How Accurate are Energy Intensity Projections?

David I. Stern

Crawford School of Public Policy, The Australian National University, 132 Lennox Crossing, Acton, ACT 2601, Australia. david.stern@anu.edu.au. Phone: +61-2-6125-0176.

ORCID: 0000-0001-6595-4268

22 May 2017

Abstract: Recent projections of energy intensity predict a more rapid decline in intensity than has occurred in the recent past. To assess how well such projections have performed in the past, I assess the accuracy of the business as usual energy intensity projections embedded in the annual *World Energy Outlook* (*WEO*) produced by the International Energy Agency since 1994. Changes in energy intensity depend on economic growth, and historical errors in projecting energy intensity can partly be explained by errors in projecting the rate of economic growth. However, recent projections of the elasticity of energy intensity with respect to economic growth probably overstate the likely future reduction in energy intensity even if economic growth is projected accurately. This could be because energy efficiency policies are not implemented as effectively as expected or because the economy-wide rebound effect is larger than modeling assumes.

Keywords: Integrated Assessment Models, Business as Usual, Projections

Acknowledgements

I thank Ken Baldwin for inviting me to give a presentation on the 2016 World Energy Outlook at the ANU Energy Change Institute 2016 Energy Update. I thank Stephan Bruns, Paul Burke, Bob Costanza, Ida Kubiszewski, and two anonymous referees for their very helpful comments and encouragement. I also thank the Australian Research Council for funding under Discovery Project (DP160100756) "Energy Efficiency Innovation, Diffusion and the Rebound Effect."

Competing Interests

The author declares no competing financial interests.

Introduction

The future development of energy intensity – the ratio of energy use to gross domestic product (GDP) – is of interest both for projecting future energy demand based on projections of economic growth and, as one of the factors in the Kaya Identity, future greenhouse gas emissions. Marangoni *et al*. (2017) show that energy intensity is one of the two more important Kaya factors – the rate of economic growth is the other. If we are over-optimistic about the potential for limiting the increase in energy use under business as usual (BAU), climate policy may be weaker than it needs to be. Various researchers and organizations routinely project future energy intensity. Recent projections tend to predict faster future reduction in energy intensity than has occurred in recent history. The IPCC 5th *Assessment Report* integrates projections from many different models (Clarke *et al*. 2014 Figure 6.1) finding that 95% of models predict that energy intensity will decline more rapidly than in the past. The 2016 *World Energy Outlook* (*WEO-2016*) also projects more rapid decline in energy intensity in the future under the "Current Policies" scenario than has occurred in the last couple of decades (Figure 1).[1] Here, I investigate how well the *WEO* has projected changes in energy intensity to date and evaluate the prospects for achieving such a rapid decline in the future.

The mean rate of decline of world energy intensity from 1990 to 2015 was 1.46% p.a. (Figure 1). *WEO-2016*'s Current Policies projection sees energy intensity declining by 2.09% p.a. till 2020 and by 2.13% p.a. between 2020 and 2030, after which the rate moderates to 1.7% p.a.[2] Energy intensity did decline more rapidly than this in a few recent years during the later years of economic booms. But these were exceptions. In the immediate aftermath of the Great Recession of 2008-9, energy intensity actually increased, and its decline was quite slow in the early part of the previous boom too (Jotzo *et al*. 2012). The New Policies scenario expects

[1] Following IEA practice, I refer to each annual *WEO* by attaching the date of publication with a hyphen. The "Current Policies" scenario assumes that only energy and climate change policies that are already implemented will be in place in the future. The IEA's "New Policies" scenario assumes that other policies that have been announced but not yet implemented will be implemented. In *WEO-2016* this includes policies that countries agreed to as part of the Paris Climate Change Accord (IEA, 2016)

[2] IEA makes projections for the level of energy use for a number of specific years in the future – in *WEO-2016*: 2020, 2030, and 2040 for the Current Policies scenario. I derived these rates of change in energy intensity from IEA's stated assumptions on the future rate of economic growth and their projections of the level of energy use at these future dates. IEA makes both global and regional projections. Here, I only analyze the global projections.

more rapid decline still in future energy intensity.

