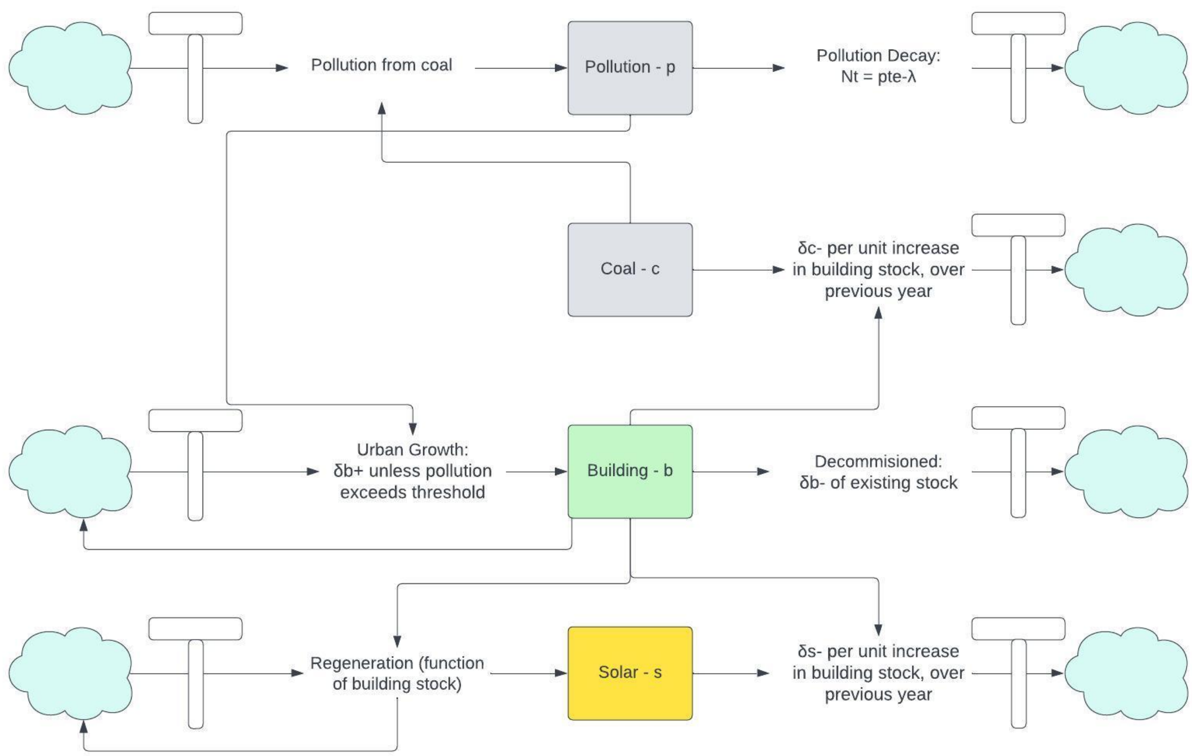
CEE 243 Systems Modeling

Group 6 - Hemanth Hariharan, Melissa Tanaka, Fletcher Chapin, Asagi Nagatoishi

Part 1 – Setting up the system



Equations

- Pollution stock

$$p_t = p + E_t^c \times pI_t - N$$

- Building Stock

$$b_t = b + U_t - D_t$$

- Coal stock

$$c_t = c - E_t^c$$

- Solar stock

$$s_t = s + R_t - E_t^s$$

(Outflow)

・The amount pollution decayed

$$N_t = p_t \times e^{-\lambda}$$

・Decommissioned Building

$$D_t = \delta_b^- \times b$$

・The amount of solar extracted and consumed

$$E_t^s = E_s + \delta_s^- \times (b_t - b)$$

・The amount of coal extracted and consumed

$$E_t^c = E_c + \delta_c^- \times (b_t - b)$$

(Inflow)

・Pollution intensity

$$pI_t = pI \times (\frac{|c_t - c|}{c_0})$$

・Urban growth

$if\ p < \alpha_p$

$$U\_t = \delta_b^+ \times b$$

else 0

・The solar inflow

$if\ bt > 3\ b_0$

$$R\_t = (1 - \frac{b_t - 3b_o}{3b_0}) \times R$$

else:

