IEooc_Application1_Exercise2: Quantifying sociometabolic transitions with the IPAT equation

Sample Solution

Goal: *Understand how population, affluence, and a cap for a certain emission to the environment determine how industry must decouple from that emission. Learn about and apply the IPAT equation and link it to global climate and development targets.*

Problem setting

Sustainability, at the large scale, is about meeting both environmental and societal goals. Simply speaking, environmental sustainability means putting a cap on certain environmental impacts I, such as greenhouse gas emissions or emissions or particulate matter. Economic development (still) is a major societal goal; it is commonly measured by the personal affluence, that is, the average spending A per person.

The following equation, called IPAT after its four constituents I, P (Population), A, and T (Technology), links the two sustainability goal indicators: the impact I with the affluence A:

$$I = P \cdot A \cdot T$$

$$[\frac{kg}{yr}] = [p] \cdot [\frac{\$}{yr \cdot p}] \cdot [\frac{kg}{\$}]$$

The IPAT equation is an accounting identity. It always holds, as the right side of the equation is simply a different breakdown of total impacts:

$$I = I$$

$$I = GDP \cdot \frac{I}{GDP}$$

$$I = P \cdot \frac{GDP}{P} \cdot \frac{I}{GDP}$$

The equation above always holds for nonzero P and GDP. The term GDP/P is the per capita affluence A, and the term I/GDP is the average environmental impact per economic output T.

In the IPAT framework, emissions have three drivers: The scale of a society, measured by its population, the personal affluence, measured by per capita spending, and the average emissions intensity of the economy, measured by impact per dollar of GDP produced.

Application 1: Sociometabolic regimes and transitions

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One can use the IPAT equation to get an idea of how the change of P, A, and T plays together to determine changes in I over time. In particular, we want to investigate to what extent T, the aggregate emissions intensity of the economy, needs to change compared to historic values.

Focussing on climate change mitigation, we want to understand the option space for A and T given global and national reduction targets for greenhouse gas emissions I and population scenarios P.

This exercise focusses on the US and China as examples of countries that were industrialized and industrializing in 1990, respectively. The example below was adopted from Tim Jackson's "Prosperity without growth" (Jackson, 2009).

Question:

Is a continuation of the historic development of the coupling between emissions and economic output, expressed by T, sufficient to reach ambitious climate targets in 2050? *Or, more simply:* ***If we extrapolate the trend seen in T over the last decades to 2050, will the countries be able to reach their climate targets under reasonable growth assumptions?***

Data

To answer these question, a number of data on P, A, and I for the years 1990 and 2017 (reference period) and for 2050 (scenario benchmarks) are given (Tables 1 and 2).

Table 1: IPAT data for the USA.

USA	1990	2017	2050 base	2050 max	Ref
Population (million)	252.53	324.459	389.592		UN Population Division. World Population Prospects: The 2017 Revision.
GHG emissions (Mt CO_2-eq/yr) (I)	6400	6400	3200	640	https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
PPP-GDP-pC (constant 2011 I$) (A)	34062	54255.4			https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD
Red numbers: 50% and 90% reduction					

Table 2: IPAT data for China.

China	1990	2017	2050 base	2050 max	Ref
Population (million)	1172.445	1409.517	1364.457		UN Population Division. World Population Prospects: The 2017 Revision.
GHG emissions (Mt CO_2-eq/yr) (I)	3211	11735	11207	2241	https://climateactiontracker.org/countries/china/
PPP-GDP-pC (const. 2011 I$) (A)	1526.4	15308.7			https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.KD
Red numbers: Same per capita emissions as for USA with 50% and 90% reduction rel. to 1990.					

Guidance:

For both countries and for the years 1990 and 2017, the IPAT equation can be formulated and used to calculate T. One can then determine the average annual change rate of T for both countries.

For 2050, we need an economic growth scenario. Simply extrapolating historic growth rates could work for the US but probably not for China, which has seen a tenfold increase in purchase power parity (PPP) GDP over the 1990-2017 period.

For comparison purposes, an average *annual growth rate of per capita GDP* of 2% for the US and 4% for China shall therefore be assumed for the period 2017-2050. Any other reasonable rates can be used as well.

