Instructions for Bottom-Up Decarbonization Policy Analysis Lab

Jonathan Gilligan

Reading for Lab on Monday Oct. 22

Contents

1 Introduction

The purpose of this homework is to get a sense of the challenges to cutting emissions significantly by analyzing several representative emissions-reduction policies. These policy analyses will follow the methods Roger Pielke used in Chapters 3–4 of *The Climate Fix*.

I encourage you to work with a partner on this lab, but you should write up your own lab report individually.

1.1 Data Resources

To make things simple for you, I have prepared an interactive 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.

I have also provided an R package that you can install on your own computer through R Studio:

```
library(pacman)
p_load_gh("jonathan-g/kayadata")
```

Finally, there is an experimental version of the interactive web application that you can install and run on your computer using RStudio, but it is still experimental and may not work perfectly. You can install it in RStudio like this:

```
library(pacman)
p_load_gh("jonathan-g/kayadata")
```

and then you can run the application like this:

```
library(kayatool)
launch_kayatool()
```

Note: you should not put `launch_kaya_tool()` in RMarkdown documents, like your lab report, because launching an interactive web application when you knit your report will prevent the report from knitting correctly.

1.1.1 Using the interactive web application:

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 2005, you would put 2050 for the target year, 80% for the emissions reduction, and 2005 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 2017, 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` file.

2   Background and Context

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

$$F = P \times g \times e \times f,$$

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).[1] 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 $e \times f$.[2]

---

[1] One metric ton = 1000 kg = 1.1 English tons = 2200 pounds

[2] 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.

2.1 Growth Rates and Trends

We will assume that all of the rates of change in the growth and decarbonization trends we are studying will be constant from year to year. A constant percentage rate of change implies that the quantity follows an exponential growth function, so if you know the values for P, g, e, and f in 2017, then at some future year y:

$$P(y) = P(2017) \times \exp(r_P(y - 2017)),$$
$$g(y) = g(2017) \times \exp(r_g(y - 2017)),$$
$$e(y) = e(2017) \times \exp(r_e(y - 2017)),$$
$$\text{and}$$
$$f(y) = f(2017) \times \exp(r_f(y - 2017)),$$

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 ($2.718...$). 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:

$$\text{GDP}(y) = P(y) \times g(y)$$
$$= P(2017) \times \exp(r_p(y - 2017)) \times g(2017) \times \exp(r_g(y - 2017))$$
$$= P(2017) \times g(2017) \times \exp((r_P + r_g)(y - 2017))$$
$$\text{so}$$
$$r_{\text{GDP}} = r_{P \times g} = r_P + r_g.$$

The web app does these calculations so you can check your results. So that errors in the first parts of a problem don't cascade through the whole exercise, you should 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.

3 The Assignment

For this assignment, analyze the economy and carbon emissions from the whole world, and then for individual countries.

3.1 Decarbonization Lab #1, due Tuesday, October 30

For this lab, you will do a bottom-up analysis of the following countries/regions:

class	regions
Grad Students	World, United States, China, India, Brazil
Undergraduates	World, United States, China

For the bottom-up analysis, use the Kaya Identity to make reasonable extrapolations of the population and per-capita GDP through 2050.

Repeat the steps below for each country or region:

3.1.1 Outline:

To analyze the policy for each country:

1. Get the Kaya identity data for the country
2. Figure out appropriate starting years for calculating the historical trends for the Kaya variables P, g, e, and f.
3. Calculate the *historical trends* for the Kaya variables from the starting year you determined in step (2).
4. Use the *historical trends* to extrapolate projected values for P, g, e, and f in 2050.
5. Calculate the policy goal for emissions F in 2050. This uses the policy criteria (target emissions reduction) and the measured emissions F in 2005, from the Kaya data for your country.
6. Calculate the *implied rate of change* of F between 2017 and 2050, in order to reduce emissions to the policy goal that you calculated in step (5).
7. Combine the *implied rate of change* of F with the *historical trends* of P and g to calculate the *implied rate of change* of ef that you calculated in step (3) in order to meet the policy goal from step (5).
8. Compare the *implied rate of change* of ef that you calculated in step (7) to the *historical trend* of ef that you can determine from the *historical trends* of e and f that you calculated in step (3).