$$R_t = \delta_s^+ \times (b_t - b) + R$$

・Maintain energy balance if coal is depleted

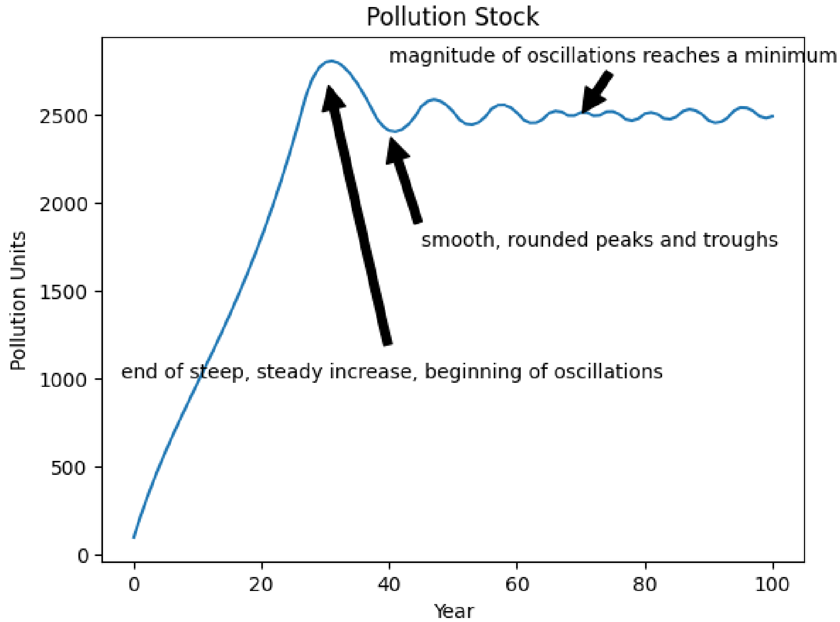
if $E_t^c > c$

$$E_t^s = 2 \times (E_t^c - c)$$

$$E_t^c = c$$

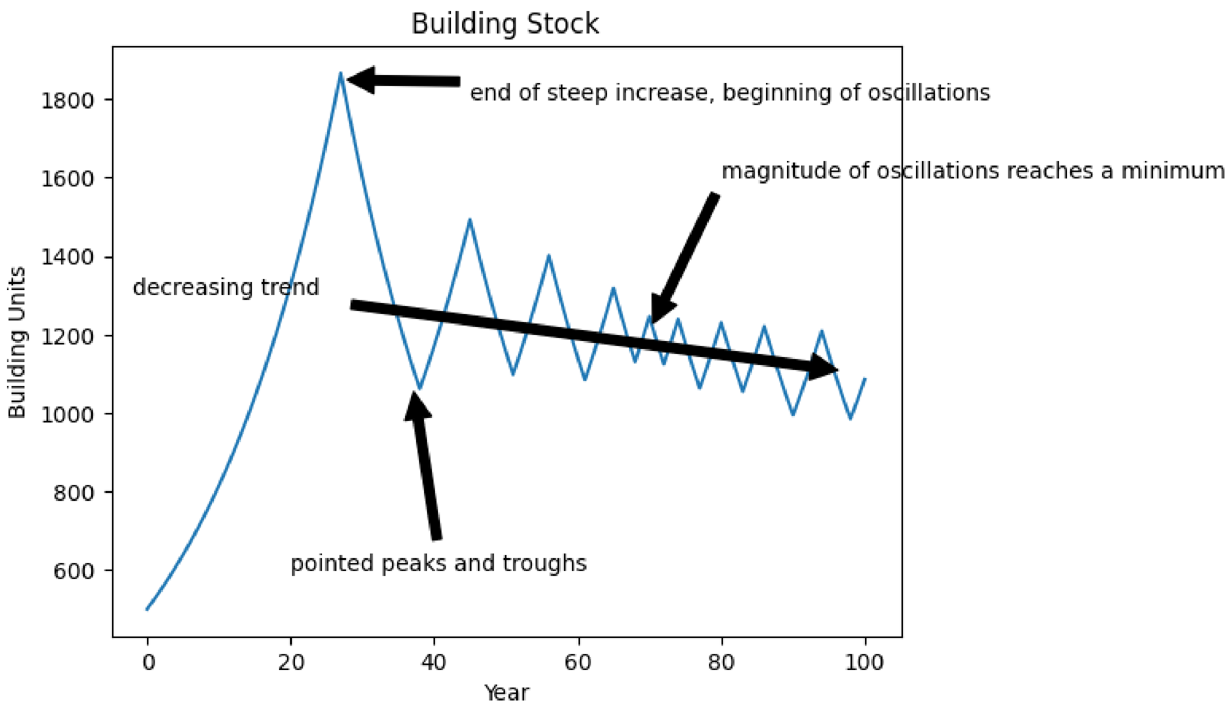
Part 2 – modeling the system

2.2



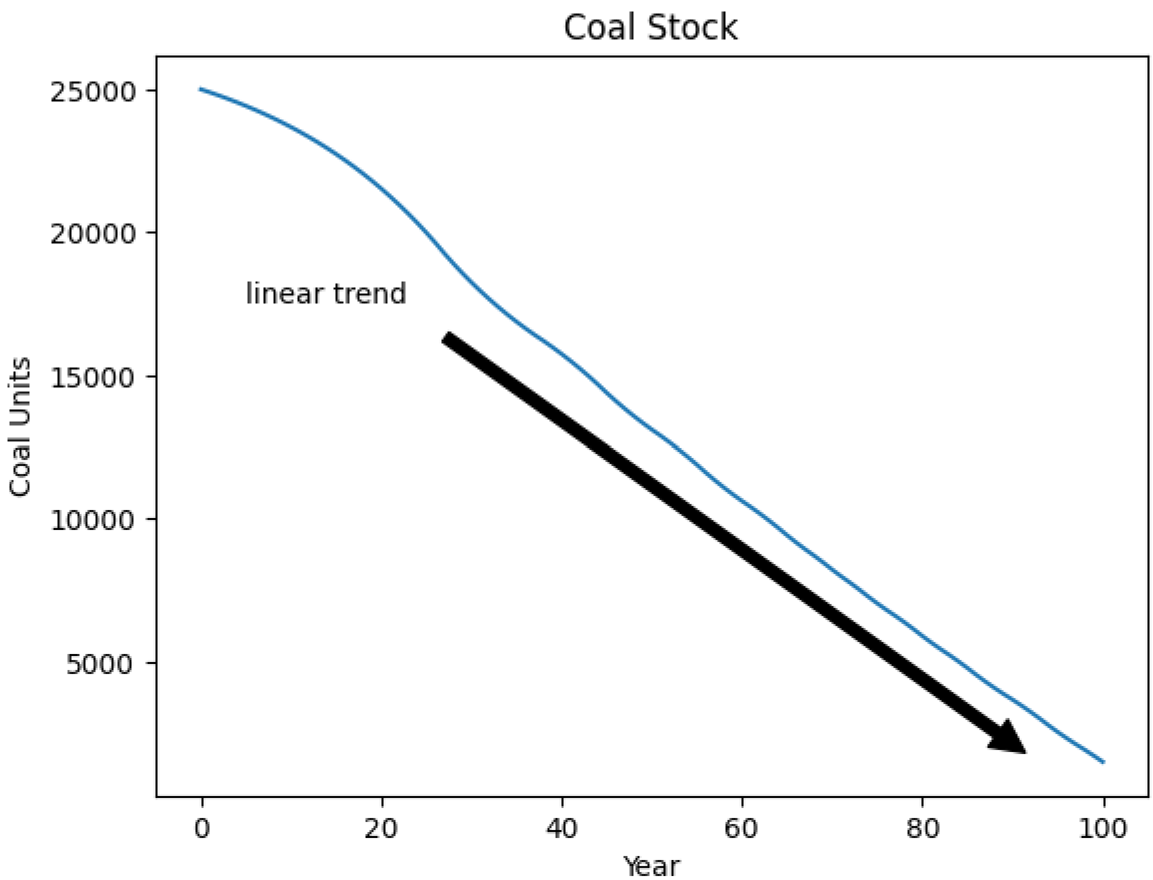
The pollution stock shows an initial increase and then smooth, rounded oscillations as time increases. The value of the pollution stock begins near zero and shows a steep, steady increase until about 30 years. After 30 years, oscillations begin and dampen until about 70 years where the magnitude of the oscillations reaches a minimum. After 70 years, the oscillations increase in magnitude until 100 years.

Initially, pollution increases steadily because the levels are low enough that there are no immediate consequences to be faced by the city. Once the pollution threshold is reached, the consumption of coal decreases and pollution falls back below the threshold value. Since pollution stays in the air for some time after the coal has been burned, there is a delay in the response of the system and the pollution slows its increase, becomes stagnant, and then slowly decreases as the pollution lingers in the air while no new pollution is added, leading to the rounded peaks of oscillation. As the amount of pollution decreases as pollution decays in the atmosphere, coal begins to be burned again, thus increasing the pollution. This pattern follows as time increases as the response to the current amount of pollution is delayed by the time the information is obtained.

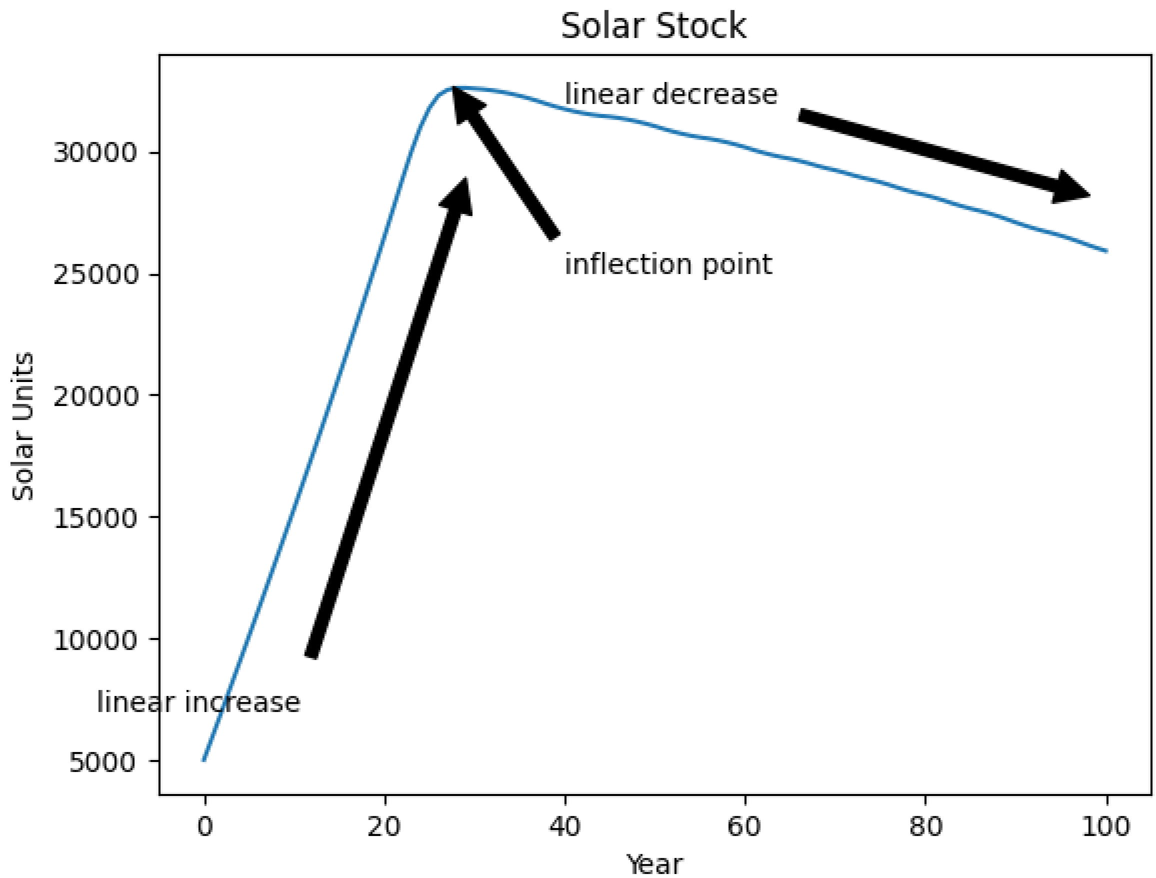


The building stock shows a similar pattern to the pollution stock with an initial increase, followed by oscillations. The oscillations in the case of the building stock show clear, pointed peaks. The initial increase with the building stock is less linear than with the pollution stock. The increase is slower at the beginning and increases at a faster rate as time increases. As with the pollution stock, the maximum value of the building stock peaks at about 30 years. The magnitudes of the oscillations are greater with the building stock, however, as with the pollution stock, the magnitude of the oscillations reaches a minimum around 70 years. There is an overall downward trend of the oscillations as time increases.