Though the projected rate of decline under BAU is more rapid than that in the recent past, this does not mean that such a rate of decline is impossible. Perhaps there are good reasons why the decline should accelerate. How well have past projections matched subsequent reality? The *WEO* provides a good case study, as the IEA has published the *WEO* annually since 1993 (with the exception of 1997) and most editions contain a Baseline, BAU, Reference, or Current Policies projection of world economic growth and energy use. I analyze projections of economic growth and energy use in all *WEO*s published since 1994, which are available online, to find out how well they have projected energy intensity to date. Of course, the IEA has always warned that real world developments may turn out differently to what they expected at the time of projection (IEA, 1994 to 2016). Still, it is important to know if there is a systematic bias in these projections rather than simply random forecast errors.

Projections vs. Actual Outcomes

Researchers have previously assessed how well the *WEO* has projected developments in solar PV and other renewable energy technologies (Metayer *et al*. 2015) and how well IPCC reports have projected carbon dioxide emissions intensity (Pretis and Roser 2016).[3] Metayer *et al*. (2015) analyze projections in all *WEO*s from 1994 to 2014. They find that the growth of solar technologies and wind energy has been consistently strongly underestimated, suggesting that there could be systematic biases in the underlying modeling.

The IEA also assessed past *WEO* projections for OECD primary energy demand and world oil demand (IEA 2000). They found that from *WEO-1993* to *WEO-1995* they underestimated OECD energy demand to 2000 while *WEO-1996* and *WEO-1998* overestimated it. The cumulative deviations by 2000 were, however, small – ranging from about -1.5% to +0.75%.

Figure 2 shows, for each *WEO*, the difference between the actual annual rate of change of energy intensity and its projected rate of change in subsequent years. Positive deviations indicate that energy intensity declined by less (in absolute value) than it was projected to, so that the level of energy intensity was higher than projected in 2015 (2010 for *WEO-1994* to *WEO-1996*) and *vice versa*. Intensity declined more slowly in following years than *WEO-*

[3] Other studies such as Aleklett *et al*.'s (2010) review of *WEO-2008*'s projection for world oil production do not compare projections to actual outcomes.

1994 to *WEO-1996* projected. Then from *WEO-1998* to *WEO-2003* energy intensity declined much faster in subsequent years than projected. Finally, from *WEO-2004*, with the exception of *WEO-2014*, the projections have been over-optimistic about the rate of decline in energy intensity.

It turns out that the correlation between these cumulative projection errors and the respective cumulative projection errors in GDP is -0.8. Csereklyei *et al.* (2016) show that the rate of change in energy intensity is negatively correlated with the rate of economic growth and that in the absence of economic growth energy intensity tends to increase slowly. As IEA uses external projections of GDP growth, a better assessment of the performance of the projections would remove the effect of economic growth.

Decomposing Projections

We can use an identity decomposition to investigate the role of economic growth rate projections in projections of energy intensity. Denote the growth rate of energy intensity by $g(E/Y)$, where E is global energy use, Y is total GDP, and $g(.)$ is the average percentage growth rate over a given period. Then multiplying and dividing $g(E/Y)$ by the growth rate of GDP, $g(Y)$, we have:

$$g(E/Y) \equiv \frac{g(E/Y)}{g(Y)} g(Y) \tag{1}$$

The term $g(E/Y)/g(Y)$ can be seen as the elasticity of energy intensity with respect to economic growth assuming that the rate of decline in energy intensity is zero in the absence of economic growth. Figure 3 presents actual and projected $g(E/Y)/g(Y)$ from the base year of each *WEO* to either 2015 or 2010. The realized elasticity has increased (in absolute value) over time from around -0.3 to -0.6.[4] The major changes in the elasticity are associated with events in 2010 when energy intensity increased (Figure 1). The projections of *WEO-1994* to *WEO-1996* end in 2010. Hence their realized elasticities are relatively small. 2010 is included in the projection periods for *WEO-1998* to *WEO-2011* but the following years up to 2015 are also included in the calculations of the elasticity. From *WEO-2012* on, 2010 is no longer included in the projection period, and, as a result, there is a sharp increase in the realized elasticity. This suggests that the range of values from *WEO-1998* to *WEO-2011* is likely to be more representative of the long-run value of the elasticity.