3.1.2 Detailed steps:

Each step has two alternative methods: using the interactive web application or using the `kayadata` library in RStudio:

1. Open the web app at https://ees3310.jgilligan.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 (2017) values for P, g, e, f, ef, and F.

   Alternately, use the `kayadata` package in RStudio to load the data for your country or region. Below is an example of looking up the data for the OECD:

   ```
   library(kayadata)
   oecd_data = get_kaya_data("OECD")
   oecd_latest_year = oecd_data %>% filter(year == 2017)
   ```

   You can get a list of all the countries and regions that are available from `kaya_region_list()`.

   Start with the whole world first and do the whole analysis for the world before doing it for the individual 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 blue 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 trend line for the next several decades?

   You should also plot these in your report using RMarkdown. Following from the example above, you can use the `plot_kaya` function:

   ```
   plot_kaya(oecd_data, "e", log_scale = TRUE, font_size = 12)
   ```
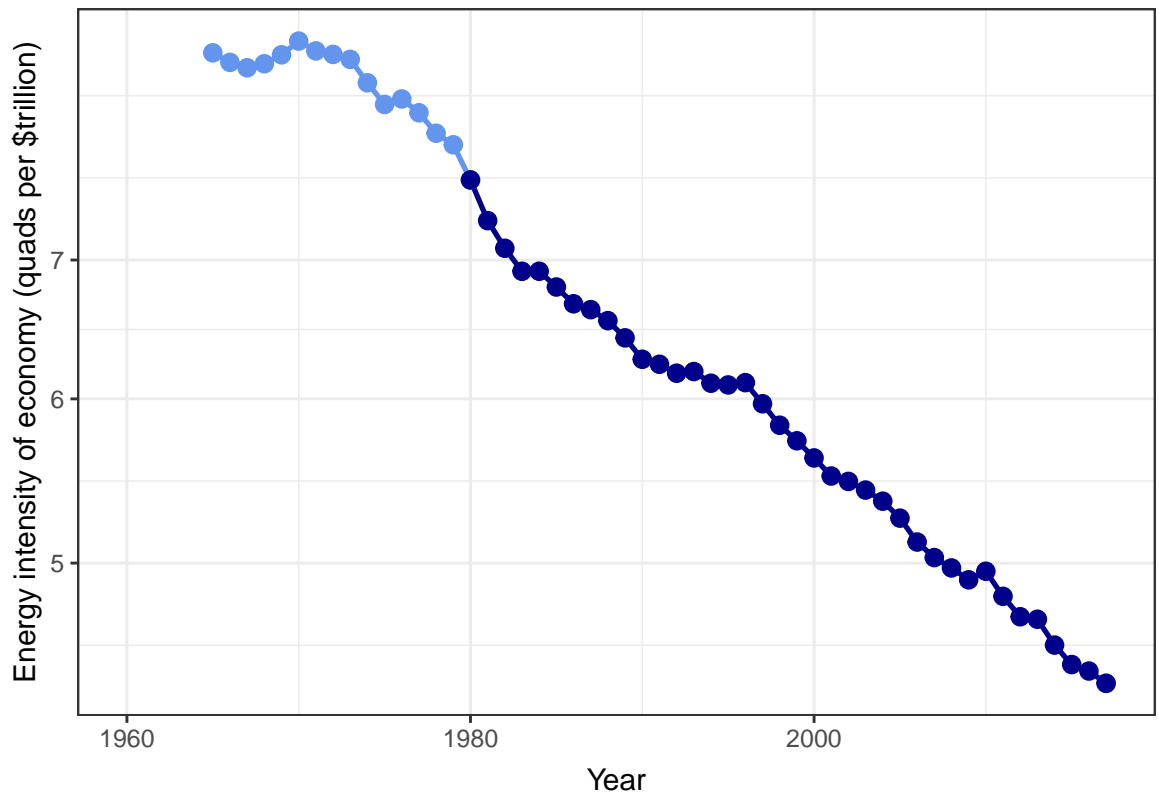
Be sure to set `log_scale = TRUE` in the `plot_kaya` function because a constant percentage rate of change corresponds to a linear trend in the logarithm of the variable.