These oscillations are again caused by the delayed response from the time it takes to build the buildings and the time it takes to obtain information on the amount of buildings and the impact of these buildings. In the case of the building stock, the oscillations have sharp points because once the pollution threshold is reached, urban growth becomes zero and buildings maintain the building decommission rate. Instead of a gradual switch from increase to decrease, the increase in buildings stops abruptly as the pollution threshold is reached and the building decommission rate immediately contributes to the decrease in building stock. Once the pollution is again below the threshold, buildings are built again and the stock sharply goes up. As more buildings are built, the pollution increases as coal consumption is needed to build and maintain buildings. Since there is a fixed amount of space in the city, the amount of buildings built each year decreases as space becomes less available. This limit of space in the city contributes to the overall downward trend of the oscillations. The magnitude of the oscillations in the building stock is related to the amount of urban growth. As the peaks of urban growth are decreasing, so is the magnitude of the oscillations in building stock, and as the peaks in urban growth increase, so do the magnitudes of the oscillations.



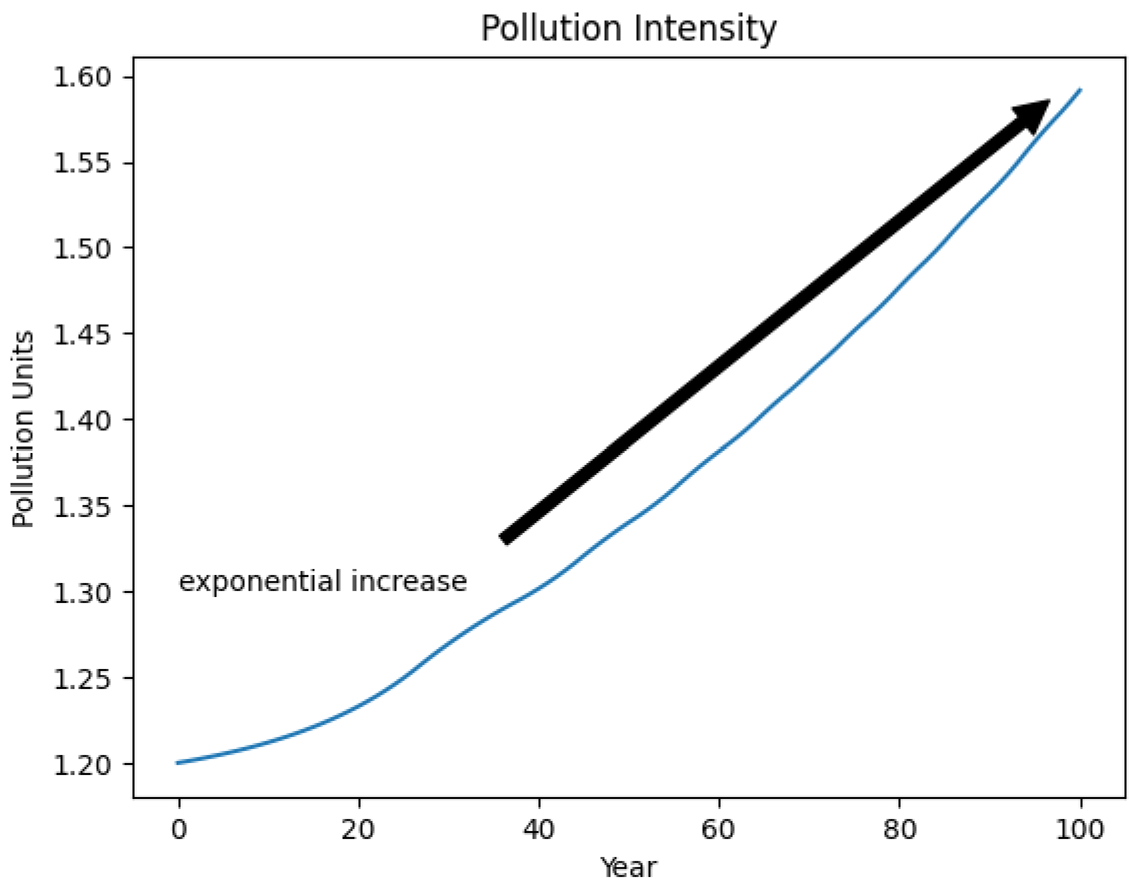
The value of coal stock begins high and decreases linearly with time, indicating that it is being depleted at a constant rate. Since coal is a non-renewable resource, the coal will begin with a large value and decrease with time as the coal is used up, with no source to replenish what has been lost.



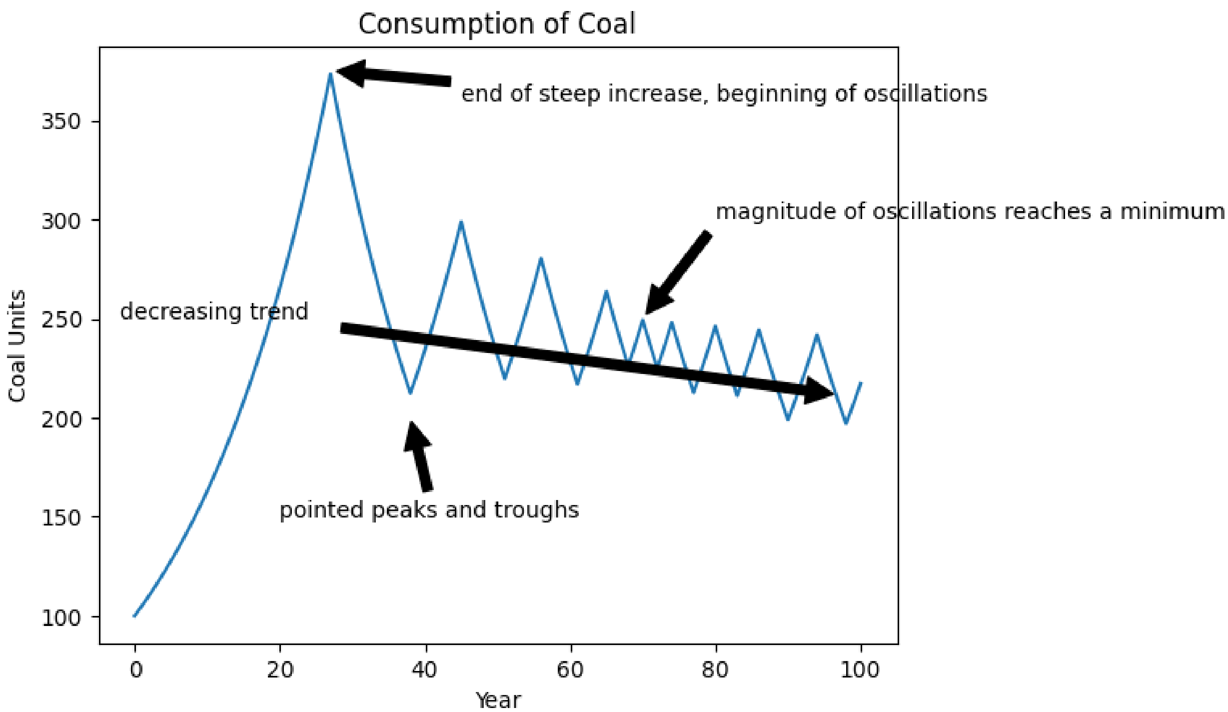
The solar stock begins at a low value and increases linearly until an inflection point at 30 years, where the solar stock takes a rounded turn and decreases linearly until 100 years. The rate of change in solar stock is much greater before the inflection point and changes at a much slower rate after the inflection.

Since solar stock is related to building stock, with more buildings allowing for a greater amount of surface area for solar energy to be obtained, as building stock increases, so does solar stock. The inflection point is reached when the pollution threshold is reached and building stock, consumption of coal, and urban growth all decline as well. When the building stock begins its oscillating decline, the solar stock sees a similar decline with no oscillations. The oscillations are evened out for the solar stock because as more buildings are built, there is more room for solar energy to be captured. But as more buildings are built, there is also a decrease in solar potential as more shadows are cast on surrounding buildings. These opposing interactions with the number of buildings flattens out the oscillations of the solar stock, leading to a linear decrease.