[4] From here on, when comparing values of the elasticities, absolute values are assumed.

Figure 3 shows that *WEO-1994* to *WEO-1996* overestimated the elasticity. From 1998 to 2001 the *WEO* estimated smaller elasticities, but these underestimated the actual elasticities. Since then, the projected elasticities have become larger. *WEO-2009* to *WEO-2011* overestimated the elasticity, whose realized value was influenced by the increase in energy intensity in 2010. From 2012, that increase in energy intensity was no longer in the projection period, the realized elasticity increased, and *WEO-2012* to *WEO-2015* underestimated the elasticity.

Figure 4 decomposes the errors in projected energy intensity in Figure 2 into the parts due to the error in projecting the elasticity and the error in the projected economic growth rate. I compute (1) for each projection period by substituting on the right hand side of (1) the projected elasticity for $g(E/Y)/g(Y)$ but the actual realized growth rate of GDP for $g(Y)$.[5] The error in projecting energy intensity using this substituted formula is then the part of the total error due to the elasticity, and the remaining error is due to the growth rate. Through 2001, the two components of the projection error are highly positively correlated ($r = 0.995$), while from 2002 to 2016 the correlation is -0.33. The correlation for the full period is 0.12. The mean absolute value of the two error components is similar, with the role of growth rate errors increasing relative to that of elasticity errors over time.

Explaining Changes in the Projection Errors

Explaining changes in the behavior of the elasticity projection error over time has to be somewhat speculative, but we can point to some potential factors. The number of variables about which assumptions are made in IEA's modeling has changed over time, as has the number of explicit policies that the modelers have tried to take into account. In the earliest reports, the rate of economic growth, the future development of energy prices, the future development of energy efficiency in some sectors, future power generation capacity, and energy policies, in terms of taxes on energy, were all fed into the model that produced the energy use projection (IEA 1994, 1995, 1996). *WEO-1998* was based on a new world energy model (WEM, IEA 1998). In particular, additions to power generation capacity were modeled as an outcome of an economic optimization decision.

In *WEO-2000* the BAU scenario was replaced with a Reference scenario that took into

---

[5] The decomposition results are only very slightly different if instead the projected growth rate is used together with the actual elasticity first and then the residual found.

account specific new energy and climate change policies in OECD countries (IEA, 2000). However, these changes do not have an apparent effect on the elasticity itself in Figure 3 or on the behavior of the elasticity projection error in Figure 4, which was highly correlated with errors in the rate of economic growth through *WEO-2001*.

“The WEM underwent a major overhaul in 2004” (IEA 2006 p. 55), which was further extended in following years (IEA 2006, 2007). This allowed more detailed modeling of specific energy policies and measures (IEA, 2006). The 2004 revision coincides with larger positive elasticity projection errors in Figure 4 and an increase in the absolute value of the elasticity in Figure 3. In *WEO-2008*, “the integration of the WEM into a general equilibrium model, started in 2007, was taken a step further, in order to model more precisely the feedback links between energy markets and the macro-economy” (IEA 2008 p. 61). These changes do coincide with a marked increase in the projected elasticity in Figure 3. Subsequent reports (e.g. IEA 2011, 2013, 2014) increasingly emphasized that energy price projections were derived iteratively rather than being based completely on exogenous assumptions, but noted that the model was still a partial equilibrium model.

As the actual elasticities in recent years are based on very short time series that do not include a recession, they are likely to overestimate the true elasticity. Csereklyei and Stern (2015) find that, contrary to conventional wisdom, the elasticity of energy use per capita with respect to GDP per capita increases with GDP per capita. Therefore, we should not necessarily expect the elasticity of interest here to decline over time. Instead, Csereklyei and Stern (2015) find that the slow growth of energy use in high income countries relative to upper middle income countries is mostly due to convergence effects – countries that were initially relatively energy intensive have converged in energy intensity with those that initially had relatively low energy intensity. It is likely, therefore, that since 2008 the *WEO* has overestimated the elasticities that will eventuate over the full projection horizons of 2030 to 2040.