3. Next, calculate the rates of change 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 2017, using the `lm` function in R.

   A constant rate of change is represented by a linear relationship between the natural logarithm of the kaya variable and time: for the variable `P` (population), we would write this formula in R as `log(P)~year`.

   Here is an example of calculating the rate of change of e (the energy intensity of the economy) for the OECD, using the variable `oecd_data` that you calculated above:

```
# Load the broom library for organizing lm results
library(broom)
# Load the magrittr library with helper functions for piping data
library(magrittr)

e_trend = oecd_data %>% filter(year >= 1980) %>%
  lm(log(e) ~ year, data = .) %>%
  tidy() %>% filter(term == "year") %$% estimate
```

   For more detailed explanation of the code above, see the handout "New Tools for Data Analysis."

7

Here, we find that `e_trend` = -0.0138 (-1.38% per year).

You can check your results against the interactive web application by looking at the rates of change reported on the "Trends" tab. Be sure to set the start year on the web app to the same values that you used for calculating the slopes in RMarkdown.

These numbers are the slopes of the trend lines that you looked at in part 2.

4. Using the rates of change that you determined in part 3, use the formulas from the "Growth Rates and Trends" section to compute the values for P, g, e, and f in the year 2050.

Next, use the growth rates of P, g, e, and f to calculate the growth rate of the total emissions F. Calculate the total CO_2 emissions (F) from the country in 2050, assuming that emissions continue to grow at historical rates.

I recommend that you write R chunks in your report in a way that you can copy and paste the chunks from one country or region into the analysis for the other countries or regions.

It may also be useful to define functions for frequently used (e.g., see the example `growth` function in the handout on "New Tools for Data Analysis")

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, and set the target emissions reduction 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 degrees Celsius 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:

Table 2: Percent reduction in CO_2 emissions in 2050, relative to 2005.

Region	Emissions reduction
Australia/New Zealand	82%
Canada	72%
China	78%
India	73%
Japan	66%
South Korea	67%
United States	73%
Africa	28%
Latin America	40%
Middle East	32%
Southeast Asia	-17%
Western Europe	74%

Region	Emissions reduction
World	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; set the reference year to 2005; set the emissions reduction to the emissions reduction you are trying to achieve.

For each country, how much CO_2 (F) would each country emit in 2050 in order to meet your policy goal? (Remember to work this whole exercise for whole world before starting on the individual countries.)

Let's work an example using the Middle East:

```
F_2005_middle_east = get_kaya_data("Middle East") %>%
  filter(year == 2005) %$% F
F_2005_middle_east
```

```
## [1] 1374.973
```

```
middle_east_reduction = 0.32
F_goal_middle_east = F_2005_middle_east * (1 - middle_east_reduction)
F_goal_middle_east
```

```
## [1] 934.9819
```

Check this result against the interactive web application.

6. Look up what the CO_2 emission is in 2017 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_{2017}.
   b. Take the natural logarithm of this ratio (in R, the natural logarithm function is `log()`; on your calculator it is "LN").
   c. Divide the logarithm by the number of years ($2050 - 2017$). 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.

For our Middle East example:

```
F_2017_middle_east = get_kaya_data("Middle East") %>%
  filter(year == 2017) %$% F
r_F_middle_east = log(F_goal_middle_east / F_2017_middle_east) /
  (2050 - 2017)
r_F_middle_east
```

```
## [1] -0.02469655
```

so total emissions for the Middle East would need to drop by -2.47% per year between 2017 and 2050

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~7, to get the rate of change of *ef*. Multiply the rate of change of *ef* by -1 to get the rate of decarbonization (because negative rate of change is a positive rate of decarbonization and vice-versa). 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?