ENE467

Energy And Climate Policy

Spring Semester 2025

Date: January 11, 2024

Reference list

Assignment 1

Question 1:

The expression,

$$\frac{dx}{x} = dlnx$$

plays an important role in analyzing the relationship between GDP and energy consumption. It's primarily used for calculating growth rates. This approach also facilitates the computation of elasticity, showing how percentage changes in energy use impact GDP.

The regression analysis shows a strong positive correlation between energy consumption and GDP (0.886). This indicates that as energy consumption increases, GDP also tends to increase. The R-squared value of 0.785 tells us that 78.5% of the variation in GDP can be explained by changes in energy consumption.

The growth rates provide further insight:

- Energy growth: 1.03% per year
- GDP growth: 2.51% per year
- GDP per capita growth: 1.84% per year

These figures demonstrate that GDP is growing faster than energy consumption, suggesting an improvement in energy efficiency over time, as discussed in the lecture.

The difference between GDP growth and energy growth supports the idea of "decoupling," where economic growth is achieved with a relatively smaller increase in energy consumption. This may be attributed to technological advancements and structural changes in the economy.

The linear regression equation,

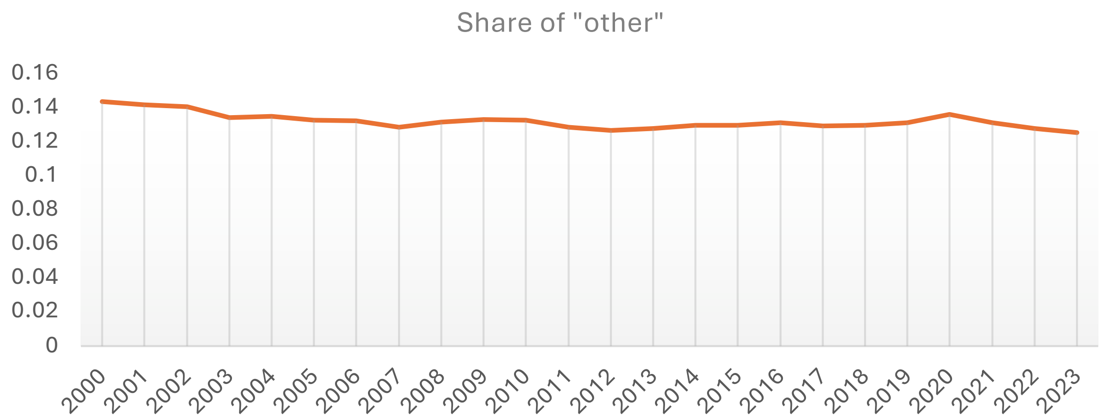
$$GDP\ (2015\$) = -19{,}150.87\ +\ 373.99 * Energy\ Consumption$$

quantifies the relationship, indicating that for each unit increase in energy consumption, GDP increases by 373.99 units.

These findings emphasize the importance of understanding the relationship between energy use and economic growth. They also highlight the need to continue improving energy efficiency to achieve sustainable economic growth.

Question 2:

In 2023, the share of other sources of energy – nuclear, hydro, geothermal and biofuels – was approximately 12%. As illustrated in graph 1, the share of other energy sources has been somewhat consistent since 2000. If we consider that the share will remain constant, we can calculate how many years it will take until the share of solar & wind consumption will equal the share of fossil fuel consumption.



Graph 1

Solar & wind consumption will overtake when the share (s) is larger or equal to $(1 - 0{,}12)/2 \geq\ 0{,}44$. Based on the formula below, we can calculate the number of years (T) it will take to reach a share of 0,44.

$$s = 0{,}44 = \frac{x_{s\&w_{00}}\ (1 +\ g_{s\&w})^T}{x_{e_{00}}\ (1 +\ g_e)^T}$$

Where:

- $x_{s\&w_{00}}$= share of solar & wind consumption in 2023
- $x_{e_{00}}$ = total energy consumption in 2023
- $g_{s\&w}$ = growth rate for solar & wind consumption
- g_e= growth rate for total energy consumption

By rearranging the equation, we can solve for T.