The projected elasticities for recent years in Figure 3 actually understate the elasticities that IEA expects to eventuate. IEA has stated that they expect countries to implement more policies than in the Current Policies scenario in subsequent years and that their central scenario is now the New Policies scenario (IEA 2015). One possible reason for overestimating future elasticities is that not all stated policies are implemented as effectively as IEA expects, and over time there have been more and more explicit policies for IEA to incorporate in the WEM. The WEM now takes into account thousands of individual policies and measures (IEA 2011).

Another possible reason why both IEA and the IPCC consensus projections overestimate the future decline in energy intensity is that they do not take the economy-wide rebound effect sufficiently into account (Saunders 2013). Improvements in pure energy efficiency lower the cost of providing energy services and thus, via the law of demand, result in greater consumption of those energy services, so that the reduction in energy use is less than the improvement in energy efficiency. Economy-wide, this micro-level direct rebound effect may be amplified or attenuated by indirect rebound, general equilibrium, and dynamic effects (Stern 2011). There are many empirical estimates of the micro-level direct rebound effect, but there are no good empirical estimates of the economy-wide rebound effect. Simulation models show that the economy-wide rebound could be larger or smaller than the micro-level rebound (Turner, 2013). Depending on assumed model parameters, Turner (2009) finds that the economy-wide rebound effect for the UK could range from a negative value – where energy use falls by more than energy efficiency improves - to more than 100% - where energy use actually increases following an efficiency improvement.

However, the consensus is that the effect is positive and larger than the micro-level direct rebound effect (Saunders 2008; Stern 2011). Stern (2012) finds that reductions in energy intensity are considerably less than improvements in energy efficiency at the economy-wide level. The most important countervailing factor was substitution of energy for labor. Van Benthem (2015) and Csereklyei *et al*. (2016) find that energy intensity is similar in today's developing countries to what it was in today's developed countries when they were at the same per capita income level, despite the huge improvements in energy efficiency in many technologies, which are used in both developed and developing countries alike.[6]

Conclusion

In conclusion, energy intensity is likely to decline by less than projected in the most recent *WEO*'s despite their using more sophisticated and detailed modeling of the economy and energy policies. A possible reason for this is that they underestimate the size of the economy-

[6] Changes in energy intensity are of course not just the result of energy efficiency improvements and the rebound effect. Independent changes in other factors and the efficiency with which they are used and structural change in the economy can all have an effect (Stern, 20012; Saunders, 2015).

wide rebound effect. This may also be the case for other projections of future energy intensity aggregated by the 2014 IPCC report. Empirical estimation of the economy-wide rebound effect and incorporation of the findings into energy projection models should be a research priority for energy economics and the climate policy community.

Data

I used the BAU, Reference, or Current Policies projection of world economic growth rates and the level of world energy use from each *WEO* for each sub-period and specific year that they were given, respectively. *WEO-1999* did not report specific quantities of projected future energy use but did state that energy use was expected to rise by 65% by 2020 and that the same economic growth rate projections were used as in *WEO-1998*. For *WEO-1995* and *WEO-1996*, I used the "capacity constraints" scenario, which assumes historical trends in energy efficiency. In the case of *WEO-1996*, where separate market (MER) and purchasing power parity (PPP) exchange rate economic growth rate projections were given, I use the PPP growth rate. WEO-1994 and *WEO-1995* give only a MER world economic growth rate. This is 0.1% p.a. lower than the MER growth rate in *WEO-1996* in 1995 and 0.3% p.a. lower in 1994 and so I assume that the respective PPP growth rates are also 0.1% and 0.3% p.a. lower. I used actual world GDP in 2011 PPP dollars from the World Bank's *World Development Indicators* for the base year of the projections in the report and projected GDP at future dates using the given growth rates. I then divided the projected energy use at each future date by projected GDP to give projected energy intensity. I then computed the growth rate of energy intensity in each future sub-period.

References

Aleklett K, Höök M, Jakobsson K, Lardelli M, Snowden S, Söderbergh B (2010) The peak of the oil age – analysing the world oil production reference scenario in World Energy Outlook 2008. Energy Policy 38(3): 1398–1414.

