Evaluation of the DICE climate-economy integrated assessment

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Abstract

Climate-economy integrated assessment models are often used to assess the interaction between climate change effects and the economy. A simple but powerful model, DICE (Dynamic Integrated Climate-Economy) model, was developed at Yale. This is an easily accessible model that allows exploration of various parameters that affect long-term (years 2000-2300) climate change. The global economic model estimates the future growth of economic output tempered by abatement costs and climate change damages. It uses an optimization scheme to determine the CO_{2eq} price over time that maximizes discounted utility of consumption. However, there are a few areas that may be improved.

This paper addresses those areas. First, a model of renewable energy that explicitly accounts for the capital required for the transition is added. This has the effect of smoothing the beginning of the transition, and shows that we can afford the transition. Second, a modified damage function is used that shows a greater penalty for business as usual. Third, the growth model used in DICE results in a level of economic growth too high to be supported by historical data. A modified growth model is proposed based primarily on historical data from the Penn World Table that results in lower growth and a more rapid decline in growth rate.

Keywords: economic growth, energy, climate

JEL classifications: O41, O44, Q43, Q54

* All research for this paper was self-funded (Copyright Greaves 2015). I certify that I have the right to deposit the contribution with MPRA. The author would like to thank William Nordhaus for his tireless work in this area and for making the model available, and the Center for International Comparisons at the University of Pennsylvania for making the Penn World Table available.

1 INTRODUCTION

If we are to avoid the most severe consequences of climate change, we need to drastically reduce the emissions of greenhouse gases. The best way to do that is to put a price on the emissions of greenhouse gases in the form of a tax on CO_2 emissions or a cap and trade system. Other greenhouse gases need to be included, most likely as CO_2 equivalent. In this paper, CO_2 will be used to mean CO_2 and other greenhouse gases as equivalent CO_2 emissions. Either a tax or a cap and trade system can work if done well. However, it seems that a tax would be easier to negotiate and implement. In either case, a target price of CO_2 that changes over time is required. Integrated assessment models provide a tool which can be used to estimate the CO_2 prices that meet a certain goal, such as a maximum increase in global surface temperature from preindustrial times or to maximize the discounted utility of consumption over some time period.

In this paper, the Excel version of the DICE model (specifically DICE_2013R_112513s.xlsx) is used (Nordhaus, 2012, Nordhaus, 2013a). The time period used is over the years 2010 to 2250. The model actually runs from 2010 to 2305 in 5 year time steps but the last few decades can be contaminated with artificial end effects and the interesting behavior can be observed by 2250. In addition to providing CO_2 prices, the model provides several other variables that are insightful to plot over the time period of interest. The first of these is net real global GDP. The GDP values are in 2005 dollars less the costs associated with abatement and climate change damages. All of the results discussed in this paper are global values. A common way to look at results is to compare a business as usual case to another case where some policy is implemented. For paper the policy implemented is a global price for CO_2 emissions which DICE optimizes to maximize the discounted utility of consumption. Net GDP for the base case and optimized case is shown in Figure 1 below.

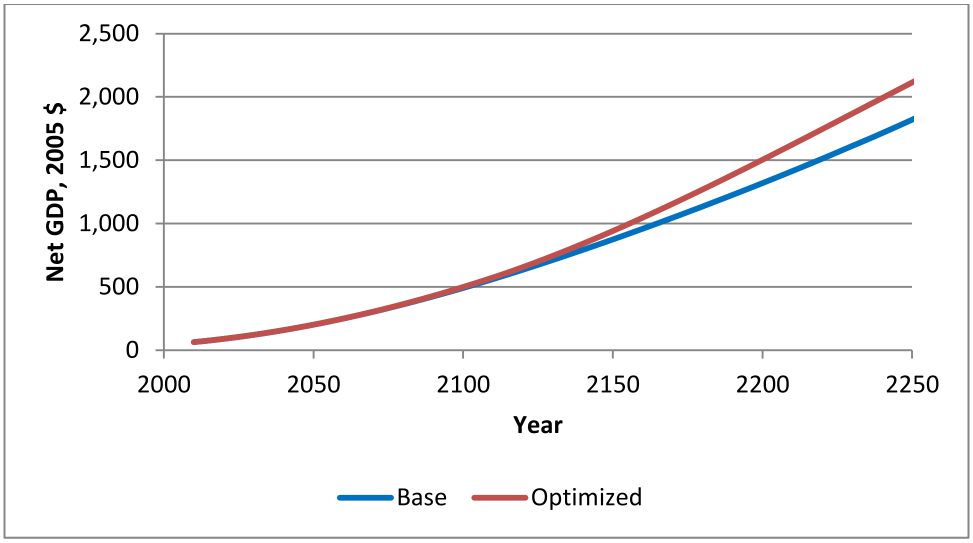
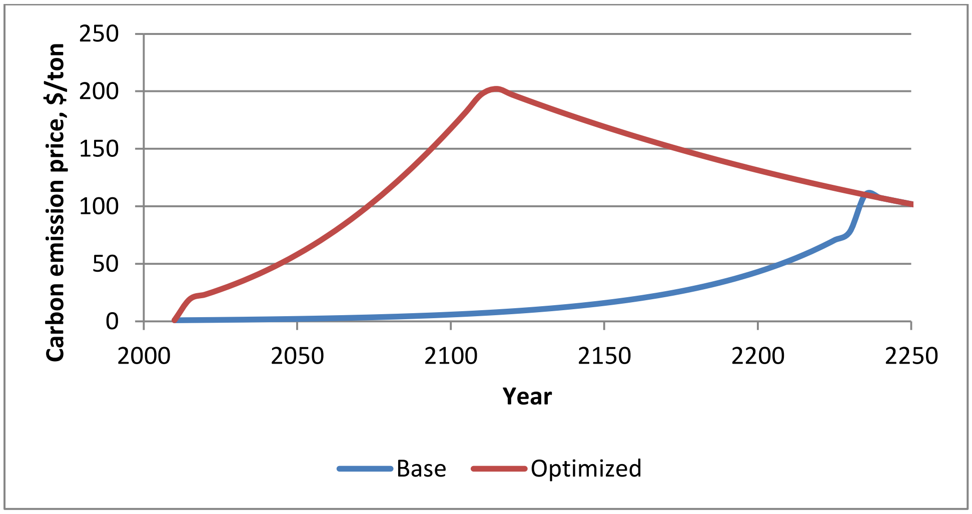


Figure 1. Net global GDP for the base and optimized cases.

There are two things that are striking about this graph. First is the continued rapid growth over the time period. In fact, the net GDP in 2250 for the optimized case is 33 times the 2010 value! This begs some questions. Is this growth realistic or even possible? Is this what we would expect based on historical data? This is reviewed in Sections 3 and 5 which indicates that we may be entering a low growth era. The other is that the base case is only a little lower than the optimized case. Transitioning to a low carbon world is going to be a massive undertaking. Is it worth doing for this modest improvement? It turns out that this difference is controlled by the assumed damage function. The damage function describes that reduction in GDP likely for a given increase in temperature from preindustrial times. There is some consensus on this function up to an increase of about 3 degrees C. Beyond that, there is an increasingly high level of uncertainty. DICE uses a fairly mild extension of the function up to 3 degrees C. Others have proposed a more drastic reduction for temperature increases greater than 3 degrees C. This has little effect on optimized cases because the temperature increase is generally kept below 3 degrees C, but significantly reduces the base case GDP. This is briefly explored in Section 2.