2.3

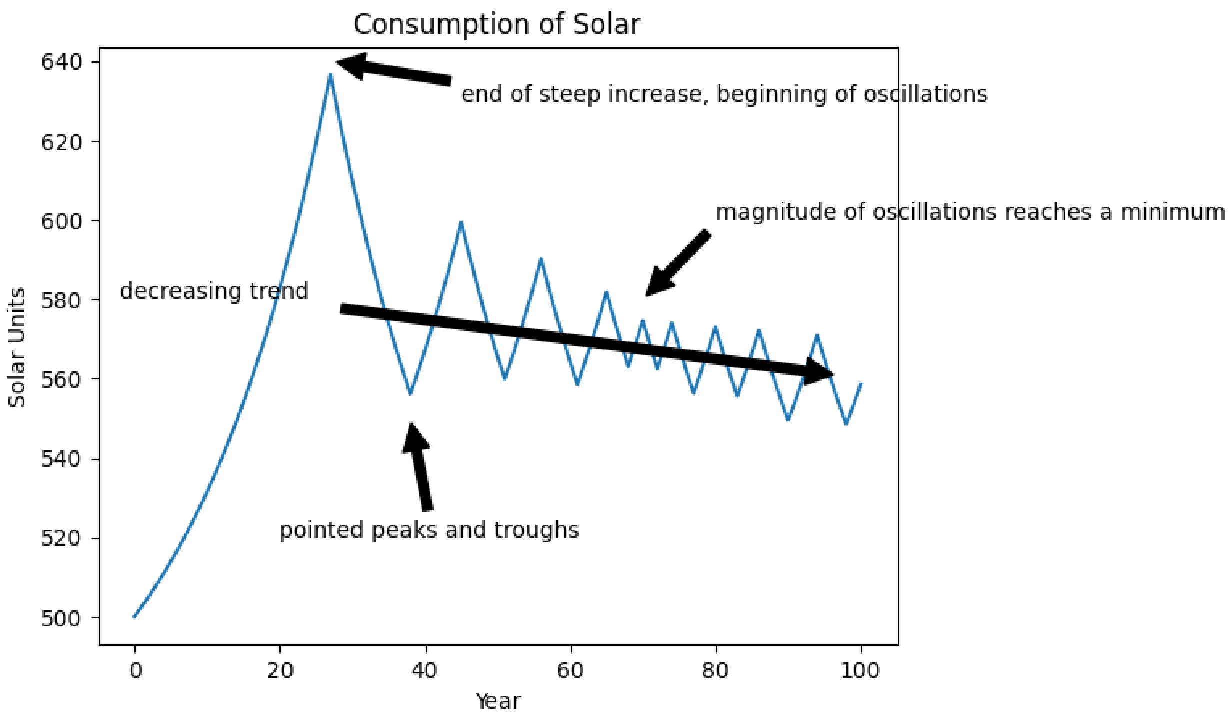


The increase in pollution intensity is exponential through 100 years. The pollution intensity begins low and increases at a slower rate in the beginning, increasing at a faster rate as time increases. The pollution intensity increases exponentially because of the assumption that we first consume cleaner coal, and then the coal we consume gradually becomes less clean as the resource of clean coal becomes depleted.

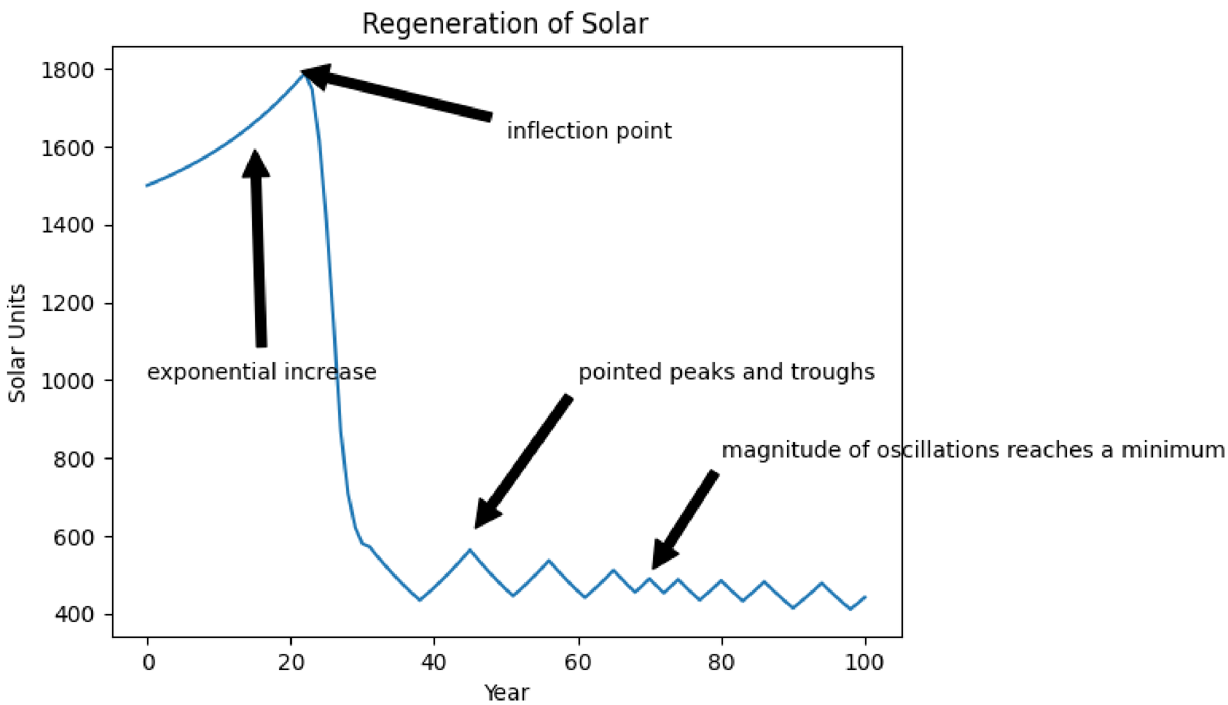


The consumption of coal follows a similar pattern to that of the building stock. There is an initial exponential increase in consumption leading into pointed oscillations following a decreasing trend as time increases. Due to the energy requirements to build and maintain buildings, buildings drive the consumption of coal.

The consumption of coal oscillates because of the delay in information from when the pollution threshold is reached. When this threshold has been exceeded, there has already been coal consumed that will continue to contribute to an increase in pollution. To dip below the threshold, coal consumption is paused and the graph sharply drops. After some time, the pollution again falls below the threshold and coal consumption can resume so the graph sharply increases. There is a gradual decreasing trend of the consumption of coal because the pollution intensity increases over time and fewer buildings are being built as the city has a fixed space. Since pollution stays in the atmosphere for some time after emission and the intensity increases as cleaner coal becomes harder to find, the pollution threshold is reached more quickly and less coal needs to be consumed to reach the pollution threshold. Additionally, with the fixed amount of space in the city, the amount of buildings built each year decreases as space becomes less available. The magnitude of the oscillations in the consumption of coal is related to the building stock, as well as the amount of urban growth. As the peaks of urban growth are decreasing, so are the magnitude of oscillations, and as the peaks in urban growth increase, so do the magnitudes of the oscillations.

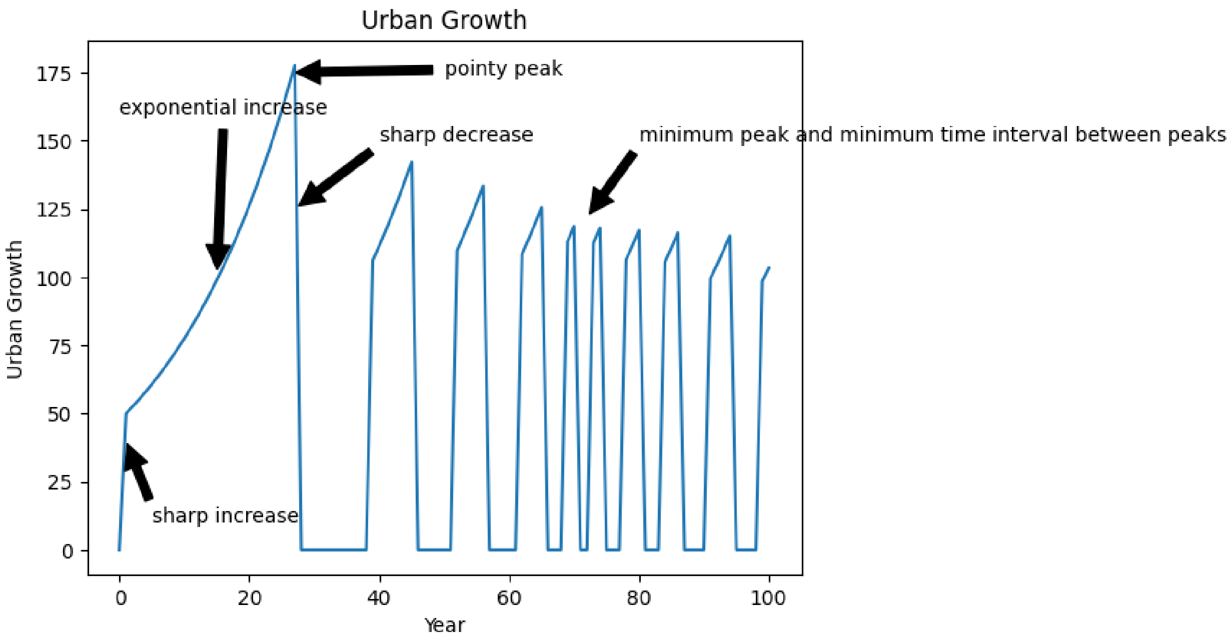


The consumption of solar follows a similar pattern to that of the building stock and the consumption of coal. There is an initial exponential increase in consumption leading into pointed oscillations following a decreasing trend as time increases. Solar stock moves with the building stock because the extraction and consumption of solar stock is related to the change in building stock. When new buildings are built, more energy is required, thus increasing the consumption of solar. This is similar to the trend seen with the consumption of coal, where buildings drive solar consumption.