Clarke, L. *et al*. (2014) Chapter 6: Assessing transformation pathways. In: Edenhofer, O. *et al*. *Contribution of Working Group III to the IPCC 5th Assessment Report*. Cambridge University Press, Cambridge.

Csereklyei Z, Rubio-Varas MdM, Stern DI (2016) Energy and economic growth: The stylized facts. Energy Journal 37(2): 223-255 (2016).

Csereklyei Z, Stern DI (2015) Global energy use: Decoupling or convergence? *Energy Economics* 51: 633-641.

International Energy Agency (1994) *World Energy Outlook: 1994 Edition*. OECD, Paris, Paris.

International Energy Agency (1995) *World Energy Outlook: 1995 Edition*. OECD, Paris.

International Energy Agency (1996) *World Energy Outlook: 1996 Edition*. OECD, Paris.

International Energy Agency (1998) *World Energy Outlook: 1998 Edition*. OECD, Paris.

International Energy Agency (1999) *World Energy Outlook: Looking at Energy Subsidies: Getting the Prices Right - 1999 Insights*. OECD, Paris.

International Energy Agency (2000) *World Energy Outlook 2000*. OECD, Paris.

International Energy Agency (2001) *World Energy Outlook: Assessing Today's Supplies to Fuel Tomorrow's Growth - 2001 Insights*. OECD, Paris.

International Energy Agency (2002) *World Energy Outlook 2002*. OECD, Paris.

International Energy Agency (2003) *World Energy Investment Outlook: 2003 Insights*. OECD, Paris.

International Energy Agency (2004) *World Energy Outlook 2004*. OECD, Paris.

International Energy Agency (2005) *World Energy Outlook 2005: Middle East and North Africa Insights*. OECD, Paris.

International Energy Agency (2006) *World Energy Outlook 2006*. OECD, Paris.

International Energy Agency (2007) *World Energy Outlook 2007*. OECD, Paris.

International Energy Agency (2008) *World Energy Outlook 2008*. OECD, Paris.

International Energy Agency (2009) *World Energy Outlook 2009*. OECD, Paris.

International Energy Agency (2010) *World Energy Outlook 2010*. OECD, Paris.

International Energy Agency (2011). *World Energy Outlook 2011*. OECD, Paris.

International Energy Agency (2012) *World Energy Outlook 2012*. OECD, Paris.

International Energy Agency (2013) *World Energy Outlook 2013*. OECD, Paris.

International Energy Agency (2014) *World Energy Outlook 2014*. OECD, Paris.

International Energy Agency (2015) *World Energy Outlook 2015*. OECD, Paris.

International Energy Agency (2016) *World Energy Outlook 2016*. OECD, Paris.

Jotzo F, Burke PJ, Wood PJ, Macintosh A, Stern DI (2012) Decomposing the 2010 global carbon dioxide emissions rebound. Nature Climate Change 2(4): 213-214.

Marangoni G, Tavoni M, Bosetti V, Borgonovo E, Capros P, Fricko O, Gernaat DEHJ, Guivarch C, Havlik P, Huppmann D, Johnson N, Karkatsoulis P, Keppo I, Krey V, Ó Broin E, Price J, van Vuuren DP (2017) Sensitivity of projected long-term CO2 emissions across the Shared Socioeconomic Pathways. Nature Climate Change 7: 113–117.

Metayer M, Breyer C, Fell H-J (2015) The projections for the future and quality in the past of the World Energy Outlook for solar PV and other renewable energy technologies. Proceedings of the 31st European Photovoltaic Solar Energy Conference, September 14-18, Hamburg Germany.

Pretis F, Roser M (2016) Carbon dioxide emission-intensity in climate projections: comparing the observational record to socio-economic scenarios. University of Oxford, Department of Economics, Discussion Paper Series 810.

Saunders HD (2008) Fuel conserving (and using) production functions. Energy Economics 30: 2184–2235.

Saunders HD (2013) Historical evidence for energy efficiency rebound in 30 US sectors and a toolkit for rebound analysts. Technological Forecasting and Social Change 80: 1317-1330.

Saunders HD (2015) Recent evidence for large rebound: elucidating the drivers and their implications for climate change models. *Energy Journal* 36(1): 23-48.