The next variable is the price of CO_2 emissions. This is closely related the fraction of CO_2 emissions abated and so they are shown together. The DICE model assumes a low but non-zero value for 2010 (1$/ton) with a slow increase over time for the business as usual case. This is intended to represent the current state of the price of CO_2 emissions and assumes we will continue to put prices on CO_2 emissions in a fragmented and uncoordinated way. In the model, the increasing price of CO_2 emissions causes an increase in the fraction of price of CO_2 emissions that are abated. This is shown in Figure 2 below.



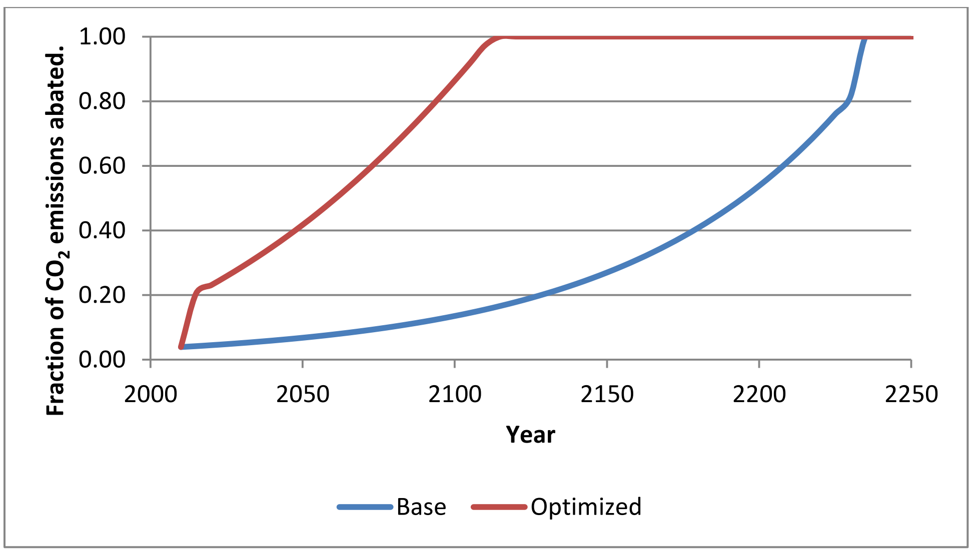


Figure 2. The top graph shows the price on CO_2 emissions for the two cases. The bottom graph shows the fraction of CO_2 emissions abated for the two cases.

An interesting observation relates to the way both the price of CO_2 emissions and the fraction of CO_2 emissions abated jump up in the first time step. While we can increase the price of CO_2 emissions with an agreement (no easy task) but the abatement requires significant capital to achieve. DICE does not explicitly address this issue. To address this issue a modification is explored to estimate the amount of capital required to make the transition. The price of utility scale photovoltaic electricity generation including an estimate of the price reduction with increased cumulative production is used to represent the price of capital required. While this will not be the only technology used, it is likely to a major factor and may set the price for other technologies. There is another reason to investigate the capital required to transition from fossil fuels to a low carbon energy source. This is to try to answer the question of whether we can actually afford to finance this transition. This modification is discussed in Section 4.

One last variable to track is the increase in temperature from preindustrial times. DICE sets that at the year 1900. DICE uses a simple model to estimate future temperatures based on CO_2 emissions, but it follows more sophisticated models well. The temperature for the base and optimized case is shown in Figure 3 below.

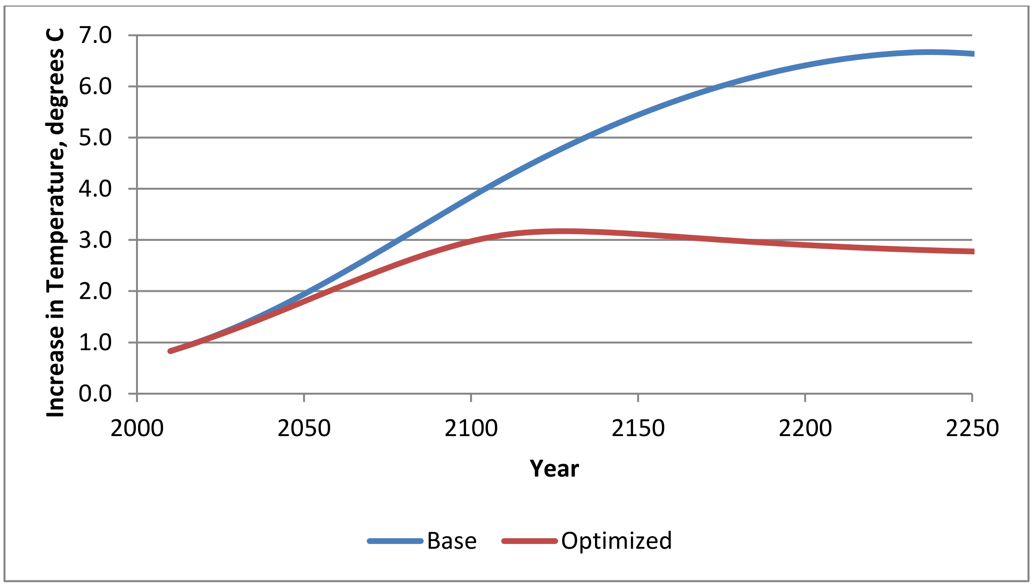


Figure 3. Increase in temperature from 1900.

This graph shows why the damage function in the range of 3 to 7 degrees C increase is important for the base case, but not the optimized case.

Section 5 summarizes some implications of some of the proposed modifications. Section 3 focuses on the long term prospects for economic growth. The trends seem to clearly indicate that economic growth rates are reducing. The rate of the reduction is certainly open to debate. This paper provides some evidence that the rate of economic growth reduction may be faster than others have been assuming. While this is good for our chances of avoiding the worst effects of climate change, it implies that there will be some challenges associated with low growth rates that lie ahead. These may include more frequent recessions and worsening inequality. We will need better tools to manage these effects.

Any look far into the future is tricky business. We can hardly imagine what the world will look like in 25 years, let alone 250 years. Still, we need to use the best tools we can develop today to glimpse that future.

2 DAMAGE

Damage functions can be presented as a percent of economic output that is lost due to the effects of increased temperature. These may take several forms from increased severe weather such as hurricanes and floods, to more severe droughts and wild fires, rising sea level, and ocean acidification. The damage function in DICE is the simple function of increased temperature in Equation 1.

$$\Omega=\psi_1\ \Delta T^2 \qquad (1)$$

In this equation, Ω is the fraction of output lost due to increased temperature, ψ_1 is a constant (0.00266375) and ΔT is the increase in global average atmospheric surface temperature since 1900. This function has a solid foundation based compilation of estimates by various studies. However, all of the estimates were conducted within the temperature increase range of 1 to 3 degrees C. Figure 3 shows the maximum estimated increase in temperature for the base case of nearly 7 degrees C. In the range of temperature increases from 3 to 6 there are several tipping points which could significantly increase the severity of the damage. However, uncertainty is very high in this range. All this is best discussed in The Climate Casino (Nordhaus 2013b).

Another damage function was used by Rezai and Ploeg (Rezai, et al 2014) and is shown in Equation 2.

$$Z=1 / (1 + (\Delta T / 20.2)^2 + (\Delta T^2 / 6.08)^{6.76}) \qquad (2)$$

In this equation, Z is the fraction of output remaining after output loss due to damage. This function which is equivalent to 1- Ω from Equation 1, matches the DICE damage function very closely up to about a 2.5 degree C change in temperature. After that the severity increases significantly faster. It is based on work by (Weitzman 2010) and (Ackerman et al 2012) and assumes that the fraction of output lost due to increased temperature 50% at 6 degrees C increase and 99% at 12.5 degrees C increase. The functions for Z and 1- Ω are shown in Figure 4 below.