Initially, the regeneration of solar increases exponentially from year 0 to year 20. After the inflection point, the regeneration drops significantly and begins to oscillate around 500 solar units. The oscillations have sharp peaks and troughs, decreasing in magnitude initially, reaching a minimum in magnitude around 70 years, and increasing again in magnitude until year 100.

The regeneration of solar increases while the building stock increases since more buildings allow for a greater potential for solar energy to an extent. When there are too many buildings, the regeneration of solar decreases because buildings begin to cast shadows on other buildings. Since the regeneration of solar is dependent on the amount of space available on buildings, the oscillations of regeneration of solar follow a similar trend to the oscillations in the building stock. The first inflection point of the regeneration of solar is reached at the same time the pollution threshold is reached, so a large decline in the regeneration of solar is experienced since there is a significant decline in building stock.

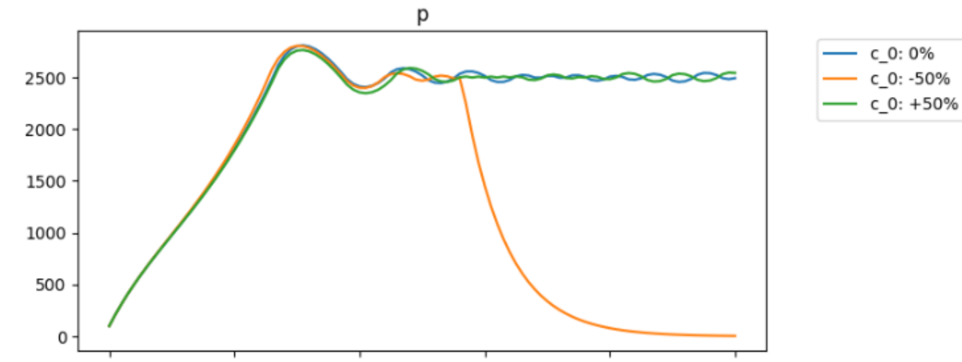


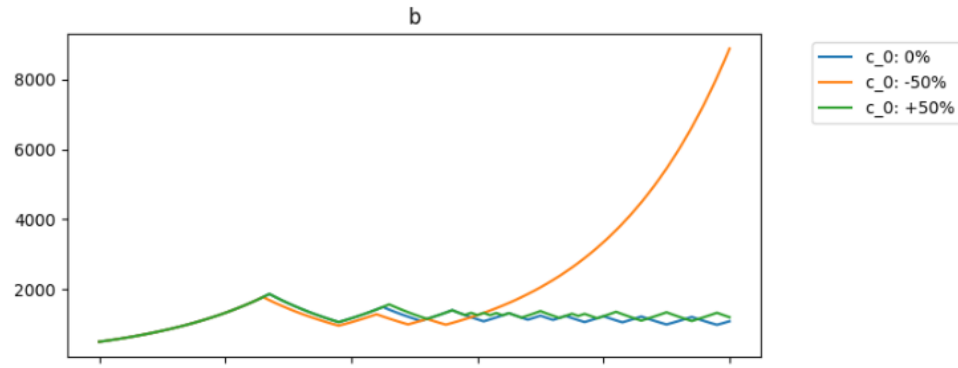
Urban growth begins at zero and quickly increases to a value of 50 before reaching a point where urban growth increases exponentially. It increases exponentially until year 25 where it then experiences a sharp decrease back to zero. The trend similarly progresses as time increases with decreasing time intervals between the spikes in growth and decreasing magnitudes of growth spikes. A minimum in the height of the spike and the time between spikes is reached around 70 years. After this point, the time intervals between spikes in growth increases again and the height of the growth peaks decrease only slightly.

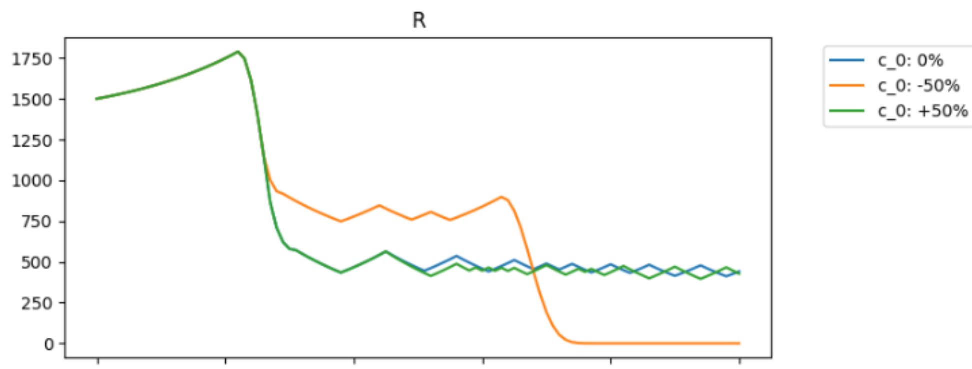
Urban growth shows sharp decreases because once the pollution threshold has been reached, growth goes to zero, thus at each peak of urban growth is where the pollution threshold has been reached. Once the pollution decays and is below the threshold level again, urban growth can again jump back near its previous level, slightly declined due to the decommissioning of building stock during the time when urban growth was zero. Urban growth again increases until the pollution threshold is reached and returns to zero. The peaks in urban growth decrease over time because space for urban expansion is fixed and as the city fills up, the potential for it to grow decreases. At about 70 years, the spacing between the oscillations is at a minimum and the decrease in the height of the peaks of urban growth is smaller as the size of the city reaches an equilibrium and remains roughly the same.