Stern DI (2011) The role of energy in economic growth. Annals of the New York Academy of Sciences 1219, 26-51.

Stern DI (2012) Modeling international trends in energy efficiency. Energy Economics 34, 2200–2208.

Turner K (2009) Negative rebound and disinvestment effects in response to an improvement in energy efficiency in the UK economy. Energy Economics 31: 648-666.

Turner K (2013) "Rebound" effects from increased energy efficiency: a time to pause and reflect. Energy Journal 34(4): 25-43.

Van Benthem AA (2015) Energy leapfrogging. Journal of the Association of Environmental and Resource Economists 2(1): 93-132.

Figure 1. World Energy Outlook 2016 Energy Intensity Projections vs Recent History

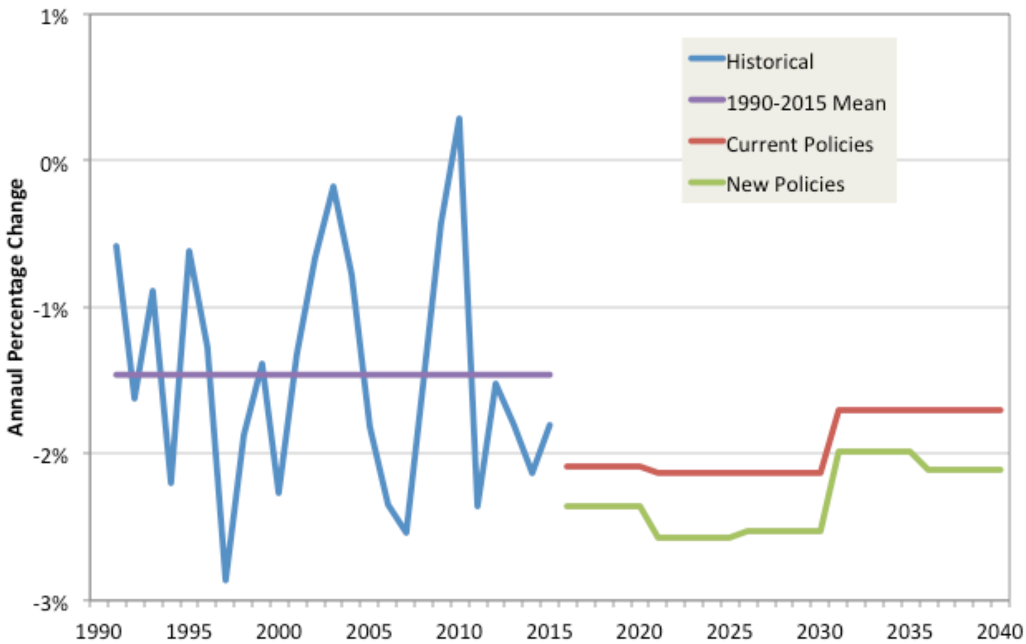
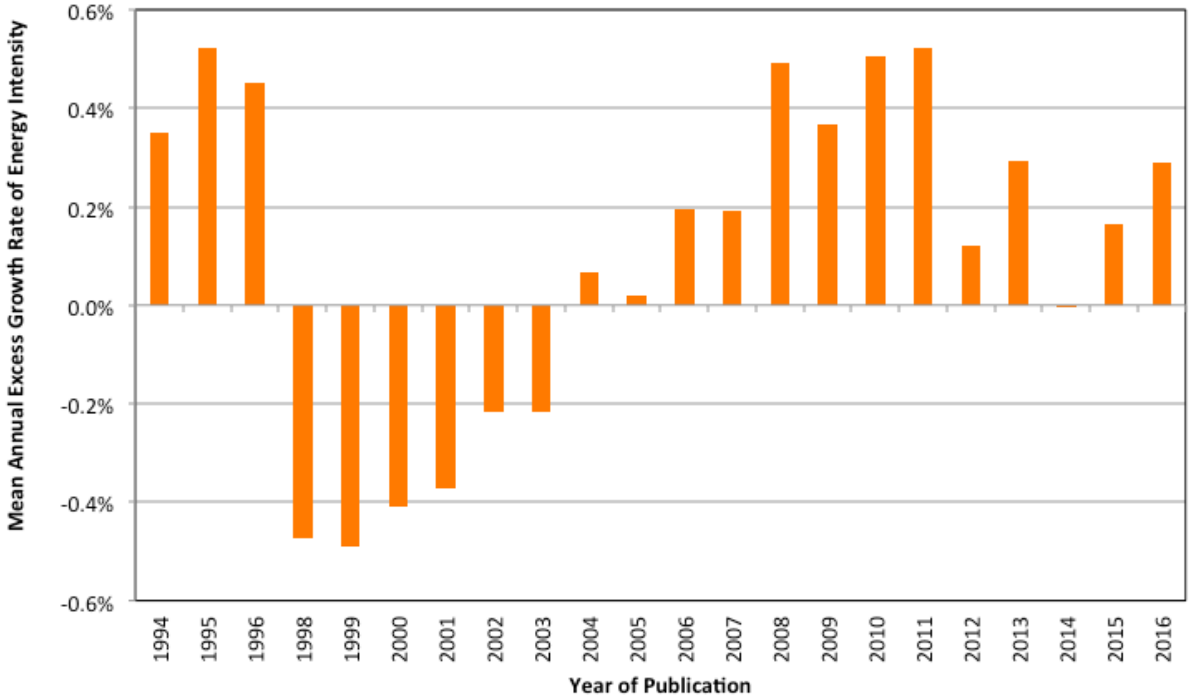
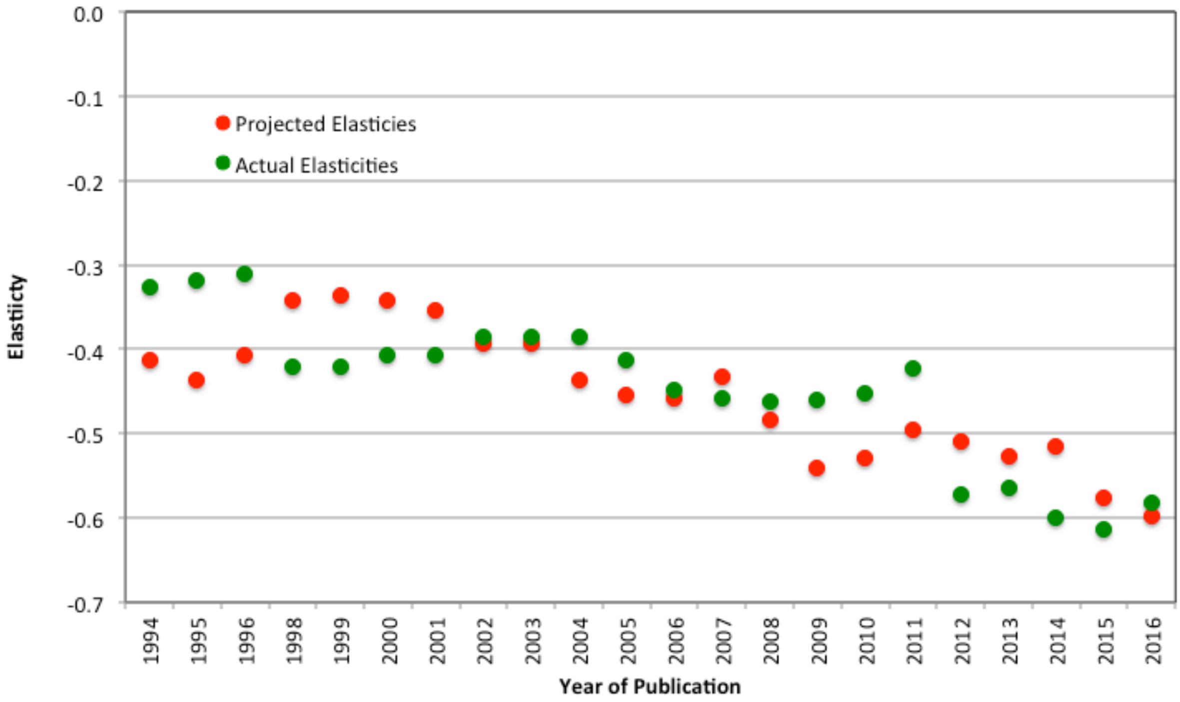