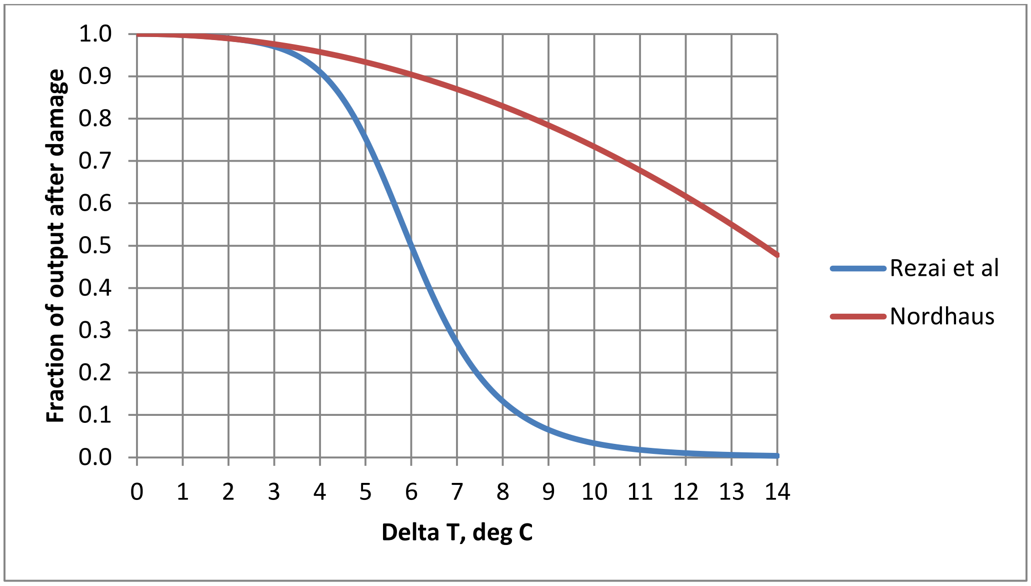


Figure 4. Damage functions Z from Rezai and 1- Ω from Nordhaus.

Because the uncertainty is so high above an increase in temperature of more than 3 degrees C, it is not possible to assess which function may be more appropriate. However, Rezai seems to better represent the very different world we would experience with very high increases in temperature. We can assess how these different functions assess the projected net economic output. This is shown in Figure 5 below.

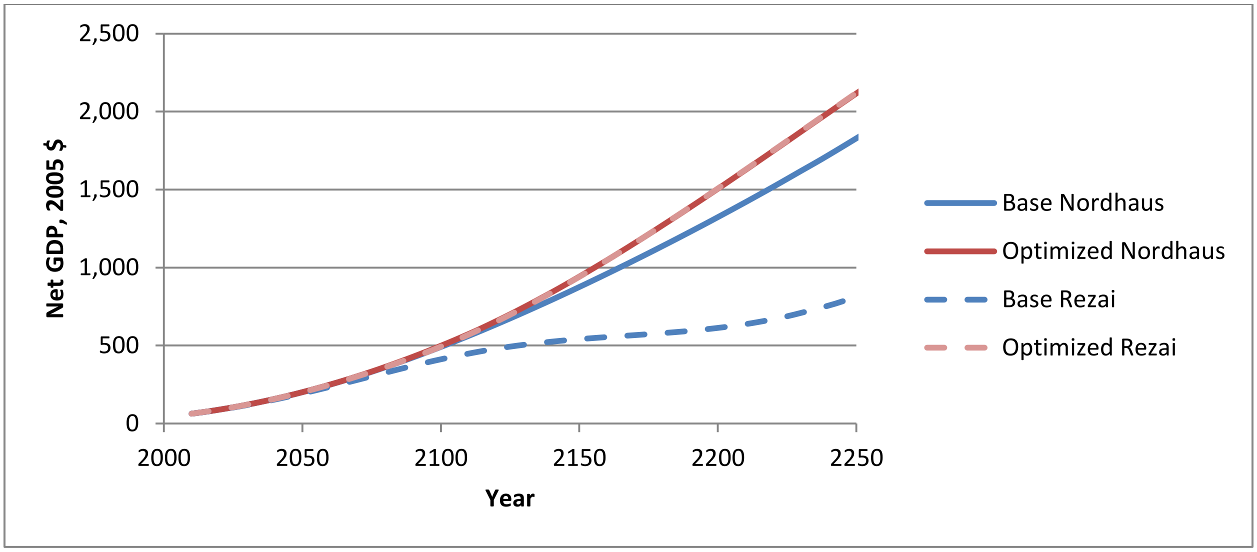


Figure 5. Net global GDP for the base and optimized cases with the Nordhaus and Rezai damage functions.

Figure 5 shows that the optimized cases are nearly identical and there is a dramatic reduction in the base case with the Rezai damage function. If the Rezai function is approximately correct, it makes a stronger case to implement the optimized policy.

3 GROWTH

The economic growth model used in DICE is a simple Solow model with a Cobb-Douglas production function which can be obtained from many sources, such as, Acemoglu 2009. This is shown in Equation 3. The numbers in parentheses show the values used in DICE for the 2010 base year. A 5 year time step is used.

$$Y = A\, K^{\alpha}\, L^{(1-\alpha)} \tag{3}$$

In this equation, Y is the economic output or GDP per year (initially 63.542 trillion 2005 \$), A is the total factor productivity (initially 3.789), K is the capital stock (initially 135 trillion 2005 \$), α is the output elasticity of the capital stock (0.3), and L is the population (6,838 million). The total factor increases according to Equation 4.

$$A_{(t+5)} = A_{(t)} \,/\, (1\text{-}0.079\ e^{(-.006\,(t\ -\ 2010)})}) \tag{4}$$

In this equation, t is the preceding year. The capital stock changes per Equation 5 shown below.

$$K_{(t+1)} = K_{(t)} (1-\delta) + I_{(t)} \quad (5)$$

In this equation, δ is the depreciation rate (0.10) per year and I is the investment. Investment is determined by the savings rate times the net GDP. The saving rate is optimized along with the price of carbon emissions for each year. Finally, the population changes per Equation 6 which is calibrated to match the latest United Nations projections.

$$L_{(t+5)} = L_{(t)} * (10{,}500 / L_{(t)})^{0.13449} \quad (6)$$

This growth function results in the output shown in Figures 1 and 5.

Rezai proposes a similar growth model but uses a different approach for the growth of the total factor productivity. The growth of the factor starts at 1 and approaches 3 over time. This is show in Equation 7.

$$A^{L}_{t} = 3 - 2.443\, e^{-0.2\, t} \quad (7)$$

While this form has the advantage of leveling off and producing more moderate growth, little justification for its use was provided. To see which if either of these approaches is appropriate, historical data was obtained from the Penn World Table, version 8.0 (Feenstra et al 2013). The Penn World Table provides data by country for the years 1950 to 2011. For this analysis, the GDP, capital stock, and population were summed for all the countries to obtain world data. In conducting this analysis, a few values from the Penn World Table different from the ones used in DICE were uncovered. First, the capital stock for 2010 was 224.003 trillion 2005 dollars versus 135.000 trillion 2005 dollars in DICE. There is no apparent reason for the difference. The second is that the GDP in 2010 was 68.064 trillion 2005 dollars versus 63.542 trillion 2005 dollars in DICE. This appears to be simply a measurement difference. Since the Penn World Table also has investment, it is possible to estimate the depreciation simply be rearranging Equation 5. A depreciation value of 0.036 appears to be more appropriate. This was calculated by minimizing the total error between the calculated and actual capital for each year. All of these changes had the effect of increasing the maximum GDP values in Figures 1 and 5 by less than 10%.

