Decarbonization Project Assignment, Part 1

EES 3310/5310 Global Climate Change

Report due Monday, October 30

Contents

Introduction

The purpose of this homework is to get a sense of the challenges to cutting emissions significantly.

I encourage you to work together with other students on this assignment. What you turn in must be written in your own words and you need to understand what you did, but you can work collaboratively with other students on the calculations as long as you participate in working through each part of the assignment so you really know how it's done.

Data Resources

To make things simple for you, I have prepared a web application, available at `https://ees3310.jgilligan.org/decarbonization/`, with almost all the data you will need for this project. It contains historical data on population, GDP, energy consumption, and CO_2 emissions for many countries and regions of the world. You can also install the app on your own computer through R Studio:

```
library(pacman)
p_load_gh("gilligan-ees-3310/kayatool")
```

Then you can run the app on a web browser on your computer by running `launch_kaya_tool()` from the RStudio console.

I have also posted to Brightspace several papers by Roger Pielke, Jr., that use this same method to analyze the challenge of decarbonizing the economies of Australia, the U.K., and Japan.

Using the web app

To use the decarbonization web app, start by selecting a country on the left-hand control panel. Then you can set the parameters for your policy goals: The target year for accomplishing the emissions reductions, the reductions you hope to achieve for the country, and the reference year. For instance, if your goal is for emissions in 2050 to be 80% less than they were in 1990, you would put 2050 for the target year, 80% for the emissions reduction, and 1990 for the reference year. If you want to indicate a growth in emissions, rather than a reduction, just enter a negative number for the emissions reduction.

You can also select what year to use for starting the calculation of bottom-up trends in the Kaya-identity parameters population P, per-capita gross-domestic product g, energy intensity of the economy e, and carbon intensity of the energy supply f. When you calculate decarbonization rates in this homework project, you will be focusing on the carbon intensity of the economy, which is given by the product ef.

After you have set the parameters you want, the bottom of the left panel will show a "Bottom-up Analysis" table that shows the average percentage growth rates for the Kaya parameters, their actual values in 2013, and the bottom-up projections for what their values will be in the target year (2050 by default).

The tabs on the right-hand side of the web page show:

- "**Trends**" shows historical trends and the calculated growth rate for the Kaya parameters. You select a variable (P, g, e, f, or various multiples ef, $G = Pg$, $E = Pge$, or $F = Pgef$) The app shows two graphs: on the right, the value of the parameter and on the left, the natural logarithm of the parameter, which we use to calculate percentage growth rates. The graphs show the points that are used in calculating the trends in darker red and the points not used in the trend calculation in lighter red. If you change the starting year on the left-hand panel, you will see the colors of the dots change to reflect this.

  The trend is shown in black on the left-hand graph. If the quantity is changing at a steady rate, the data points will follow a straight line (the trend line). Sometimes you will see that the variables e and f do not seem to be changing at a steady rate, but the product ef is. Explore the trends for the different variables and notice which seem to be following a steady growth or reduction and which do not.

  If you hold the mouse pointer over a data point on either graph, a tool-tip will pop up showing the value of that variable in that year.

- "**Calculations**" shows the steps for you to follow for each country in this homework exercise.

- "**Implied Decarbonization**" shows the historical trend in the carbon intensity of the economy (ef) and the implied future changes in order to meet the policy goal that you set.

- "**Energy Mix**" shows the mixture of energy sources (coal, natural gas, oil, nuclear, and renewables) that provide the country or region's energy supply. From this page, you can download the energy mix for the country you're looking at as a text file, using comma-separated value (csv) format, which you can read into R, Excel, or any other common data anlysis program.

- "**Historical**" shows a table of historical values for the different Kaya parameters. This is a convenient place to look up the exact numbers for your country in a particular year. This sheet also has a download button that lets you download the data in a csv vile.

Background and Context

The basic framework for your analysis will be the Kaya identity:

$$F = P \times g \times e \times f, \tag{1}$$

where F is the CO_2 emissions (in million metric tons of carbon per year), P is the population (in billion people), g is the per-capita GDP (in thousands of dollars per person per year), e is the energy intensity of the economy (in quads per trillion dollars of GDP), and f is the carbon intensity of the energy supply (in million metric tons of carbon dioxide per quad).* A quad means one quadrillion British thermal units (BTU) of energy. One quad is approximately equal to 8 billion gallons of gasoline or 36 million tons of coal. It is roughly equal to the electricity used by 26 million homes in a year, or the amount of electricity generated by 15 nuclear power plants in a year.