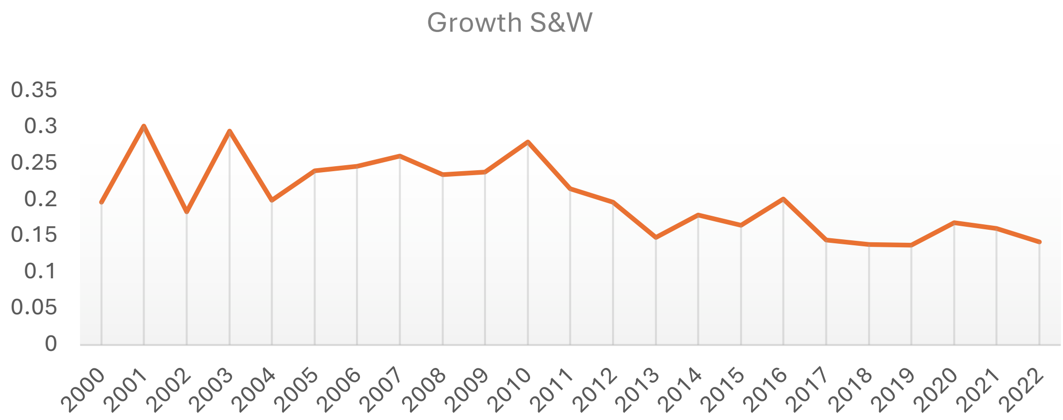
$$\ln{(0{,}44)} = \ln\left(\frac{x_{s\&w_{00}}}{x_{e_{00}}}\right) + T\ln[(1 + g_{s\&w})\,/\,(1 + g_e)]$$

$$T = \frac{\ln(0{,}44) - \ \ln\left(\dfrac{x_{s\&w_{00}}}{x_{e_{00}}}\right)}{ln\dfrac{1 +\ g_{s\&w}}{1 +\ g_e}}$$

The growth rate of each period (g_{x_t}) can be calculated using the formula below, and then used to calculate the average growth rate of the total period.

$$g_{x_t} = \ln(x_{t+1}) - \ln{(x_t)}$$

The annual average growth rate of solar & wind power from 2000 to 2023 was 0.2. Graph 2 however displays that the annual growth rate in fact has declined over the years. We should therefore consider a continued decrease and calculate the number of years (T) it will take given different scenarios.



Graph 2

With a growth rate of 0.2, it will take 12 years for solar & wind consumption to overtake fossil fuels. On the other hand, with an annual growth rate of 0.05 it will take 66.5 years until solar & wind power will overtake fossil fuels. 4 different scenarios of the growth rate are shown in table 1.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
$g_{s\&w}$	0.2	0.15	0.10	0.05
T	12	16.5	26	66.5

Table 1

Exponential growth is not suitable in the long term. While exponential growth models are suitable for short-term projections, these sources will eventually face constraints such as land availability, storage technologies, and infrastructure limitations. This aligns with the idea that growth will eventually transition from exponential to logistic growth.

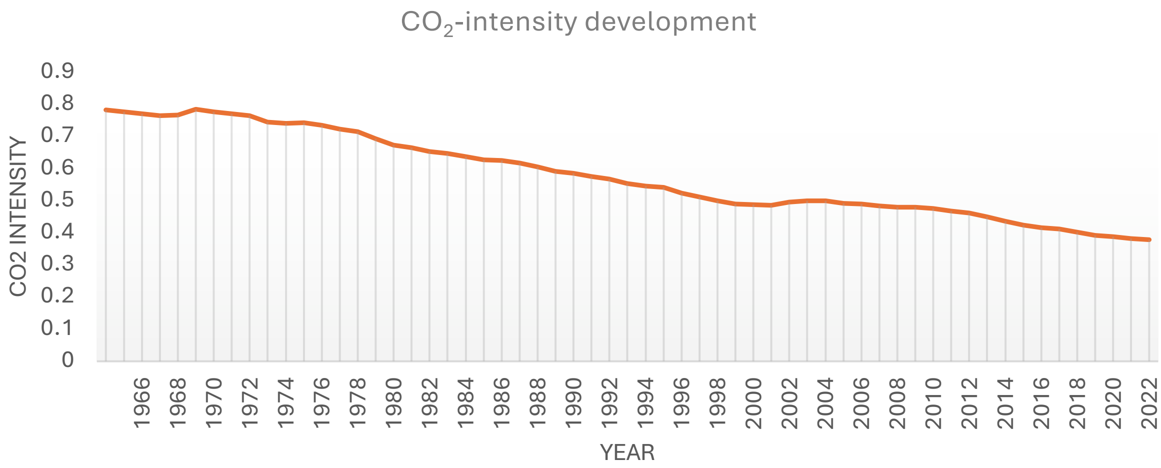
Moreover, the transition to renewable energy will not occur in isolation. Economic growth, technological progress, and policy decisions will significantly influence the pace at which renewable energy replaces fossil fuels. Energy consumption is tightly linked to economic growth, particularly in emerging economies like China and India, where energy demand is expected to rise sharply. Although renewable energy will continue to play a larger role, it remains unclear whether it can fully meet the rising demand for energy in a growing global economy.