Using this data, the total factor productivity for each year could be calculated simply by rearranging Equation 3. Plotting this data, and fitting linear and a second order polynomial shows that both fit the data almost equally well as shown in Figure 6.

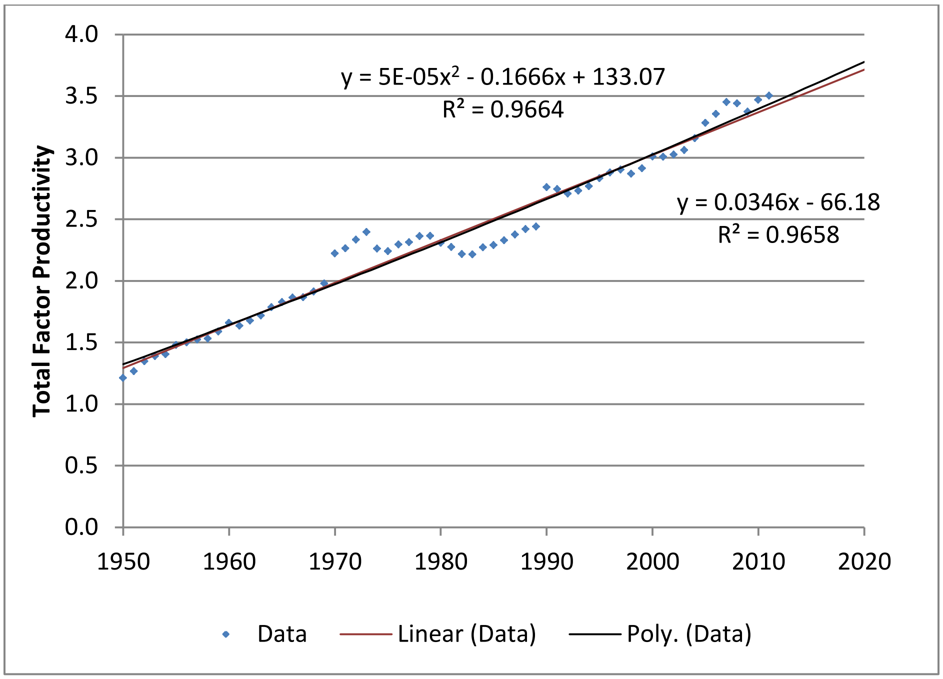


Figure 6. Total factor productivity calculated using data from 1950 to 2011.

By extrapolating this data and adjusting the Nordhaus and Rezai factors to match the data at 2010, we can see how well these are supported by the historical data. As shown in Figure 7, either of the curve fits matches the historical data much better than either of the approaches used by Nordhaus or Rezai.

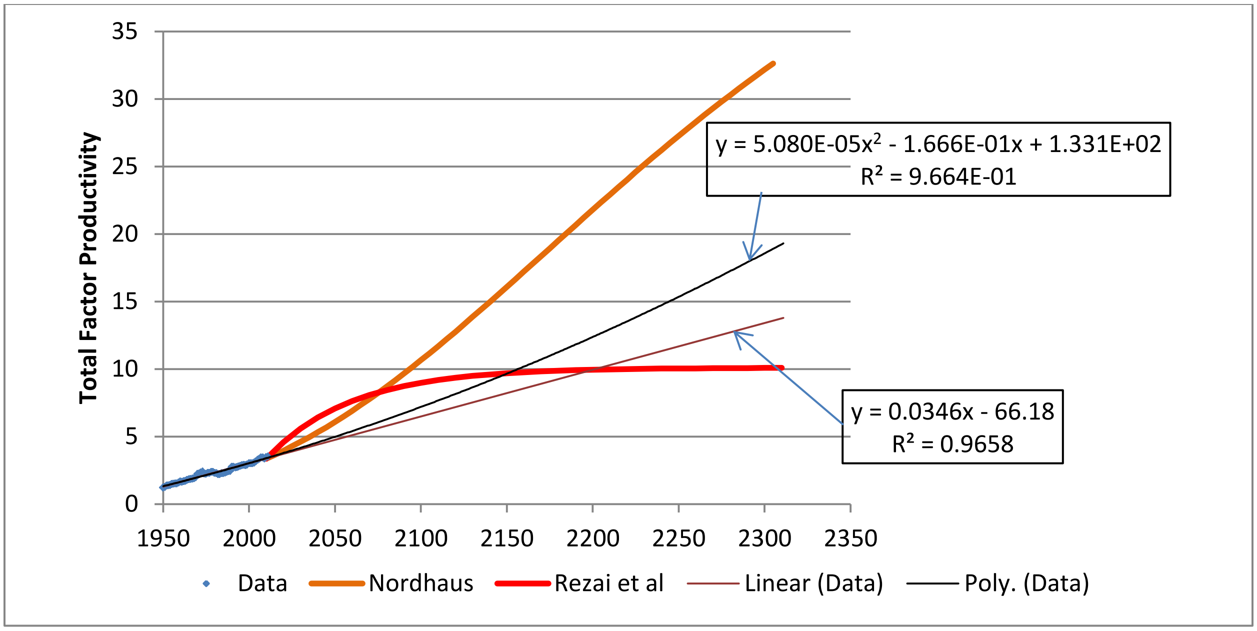


Figure 7. Comparing total factor productivity projections compared to historical data.

There are no statistical means to assess which of the 2 curve fits is more appropriate. However, Occam's razor suggests that the linear fit might be a better choice. Using the linear curve fit to project the growth of total factor productivity reduces the projected optimized GDP from Figure 1by about 67%. The GDP at 2250 is about 10 times the 2010 GDP versus 33 for DICE.

To further refine the growth projection, the growth model was further modified by using employed individuals instead total population and augmented by including education level as described in Acemoglu 2009. Again, the Penn World Table has this information in the form of the number of persons employed and in the index of human capital per person for each country. The number of persons employed is simply summed for all the countries to obtain world data. The index of human capital per person is multiplied by the number of persons employed for each country, the product is summed for all the countries and divided by the world total number of persons employed to obtain a weighted average. To include these factors Equation 3 is augmented to accommodate them as shown below in Equation 8.

$$Y = A\,K^{\alpha}\,h_c^{\beta}\,L_e^{(1-\alpha-\beta)} \qquad (8)$$

Here h_c is the global index of human capital per person, L_e is the global number of persons employed, α is modified slightly to 0.36, β is 0.26 based on work by Mankiw, Romer and Weil and summarized in Acemoglu 2009. Again we have the ability to calculate the total factor productivity for each year by rearranging Equation 8. The results of this are shown in Figure 8 below.