Part 3 – Sensitivity analysis

3.1.1 Variation in stocks - coal

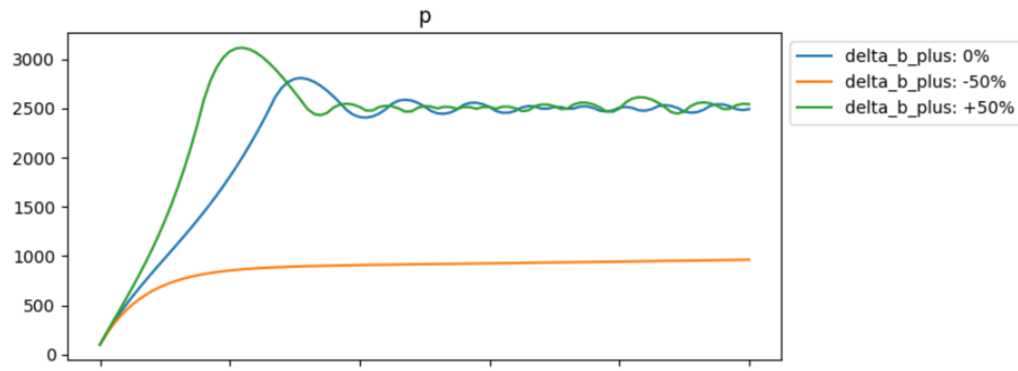


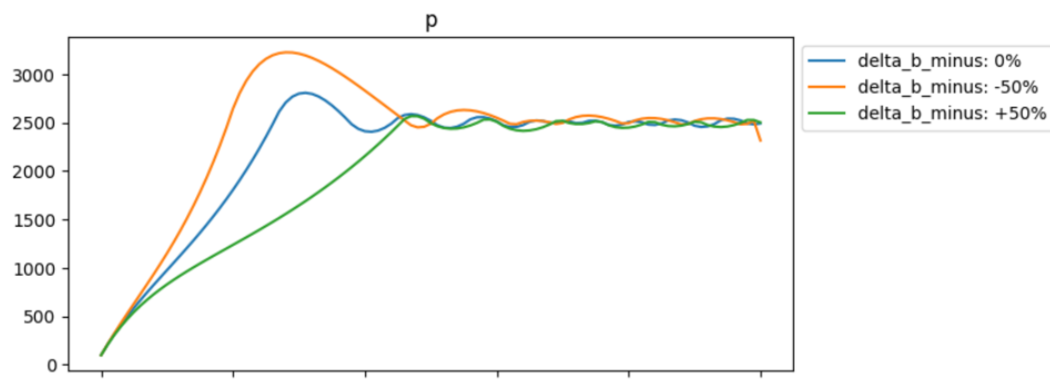


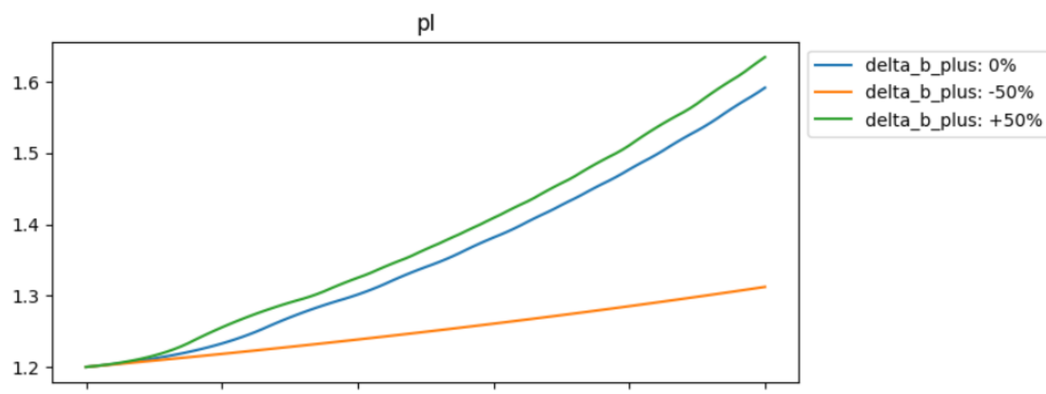


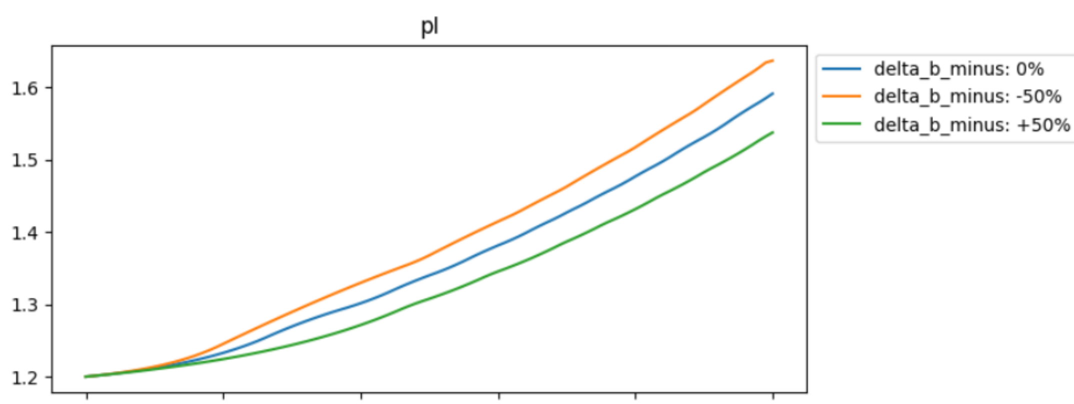
Changing the pollution stock, building stock, and solar stock by ±50% does not show significant changes in the resulting graph. However, a large change is seen when the initial amount of coal is -50%. Pollution stocks are related to coal stocks. If the initial coal stock is -50%, the level of pollution will rapidly decrease from around 55 years to 0 around 80 years as coal is depleted in around 55 years, and solar power is used thereafter. As the city grows as the pollution stock disappears, the building stock increases rapidly while shadowing each other and decreasing the solar stock and inflow.

3.1.2 Variation in change rates - δ_b



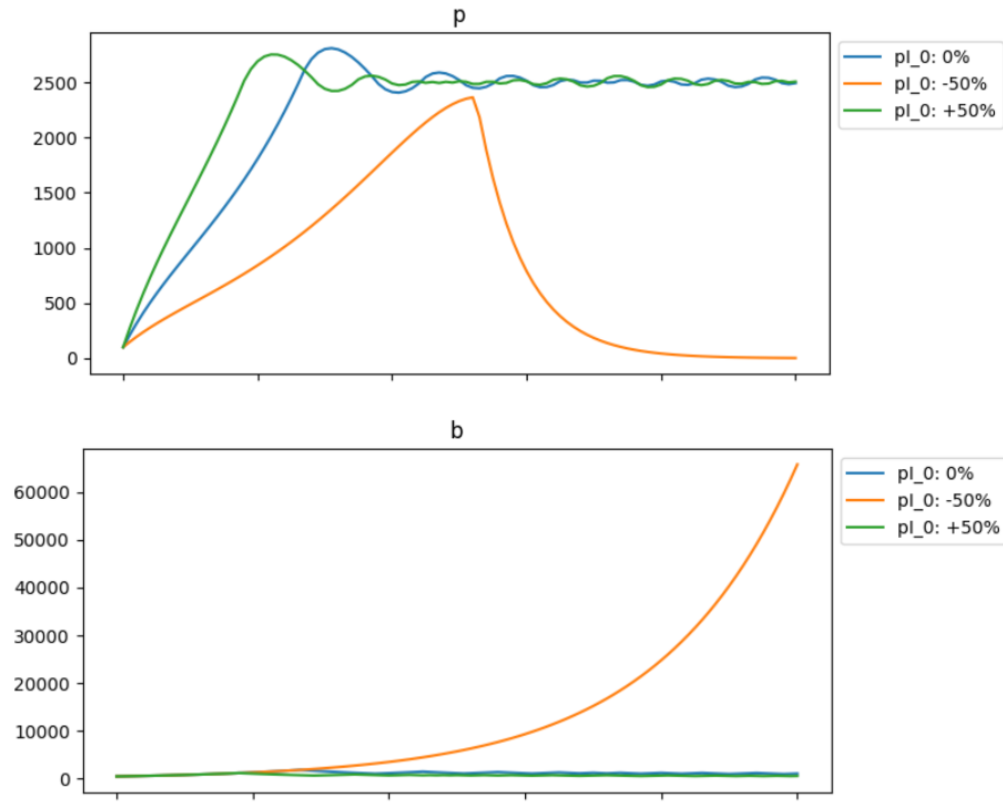






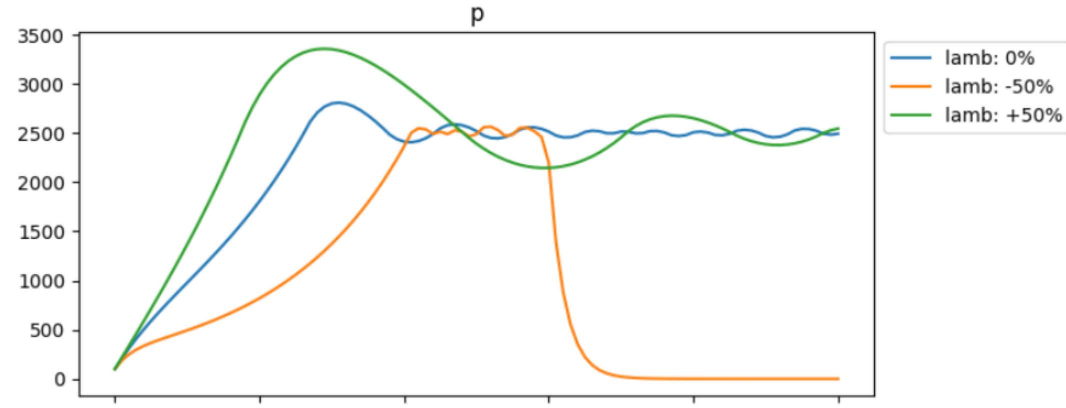
A -50% reduction in the rate of building construction equals the initial rate of building demolition, which means no urban growth, but significantly lowers the level of air pollution compared to the base case. On the other hand, a reduction in the rate of building demolition increases the pollution stock. This fact can be effectively used to control air pollution by adjusting the number of new buildings to be constructed and demolished.