Figure 2. Energy Intensity Projection Errors



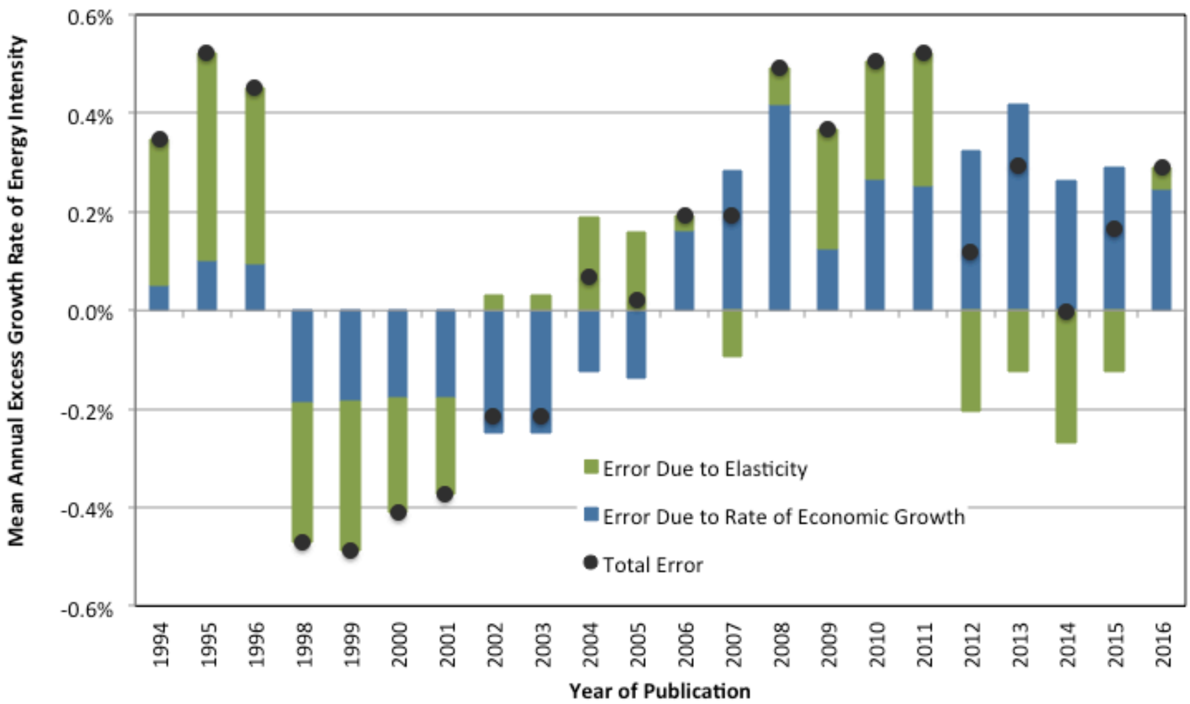
Notes: The dates refer to the publication date of the *WEO*. The percentage error is the mean annual difference between the percentage rate of change in actual energy intensity and projected energy intensity from the base year of the respective *WEO* through 2015 for *WEO-1998* forward. Positive values, therefore, indicate that energy intensity declined by less than expected and so the level of energy intensity was higher than projected in 2015 (2010 for *WEO-1994* to *WEO-1996*). Because the base year of *WEO-2015* is 2013 and of *WEO-2016* is 2014 it is possible to compute a projection error for these two latest reports.

Figure 3. Actual and Projected Elasticities of Energy Intensity with Respect to Economic Growth



Notes: The dates refer to the publication date of the *WEO*. Both elasticities are computed from the base year of the *WEO* through 2015 for *WEO-1998* forward using. For *WEO-1994* to *WEO-1996* the projection error is computed through 2010.

Figure 4. Decomposition of Projection Errors



Notes: The dates refer to the publication date of the *WEO*. Total error is equal to the projection error in Figure 2, which is the sum of the errors due to incorrect projection of the elasticity of energy intensity with respect to the rate of economic growth and incorrect projection of the rate of economic growth.