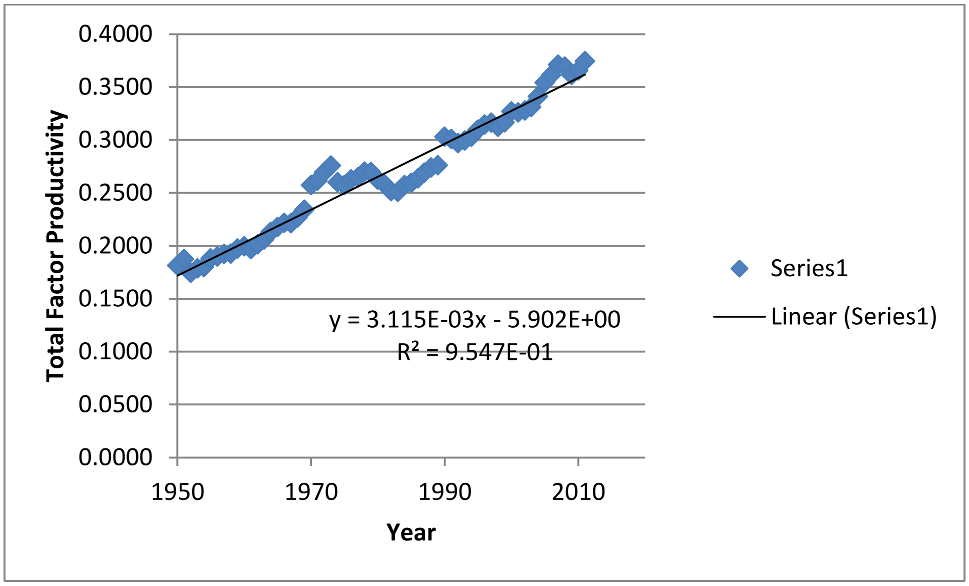


Figure 8. Total factor productivity using the number of employed persons and the index of human capital per person.

One thing is immediately apparent. The value is much lower than it was. We cannot compare the total factor productivities directly. We need to compare the projected GDPs. To use this approach to project the GDP a bit more work is required. First, we need as estimate of the projection of the index of human capital per person. The global index of human capital per person is increasing approximately linearly with time. However, mature economies seem to be approaching a limit. Germany has been constant for the last seven years. Extrapolating linearly puts the global index of human capital per person at 2250 at about twice the level that the country with the highest 2011 index of human capital per person (USA) appears to be approaching. To model this, the US data was fit with a logistic curve as shown in Figure 9.

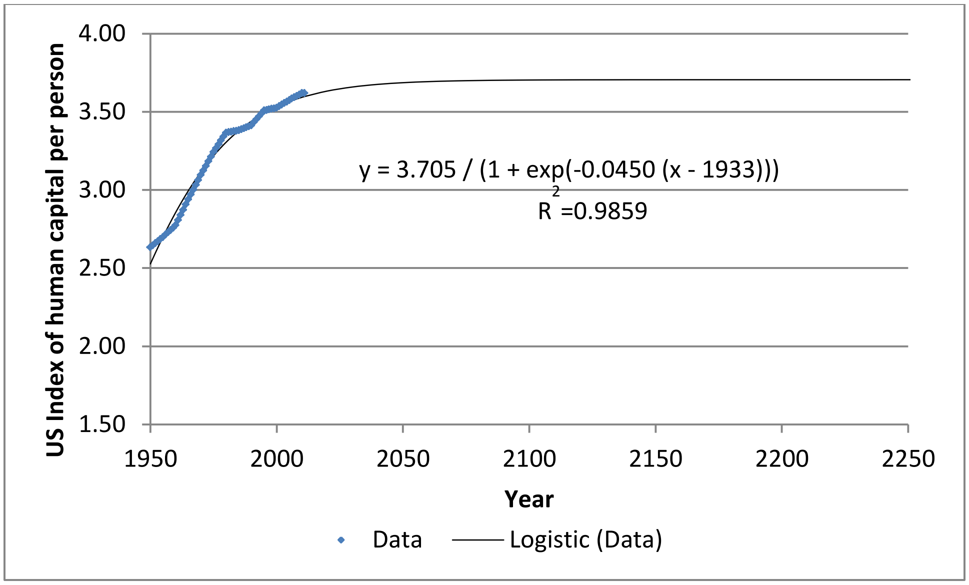


Figure 9. US Index of human capital per person.

The global index of human capital per person data is analyzed in a similar manner by a logistic fit but the limit is set to match the apparent US limit as shown in Figure 10.

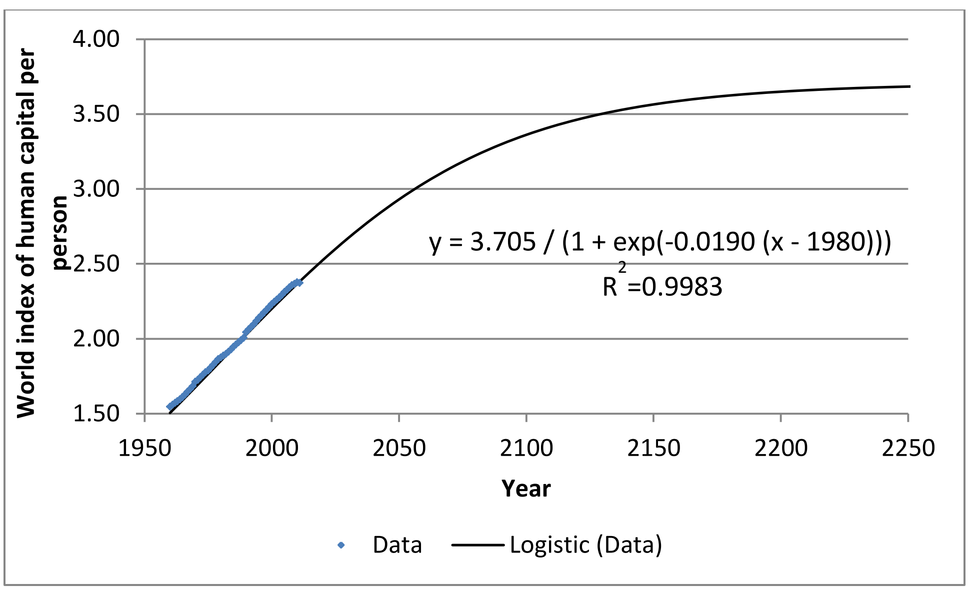


Figure 10. World index of human capital per person.

Next, we need a projection of the number of employed persons. First, the long term trend in the percentage of people with ages 15 through 64 is expected to approach 52%. It was 63% in 2000 and is expected reach a maximum of 64% in 2050 (UN 2004). From the Penn World Table data the percentage of the global population that is employed can calculated simple by dividing number of employed persons by the population for each year. In 1960 this was 37.1% and has been increasing to 45.0% in 2011. Since the percentage of people with ages 15 through 64 is expected to approach 52%, it is assumed that the percentage of the global population that is employed will approach 52%. Of course, this does not mean that all people in ages 15 through 64 will work nor that no one outside that range will work. Using this information, a logistic fit was applied to the percentage of the global population that is employed and projected to 2250 as shown in Figure 11 below.