We will also focus on the carbon intensity of the economy (in metric tons of CO_2 emissions per million dollars of GDP), which equals $e \times f$.†

Growth Rates and Trends

We will assume exponential functional forms for all growth and decarbonization functions, so if you know the values for P, g, e, and f in 2016, then at some future year y:

$$\begin{aligned} P(y) &= P(2016) \times \exp(r_P(y - 2016)), \\ g(y) &= g(2016) \times \exp(r_g(y - 2016)), \\ e(y) &= e(2016) \times \exp(r_e(y - 2016)), \\ &\text{and} \\ f(y) &= f(2016) \times \exp(r_f(y - 2016)), \end{aligned}$$

where r_P is the growth rate of the population, r_g is the growth rate of the per-capita GDP, etc. Increasing energy efficiency and/or decarbonization of the energy supply mean that r_e and/or r_f are negative.

Remember that you have to divide percentages by 100 to get the rates for these equations: if r is 3%, you use 0.03, not 3.0 in the equations.

In your math classes and on your calculator, you have probably seen the exponential function $\exp(x)$ written as e^x, where e is the base of the natural logarithm ($2.718\ldots$). But since I am using the letter e to represent the energy intensity of the economy (the energy consumption divided by the GDP), I am writing it as $\exp(x)$ so you won't get confused by two different meanings of "e." Also, in R the exponential function is `exp()`.

Because of the properties of the exponential function, when you multiply two or more quantities together, the rate of change of the product is the sum of the rates of change of each of the quantities:

$$\begin{aligned} \text{GDP}(y) &= P(y) \times g(y) \\ &= P(2016) \times \exp(r_p(y - 2016)) \times g(2016) \times \exp(r_g(y - 2016)) \\ &= P(2016) \times g(2016) \times \exp((r_P + r_g)(y - 2016)) \\ &\text{so} \\ r_{\text{GDP}} &= r_{P \times g} = r_P + r_g. \end{aligned}$$

The web app does these calculations so you can check your results, and so that errors in the first parts of a problem don't cascade through the whole exercise. What I want you to do is work the problems exercises with RMarkdown and compare your work to the "Bottom-up Analysis" table to make sure you know how to do it.

The Assignment

For this assignment, analyze the economy and carbon emissions from the whole world, and then for individual countries: United States and China. Graduate students will also do calculations for India, and Brazil.

*One metric ton = 1000 kg = 1.1 English tons = 2200 pounds

†Note that e is in units of quads per trillion dollars of GDP and f is in units of million metric tons of CO_2 per quad, so if you multiply the units you get million metric tons of CO_2 per trillion dollars of GDP, which equals metric tons of CO_2 per million dollars of GDP.

Part 1, due Monday, October 30

For countries (whole world, USA and China for undergraduates; whole world, USA, China, India, and Brazil for graduate students) I want you to perform a bottom-up calculation of decarbonization rates for Monday, October 30:

For the bottom-up analysis, use the Kaya Identity to make reasonable extrapolations of the population and per-capita GDP through 2050. I ask you to use data through 2016 because even though it's 2017, a fair bit of energy data is only available through 2016.

1. Open the web app at `https://ees2110.jonathangilligan.org/decarbonization`, select the country you want to analyze, to start, leave the "Calculate trends starting in" at its default value, 1980, and write down the most current (2013) values for P, g, e, f, ef, and F. **Start with the USA first and do the whole analysis for the USA before doing it for the other countries.**
2. Next, go to the "Trends" tab and look at the graphs of $\ln(P)$, $\ln(g)$, $\ln(e)$, $\ln(f)$, and $\ln(ef)$.
   - Write down the rate of change for each variable.
   - For each graph compare the real data (in red) to the trend line (the straight black line).
   - Does the trend line look a like a good description of the data?
   - Is there a better starting year for calculating trends? If so, adjust "Calculate trends starting in" to this year
   - Do you anticipate a problem if we make policy by assuming that the Kaya identity variables will follow the black trend line for the next several decades?
3. Next, still on the "Trends" tab, note the historical rates of growth of P, g, e, and f (the Population, per-capita GDP, energy intensity of the economy, and carbon-intensity of the energy supply) from your starting year through 2016. These numbers are the slopes of the trend lines that you looked at in part (2).
4. Using the numbers from part 3, use the formulas from the "Growth Rates and Trends" section on page 3 to compute the values for P, g, e, and f in the year 2050 if emissions continue to grow at historical rates, and use these together with the Kaya identity to calculate the total CO_2 emissions (F) from the country in 2050. Check your work against the bottom-up numbers in the "Bottom-Up Analysis" table on the bottom of the left-hand pane of the web application.
5. Calculate the emissions target for each country: Set the reference year for emissions reduction to 2005, using the table below:

   The IPCC developed many representative concentration pathways (RCPs), using a top-down approach, for hitting various targets of radiative forcing from greenhouse gases. The only RCP that has at least a two-thirds probability of keeping warming below 2 °C is RCP 2.6. This concentration pathway calls for emissions reductions (relative to 2005) for different parts of the world listed in the table below:

Country	Year	Emissions Reduction from 2005
Africa	2050	28%
Australia_NZ	2050	82%
Canada	2050	72%
China	2050	78%
India	2050	73%
Japan	2050	66%
South Korea	2050	67%
Latin America	2050	40%
Middle East	2050	32%
Southeast Asia	2050	−17%
USA	2050	73%
Western Europe	2050	74%
World Total	2050	36%

Note that Southeast Asia has a negative reduction. This means that countries in this region are allowed a 17% *increase* in CO_2 emissions (F).