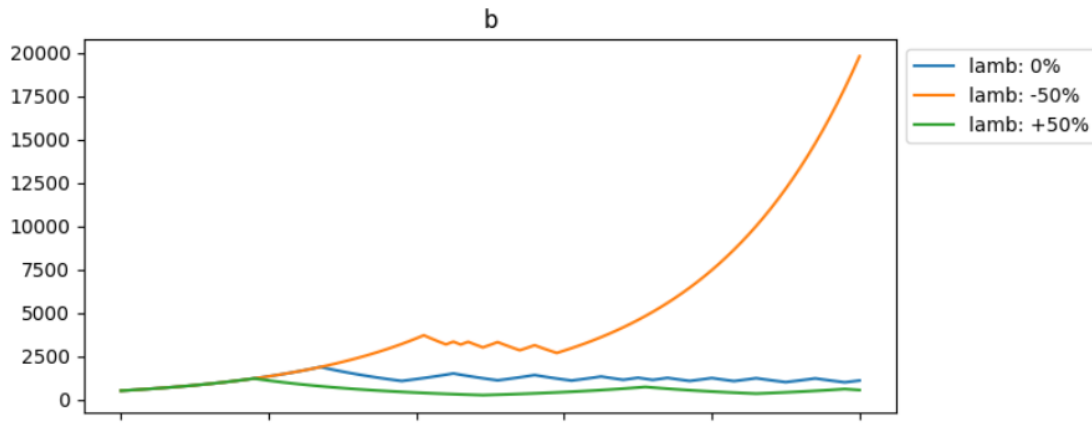
3.1.3 Variation in pI - the pollution intensity

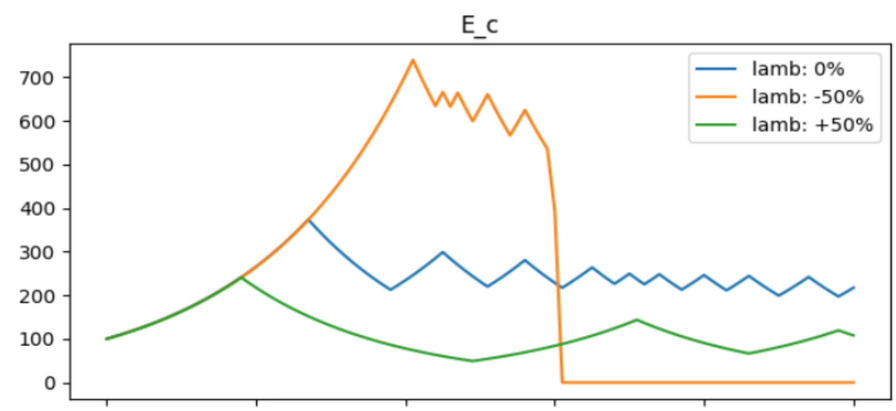


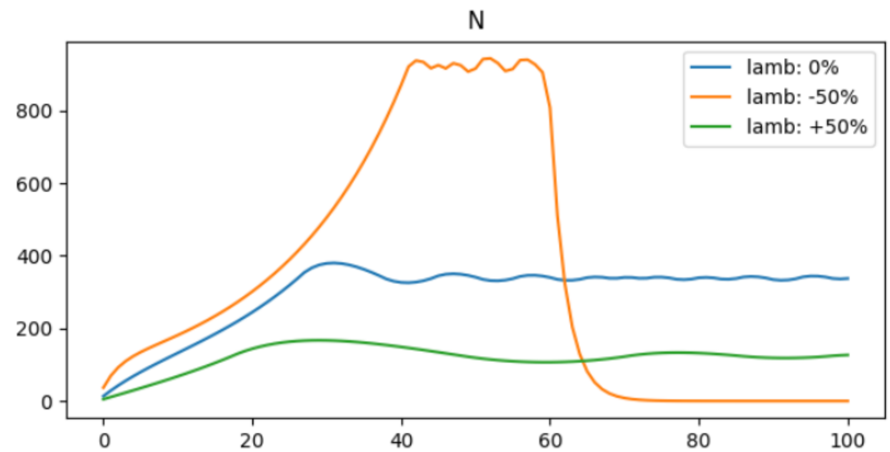
By controlling the level of pollution, the number of pollutants in the air decreases and the number of buildings increases exponentially.

3.1.4 Variation in λ - Pollution decay parameter



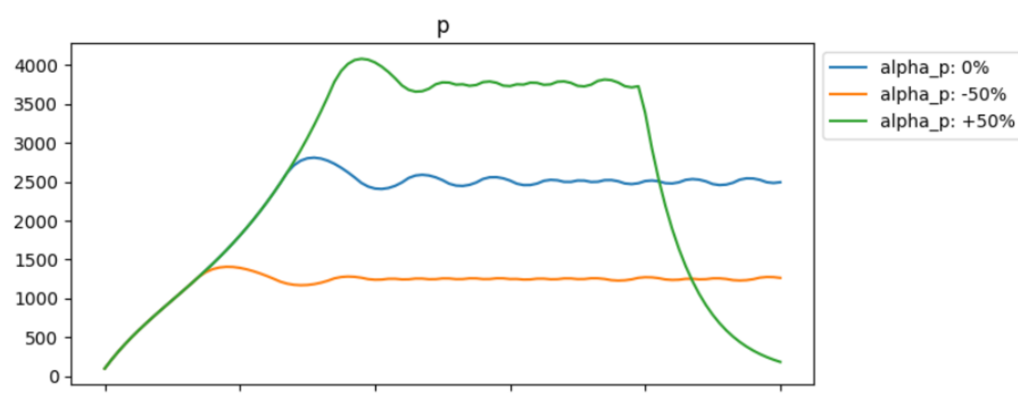


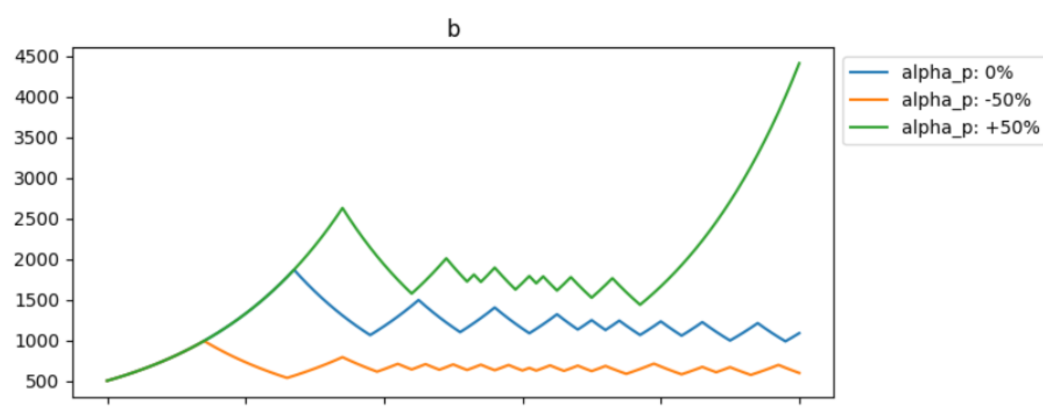




A 50% decrease in λ means an increase in the amount of pollutant decay. Also, less pollutant in the air facilitates the extraction of coal, so the entire coal stock is extracted around 60 years, earlier than the base case. Finally, once the stock of pollutants in the air disappears, urban growth expands dramatically from 60 years.

3.1.5 Variation in α_p - the pollution threshold





Allowing a bigger pollution threshold accelerates the increase in the amount of pollutant stock in the air, but also the extraction of the entire coal. Eventually, all coal is extracted for about 80 years, and the pollutant stock decreases rapidly with exponential urban growth.