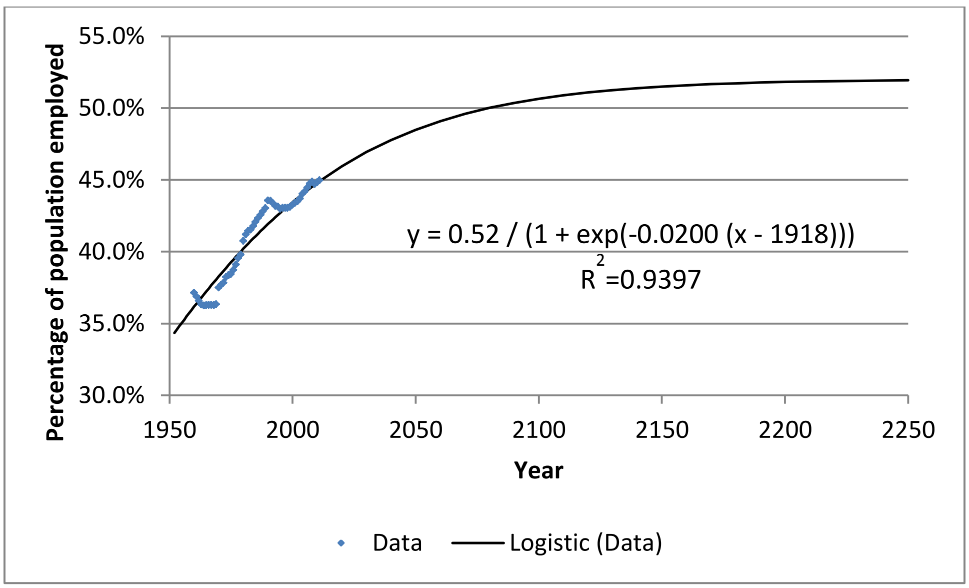


Figure 11. Global percentage of population employed.

Now we have what we need to project global GDP to 2250 using Equation 8. Using this approach, the projected optimized GDP from Figure 1 by about reduced by about 82%. The GDP at 2250 is about 6 times the 2010 GDP versus 33 for DICE. This will be explored in more detail in Section 5.

4 ENERGY CAPITAL

As shown in Figure 2, the level of abatement increases very rapidly. This section describes a modification to estimate the amount of capital required to make the transition. To make the transition from a fossil fuel driven economy to a low carbon economy will require that existing capital for the extraction, production and use of fossil fuels will have to be replaced by capital for production and use of low carbon energy sources. If this happens slowly enough, as fossil fuel capital depreciates it can be replaced by low carbon capital. However, the fossil fuel infrastructure is massive and durable. Cars, trucks, trains, and building heating, ventilation and air conditioning equipment, have relatively short lives, but power plants, ships, and refineries have much longer lives. It is likely that at least some of this capital will have to be written off as obsolete before it is worn out.

To include this in the DICE model it was assumed that utility scale photovoltaic electricity generation would be used to replace the fossil fuel capital for extraction, production, and electricity generation. For the transition this is assumed to be in addition to normal investment. Other fossil fuel capital would be replaced as it depreciates by the normal investment. One other assumption that is required is that we will develop low cost and efficient energy storage technology. Energy storage is required to match the intermittent nature of renewable energy with the variable demand, and to power mobile applications like individual transportation. This is currently a very active research area with no clear winners but with significant progress being made. It is too early to even estimate what the cost and efficiency of energy storage will be. With these assumptions, an estimate can be made for capital required to provide our energy needs with low carbon sources.

The first thing we will need is an estimate of the amount of energy we will need. The amount of energy required has been highly correlated with real GDP. So, the more the economic output grows, the more energy we will need. However, through decoupling of energy and economic output, and energy efficiency improvements, the amount of energy required per unit of real GDP has been dropping by about 1% per year. DICE assumes that this rate will reduce by about 0.1% per year. DICE actually uses this in the form of CO_2 emissions per unit of real GDP, but it is appropriate and easy to adjust it for energy use. This results in a reduction of the rate at which energy required per unit of real GDP is dropping of about 0.75% per year and an energy use per unit of real GDP of about 8% of the current value by the last time step.

There is no guarantee that this trend will continue to that level. There may be thermodynamic limits which cannot be crossed. However, there are significant inefficiencies in our current energy infrastructure which suggest that much of that reduction will be achieved. At this point, this assumption seems as good as any. In any year, the amount of photovoltaic electricity generation capacity that must be added is determined by the increase in the abatement fraction times the total energy required (plus an amount to replace the depreciated module output).

Part of the inefficiencies in our current energy infrastructure can be captured by simply by switching to a renewable energy source. Of the approximate 12,714 Mtoe (million tons of oil equivalent) or 147,864 tWh of source energy (oil, gas, coal, nuclear, etc.) used in 2012, only about 68.2% ever even reached its final use. This is best shown with a Sankey diagram (IEA 2012). Most of this is lost in electricity generating inefficiencies and transforming fossil fuels. With utility scale photovoltaic electricity generation about 94% reaches its final use. Only the approximately 6% transmission losses need be included. This means that every kWh of photovoltaic electricity eliminates about 1.38 kWh of fossil fuels. We use this in our estimate of photovoltaic capacity to add.

Photovoltaic modules are sold by the watt, but we are interested in the kWh of electricity provided. The relationship between these two depends on the amount of sunshine, the orientation of the module, temperature, soiling, shade, snow cover and the age of the module. At the utility scale, we can assume that orientation will be optimal (south facing in the northern hemisphere and tilted to the latitude), shade will not be a problem, and soiling will be managed. We will deal with aging of the module as part of depreciation. Output drops about 0.75% per year. With these assumptions and a reasonably sunny location, a 1 W photovoltaic module will produce about 1.5 kWh/yr.

Finally, we need the price per watt of utility scale photovoltaic equipment and how that is expected to change over time. This price is expected to decrease as more capacity is manufactured and installed (IEA 2014). Using the projected price of utility scale photovoltaic equipment over the years of 2015 to 2050 and the corresponding installed capacity over that time, we can determine the estimated price of utility scale photovoltaic equipment as a function of installed capacity.

When we modify DICE to include capital spent on renewable energy, we find that indeed the transition in the price of carbon and the fraction of CO_2 emission are smoothed. We see that the cost of CO_2 emissions increases more rapidly after the transition and achieves a maximum level. The abatement also increases more rapidly. The maximum net GDP achieved is about the same as is the temperature increase. So, it appears that we can afford to finance the transition to low carbon energy sources. However, we will revisit this in the next section.

5 SUMMARY

Now we have 5 projections for GDP growth: the original DICE projection, DICE adjusted with the Rezai damage function, the capital for low carbon energy, and the Penn World Table data, DICE adjusted with linear and second order polynomial based on total factor productivity from historical data, and the augmented production function. We also have an assessment of the capital required for the transition from fossil fuels to a low carbon energy source. This will also affect the net GDP projection. All of these projections of global net GDP with optimized carbon prices are shown in Figure 12 below. For comparison, the projections of base global net GDP are also shown.