Solution:

We first calculate the 2050 PPP-GDP to have a complete dataset of I, P, and A for the two countries, two historic years, and the two 2050 scenarios:

$$gdp(t) = gdp(t_0) \cdot (1+r)^{t-t_0}$$

which gives us 104300 constant 2011 I$ per capita for the US and 55850 constant 2011 I$ per capita for China.

Then, we can fill out the following table with eight IPAT equations:

Table 3: IPAT equation and results for T for the US and China for two historic dates and two 2050 scenarios.

IPAT	I (Mt CO2/yr)	P (million)	A (2011 I$ p.cap)	T (kg CO2/I$)
China 1990	3211	1172.445	1526.4	1.794236
China 2017	11735	1409.517	15308.7	0.543844
China 2050 min	11207.26914	1364.457	55851.97	0.147062
China 2050 max	2241.453829	1364.457	55851.97	0.029412
US 1990	6400	252.53	34062	0.744041
US 2017	6400	324.459	54255.4	0.363561
US 2050 min	3200	389.592	104291.4	0.078757
US 2050 max	640	389.592	104291.4	0.015751

In the table above, term T was calculated as T = I / (P·A) and the unit was converted to kg/I$.

The average emissions intensity of the Chinese economy was more than three times that of the US economy in 1990, but the two economies have become more similar in their average emissions intensity, measured in total CO2 per PPP-GDP, in 2017 (0.54 kg/I$ for China vs. 0.36 kg/I$) for the US).

In 2050, emissions intensities will have to decline much further: In our scenario, down to 0.03 and 0.15 kg/I$ for ambitious and moderate climate change mitigation targets for China, and down to 0.016 and 0.08 kg/I$ for ambitious and moderate targets in the US.

To see whether this decrease is in line with historic patters, we calculate the average annual improvement rates for T for the periods 1990-2017 and 2017-2050 (moderate) and 2017-2050 (ambitious), using the same equation as above, but this time, solving for r:

$$T(t) = T(t_0) \cdot (1 + r)^{t - t_0}$$

We find the following results (Table 4) after converting r to % and calculating the reduction rate as 100% - r(%):

Table 4: Average annual reduction rates for the T factor of the IPAT equation for China and the US, %.

Reduction rate T	China	USA
1990-2017	4.3	2.6
2017-2050 moderate	3.9	4.5
2017-2050 ambitious	8.5	9.1

Over the period 1990-2017, China has decarbonised its economy by 4.3 % the US by 2.6 % every year, based on PPP-GDP. For moderate climate targets (50% reduction in the US for 1990-2050 and the same resulting per capita emissions in China in 2050), the rate would have to be slightly lower in China for the period 2018-2050 (3.9%) but almost twice as high as previously in the US (4.5%). For ambitious climate targets (90% reduction in the US for 1990-2050 and the same resulting per capita emissions in China in 2050), the reduction rate would have to be much higher (8.5% in China and 9.1% in the US) than previously.

Coming back to our research question: "***Is a continuation of the historic development of the coupling between emissions and economic output, expressed by T, sufficient to reach ambitious climate targets in 2050?*** *Or, more simply:* ***If we extrapolate the trend seen in T over the last decades to 2050, will the countries be able to reach their climate targets under reasonable growth assumptions?***" we can now give an answer for the two countries and two scenarios that we studied:

Assuming an annual PPP-GDP growth of 4% for China and 2% for the US, only China can keep its decarbonisation path but only for a moderate climate target of reaching per capita emissions levels in 2050 that correspond to a 50% reduction of US emissions for 1990-2050. For all other scenarios studied, and the US in particular, the reduction rate of T must at least double (ambitious mitigation in China) or more than triple (ambitious mitigation in the US). This result illustrates the challenges that result from ambitious climate change mitigation.

Note: A slightly different approach to calculating the average growth rates is to use the differential of the IPAT equation:

$$I = P \cdot A \cdot T$$

$$\Delta I = \Delta P \cdot A \cdot T + P \cdot \Delta A \cdot T + P \cdot A \cdot \Delta T$$

$$\frac{\Delta I}{I} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta T}{T}$$

From the last line of the equation, the relative change ΔT/T can be determined directly and converted to annual rates via the power law given above.

References:

Link to the IPAT equation on Wikipedia: https://en.wikipedia.org/wiki/I_%3D_PAT

Jackson, T., 2009. Prosperity without growth. Routledge, London.