Set the target year in the web app to 2050 and the emissions reduction to the emissions reduction you are trying to achieve. Set the reference year to 2005.

For each country, how much CO_2 (F) would each country emit in 2050? (Remember to work this whole exercise for whole world before starting on the next country.)

6. Look up what the CO_2 emission is in 2005 and calculate the rate of change in F that would be necessary to achieve your policy target. For the 2050 calculation:
   (a) Calculate the ratio of F_{2050}/F_{2005}.
   (b) Take the natural logarithm (ln) of this ratio (in R, the ln function is `log()`).
   (c) Divide the logarithm by the number of years ($2050 - 2005$). This is the rate of change of F. A positive number means growth, and a negative number means a reduction. The percentage rate of change per year is 100 times this number.
7. Now calculate the decarbonization rate implied by the policy goal. This is the rate of reduction of ef, the carbon intensity of the economy. $F = Pgef$, so $r_F = r_P + r_g + r_e + r_f$. Subtract the projected r_P and r_g (look them up in the "Bottom up Analysis" table) from r_F, which you just calculated in step 6c, to get the rate of change of ef. Multiply the rate of change of ef by -1 to get the rate of decarbonization. Multiply by 100 to get the percent implied rate of decarbonization.
8. How does the implied rate of decarbonization for each nation compare to the historical rate of decarbonization (i.e., the trend in ef reported in the "Bottom up Analysis" table)? Which nation will have the hardest time meeting this emission goal without damaging its economy?

Data Resources

You will use the following datasets in the assignment:

GDP and Population: The "Historical" tab on the web app has this data for 1965-2016, and allows you to download for each country. This comes from the World Bank's data sets at `https://data.worldbank.org/`

Primary energy consumption, CO_2 emissions, and balance of fuels: The "Historical" tab also has these data, which you can download for each country. These data come from the BP Statistical Review of World Energy 2017 at `https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html`

Methods: I have posted three papers by Roger Pielke on Blackboard, which give examples of these kinds of calculations:

- R.A. Pielke, Jr., "An Evaluation of the Targets and Timetables of the Proposed Australian Emissions Trading Scheme," Environ. Sci. & Pol. (submitted, 2010). Posted on Blackboard. This one has examples of the kind of analysis in parts **??** and **??**
- R.A. Pielke, Jr., "The British Climate Change Act: A Critical Evaluation and Proposed Alternative Approach," Environ. Res. Lett., **4**, 024010 (2009). Also available at `dx.doi.org/10.1088/1748-9326/4/2/024010`.
- R.A. Pielke, Jr., "Mamizu Climate Policy: An Evaluation of Japanese Carbon Emissions Reduction Targets," Environ. Res. Lett., **4**, 044001 (2009). Also available at `dx.doi.org/10.1088/1748-9326/4/4/044001`.

Appendix: How to calculate historical trends (Optional reading)

This section is not required for the homework. You can skip it if you wish. The web application does these calculations part for you, but if you're interested in doing something similar yourself, here is how you do it:

If you want to get the growth rate from empirical data, one approach is to take the natural logarithm of the quantity, plot it against time, and fit a straight line to it:

$$\ln P(y) = \ln P(2016) + r_p \times (y - 2016) \tag{2}$$

The slope of the line will be the growth rate. Be sure to use the natural logarithm, not the base-10 (Naperian) logarithm. You can easily do this fit in Excel, either by plotting $ln(P)$ versus the year and in the chart options, telling Excel to plot a trend line or using the `SLOPE` function in Excel to compute the slope of $ln(P(y))$ versus y. To do this with a chart:

1. First plot $ln(P)$ versus the year using either a line chart or an x-y chart.
2. Next, right-click on the line and select "add trendline" from the menu. Choose a linear trend, make sure you **do not** check the "set intercept to zero" box, and **do** check the box that says, "display equation on chart."
3. In the displayed equation, if it says, "$y = 0.035x + 15.73$," then the annual growth rate, r_P would be 0.035, or 3.5%.

Equation 2 also lets us calculate implied growth rates. If we know what $F(2016)$ is, and we have a goal for $F(y)$ in the year y, then the implied growth rate of F between 2016 and y is

$$r_F = \frac{\ln F(y) - \ln F(2016)}{y - 2016} = \frac{\ln\left(\frac{F(y)}{F(2016)}\right)}{y - 2016} \tag{3}$$

If you are familiar with another data analysis tool, such as Matlab, R, SPSS, or Stata, there are simple built-in methods for calculating trends.