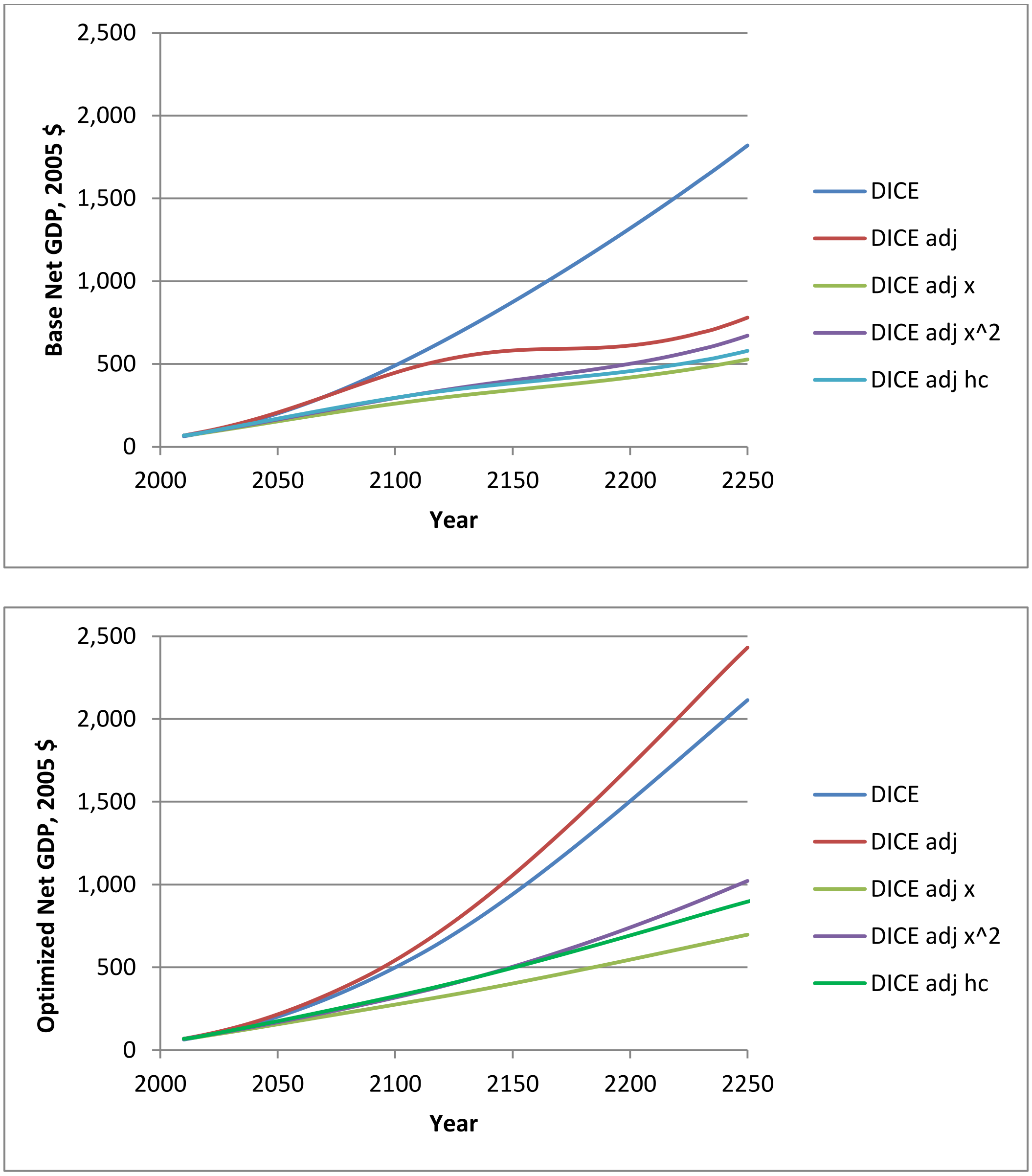


Figure 12. Global optimized net GDP for 5 growth models.

A few things stand out. First, all of the modified base cases have significantly lower GDP projections than the original DICE model. This is due to the Rezai et al damage function. In the optimized case, the last 3 result in much lower GDP projections compared to the first 2. Next is that the last 3 are very similar for the next hundred years or so, and DICE adj x^2 and DICE adj hc are very similar for about 200 years. This gives us a bit more confidence in the second order polynomial fit to the total factor productivity. What are the effects of these different growth models on the other variables we checked in Section 1? First, we look at the optimized carbon prices as shown in Figure 13.

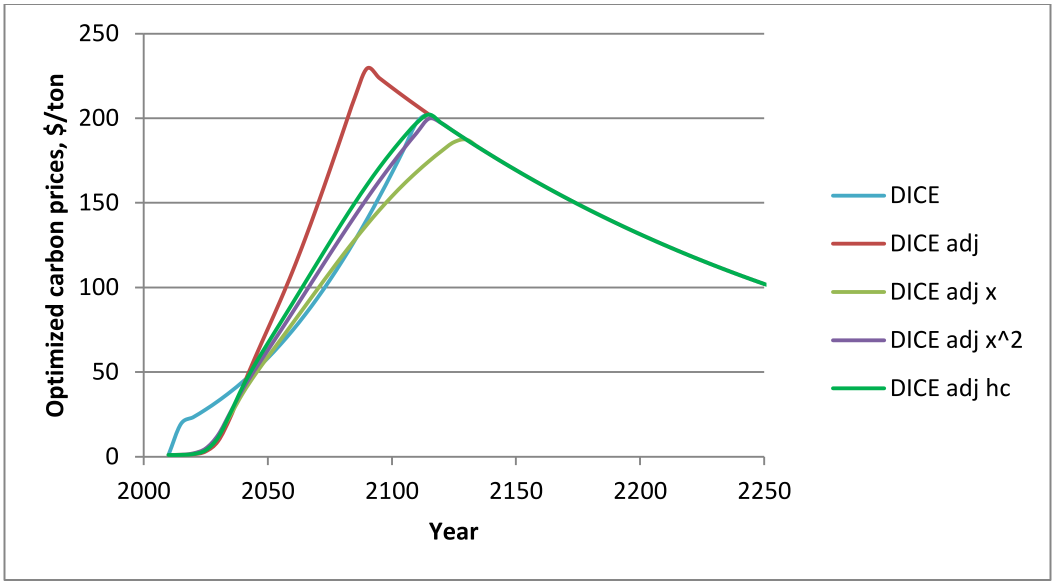


Figure 13. Optimized carbon prices for 5 growth models.

The first thing we note is the smoother transition into carbon pricing for all of the curves compared to the original DICE. This is due primarily to the capital required to transition to a low carbon energy source. This smoother transition results in a faster increase in price and a higher maximum for the second case. After that, the slower growth results in a slower increase in carbon prices and a lower maximum. The downward slope in the later part of the graph is due to a backstop technology with a decreasing price that is included in the DICE model. This means that once the price of CO_2 emissions reaches the price of the backstop technology, it then follows the price of the backstop technology.

The next variable is the fraction of CO2 emissions abated. This is shown in Figure 14.

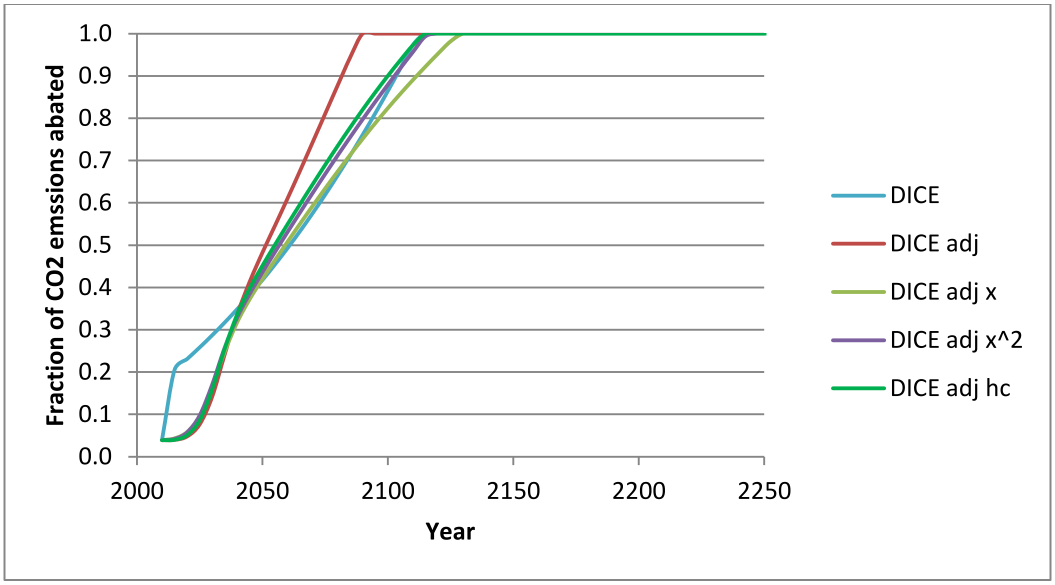


Figure 14. Fraction of CO_2 emissions abated for 5 growth models.