3.2 Policy Analysis

From the findings from the sensitivity analysis, the adjustment of factors below contributes to maximizing urban growth and minimizing the pollution stock in the air.

c: Reduction initial coal stock

δ: Reduction of the change rate of building

pI: Reduction of Pollution intensity

λ: Make pollution decay parameter smaller

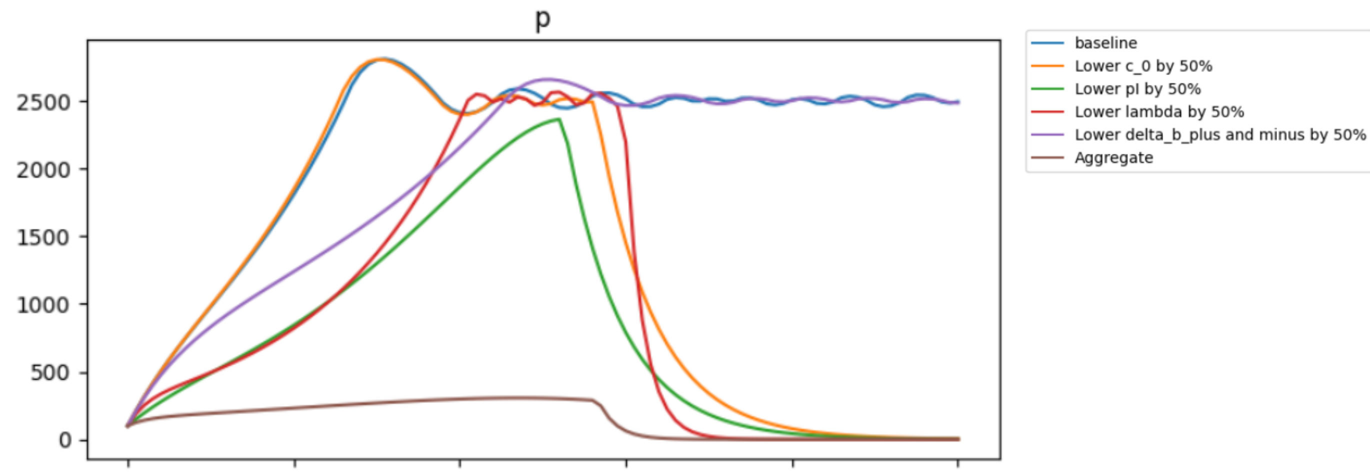
Therefore, the proposed policy interventions are below:

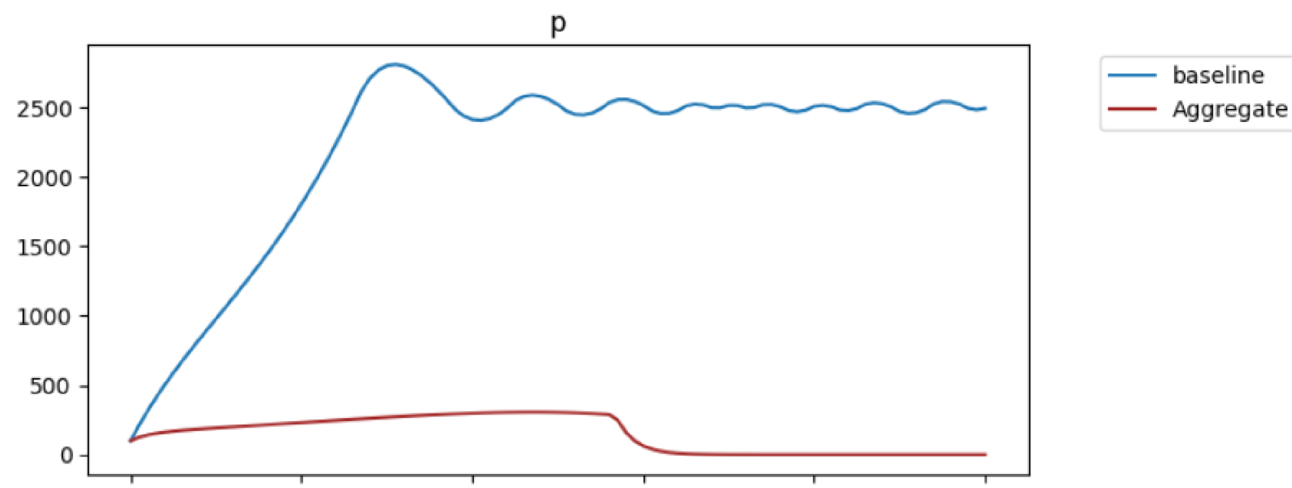
Policy 1: Control c - Reducing the usage of coal and utilizing renewable solar energy (Changing the initial amount of coal is unrealistic, so controllable factor is "usage of coal" here.)

Policy 2: Control δ - Making better use of building stock by reducing the number of buildings constructed and demolished

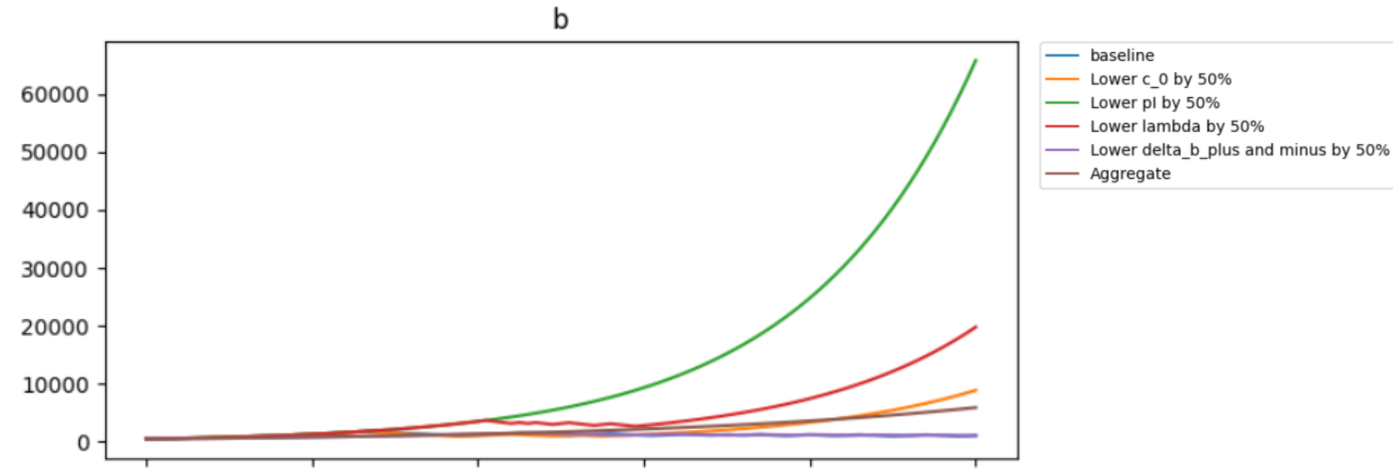
Policy 3: Control pI and λ - Reducing pollution intensity by carbon scrubbing technology, carbon capture, sequestration, etc.

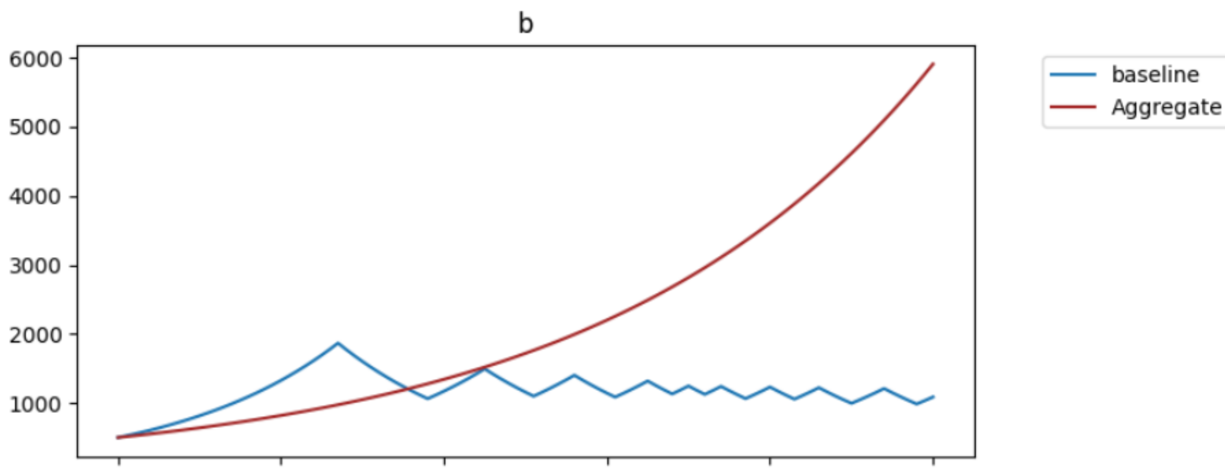
The following graphs show the changes in the stock of pollutants and the stock of buildings when the above policies are implemented. As the legend shows, the results when each policy is applied are shown. In addition, the brown line shows the results when all of the policies are aggregated.





The implementation of all measures would reduce the stock of pollutants in the atmosphere by a factor of 10 over an initial period of about 55 years. Then, after coal is depleted, p slows rapidly to 0 in about the 60th year.





For the building stock, measures such as carbon capture, i.e., reducing the intensity of air pollution and decreasing attenuation parameters, are most effective (green and red lines). However, since the policy of effectively utilizing existing buildings is also implemented, the urban growth rate when all measures are aggregated becomes the average of all cases. The city's building stock after 100 years is about six times larger than the base case.