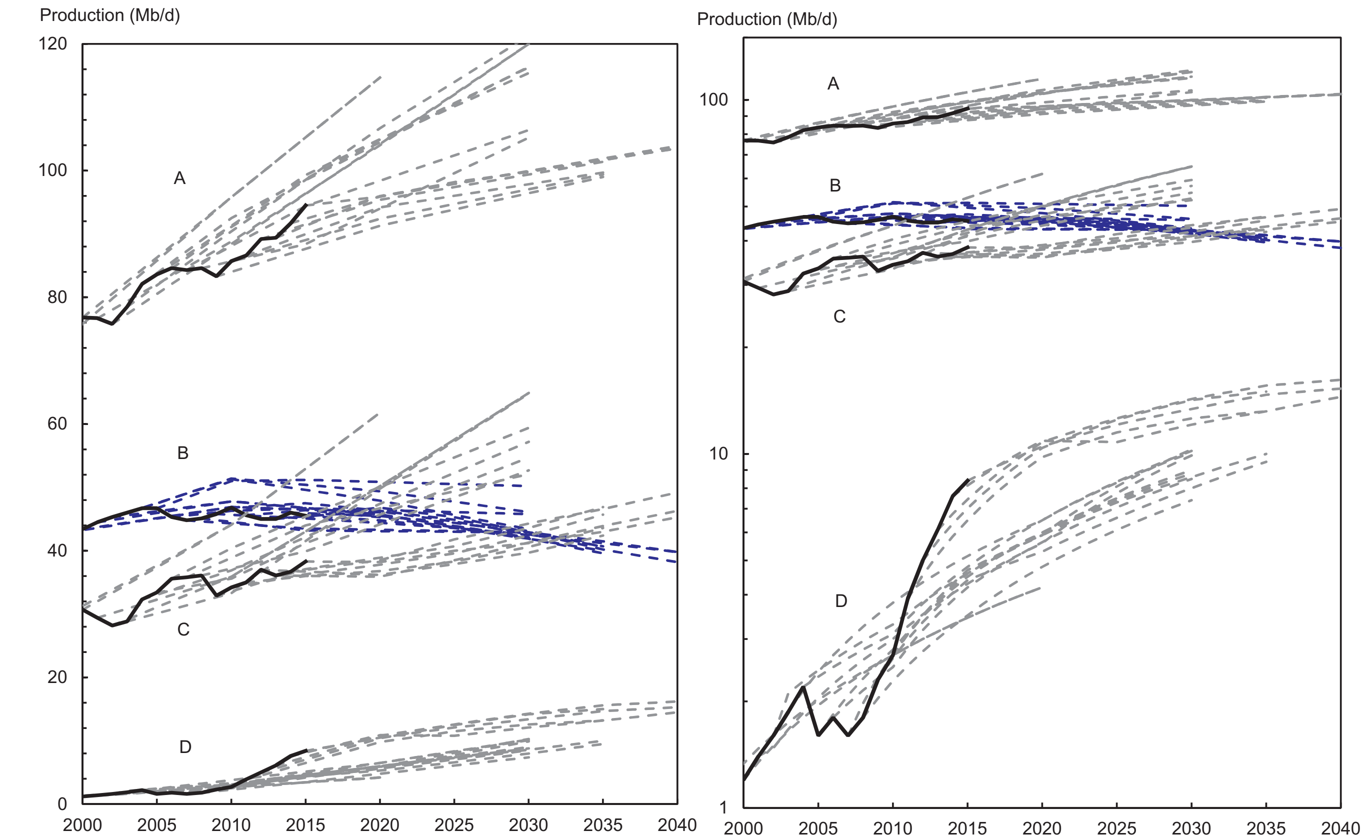

Fig. A1. Production projections in linear and logarithmic scale. World oil supply (A), Non-OPEC conventional (B), OPEC conventional (C) and World unconventional (D). World conventional oil production is not presented here, but equals B + C. Furthermore, A equals B + C + D.

technology as well as changes in modeling and central scenario design. Price and necessary upstream investment have been revised mostly upwards, with annual investments with more than 300 percent.

Analysts and scenario developers should continue to develop methods and models according to changing circumstances and new information. As shown, WEO projections have become more accurate with time, with recent Non-OPEC conventional production projections showing remarkably high accuracy (2.8 percent on a 5 year horizon).

Going forward, three areas in particular require priority in the modeling and analysis effort: tight oil, OPEC and new technology. Since US tight oil is located in a more predictable Non-OPEC environment, accuracy increases in tight oil projections can be expected as this supply source becomes better understood. This can possibly increase overall global accuracy of both production and price since tight oil can, to an increasing extent, play the role of a relatively fast balancer of global supply and demand operating on market principles. The lower accuracy of OPEC production projections can be expected to persist. One way to deal with this problem is to increase the use of OPEC specific scenarios, possibly with assigned probabilities, based on political or strategic analysis and risk assessments. The low accuracy of unconventional production projections highlight the difficulties in projecting technological development and innovation. There is no obvious way to deal with this uncertainty, except perhaps increased awareness. Also, in the longer run, accurate projections of substitute technologies will be a key determinant of oil demand.

Finally, communication is important for both scenario users and developers. Scenario developers can increase transparency, provide more scenarios and highlight relevant uncertainties. Scenario users on their hand, have responsibility not to distort scenario results and properly stress uncertainties reported by the developers.

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