This looks pretty much as expected given the optimized carbon prices in Figure 13. Finally, the last variable we checked in Section 1 is the increase in temperature from 1900. This is shown in Figure 15.

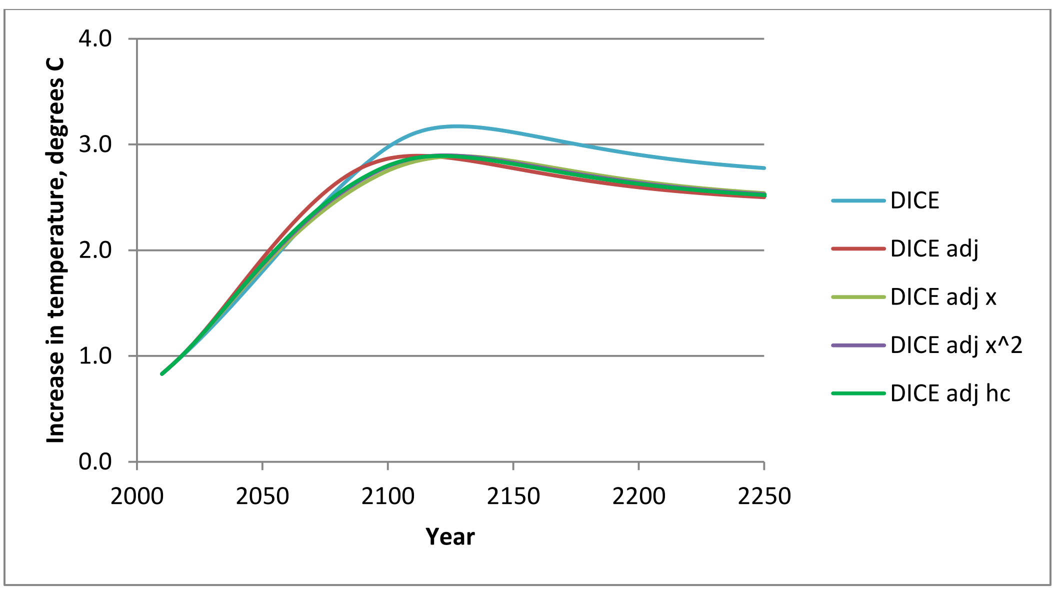


Figure 15. Increase in temperature since 1900 in degrees C for 5 growth models.

It is interesting to note that other than the original DICE model; with optimal CO_2 emission prices the models have very similar temperature curves independent of the growth rates.

With the information above, we also can look at how economic output growth rates have changed since 1950 and how the models project they will change in the future. This is shown in figure 16.

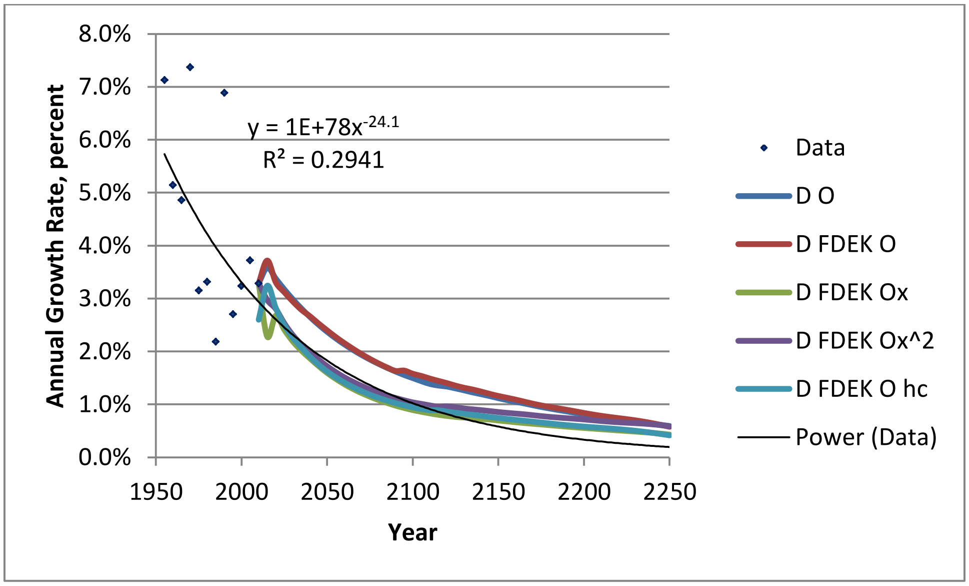


Figure 16. Five year average global annual growth rate data from 1950 to 2010 including a power curve fit, and the projected annual growth rate from the 5 models.

The global annual growth rate data exhibits significant variability even when using a 5 year average. However, it is possible to fit a power curve to the data. The fit is not great, but it suggests that global growth rates have been falling, and that we should expect them to continue falling. All the growth models show a similar reduction in the growth rate. A lower growth rate suggests that recessions and unemployment will be more difficult to manage. A lower growth rate leaves fewer margins for error since a smaller slowdown will result in a recession. A lower growth rate will also make it more difficult to avoid wealth concentration. Thomas Piketty made a good case that wealth concentrates when the growth rate is less than the return to capital (Piketty 2014). It is beyond the scope of this paper, but we will need new macroeconomic tools to guide economies.

6 CONCLUSIONS

There are several conclusions that can be drawn.

1. Despite some possible improvements, the basic recommendation of DICE, that a price on carbon emissions is an optimal policy, we need to start soon, and increase to a peak of about $200/ton by about 2115 remains sound.
2. The damage function of Rezai et al, while not on a solid foundation, seems directionally correct and should be included. It has almost no effect on optimized scenarios because the temperature increase is kept in a range where it matches the Nordhaus damage function closely. However, it does significantly reduce economic output in base case scenarios and emphasizes the need for action.
3. An energy model that addresses the capital needed for a transition to a very low carbon energy source should be added. The simple model discussed here smooths the abrupt transition in the price on carbon emissions of the DICE model. It also indicates that we can afford the transition to a very low carbon energy source.
4. The projected growth in economic output in DICE is too high based on historical data. This is due primarily to the projected increase in the total factor productivity. While investigating this, the Penn World Table historical showed a significantly higher starting capital stock. It also provided data that indicated a significantly lower depreciation rate should be used. This analysis results in the following recommendations.
   a. Use the Penn World Table 2010 capital stock of 224 trillion 2005 dollars.
   b. Use the depreciation rate of 3.56%.
   c. Use the second order curve fit (Figure 7 and below) to determine the total factor productivity.

$$A = 5.080E\text{-}05\ (\text{year})^2 - 0.1666\ (\text{year}) + 133.1$$

5. The global economic growth rate, while very variable, has been decreasing over the time period of 1950 to 2011. Projecting the historical data shows this growth rate continuing to decrease. All of the models analyzed in this paper also show decreasing growth rates. This has a profound impact on macroeconomic policy tools. Further research into economic policy tools to avoid recessions, unemployment and wealth inequality is needed.

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