In conclusion, our projection is that solar and wind energy will grow in the future, but the timing for then they will surpass fossil fuels remain uncertain.

Assignment 2

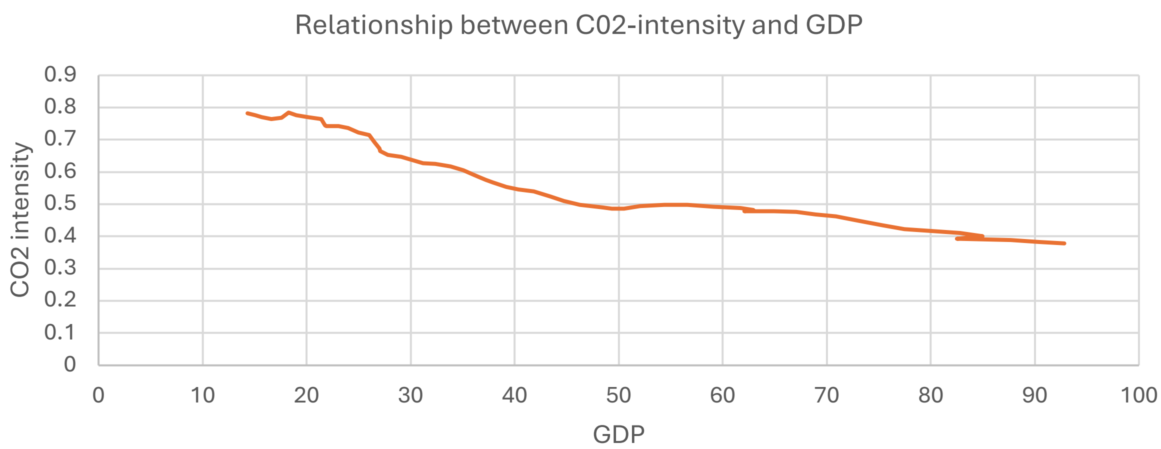
Question a)

The CO_2-intensity is a measure that evaluates the amount (kg) of carbon dioxide (CO_2 emissions) produced per unit ($) of GDP. Since 1965, the CO_2-intensity has decreased by approximately 52 percent as illustrated in graph 3. On average the annual growth rate from 1965 to 2023 was -0.012.



Graph 3

Illustrated in graph 4, we can observe that the CO_2-intensity decreases as GDP increases.



Graph 4

The graph indicates a continuous reduction in the amount of carbon emissions required to produce economic output. This trend highlights that, although global CO2 emissions have risen as the world economy has grown, the efficiency of energy use and the carbon intensity of production has improved.

Looking at the graph, it is evident that his decline in CO2 intensity reflects broader global shifts towards more sustainable forms of energy and technological advancements aimed at improving energy efficiency. For example, we have seen the rise of renewable energy sources like solar and wind, which are less carbon-intensive compared to fossil fuels. Furthermore, energy efficiency improvements across various sectors, including manufacturing and transportation, have contributed to this reduction in carbon intensity.

This decrease in CO2 aligns with the idea that many countries have increasingly decoupled economic growth from carbon emissions. This process, also known as decarbonization, suggests that it is now possible for economies to grow while reducing their carbon footprint. The graph reflects the global trend of shifting towards cleaner energy and the growing focus on reducing greenhouse gas emissions in line with international climate agreements, such as the Paris Agreement.

Question b)

The constant rate can be found by performing a regression with the CO_2-intensity as the dependent variable, and "year" as the independent variable.

SAMMENDRAG (UTDATA) brukte Y=energi, og X=årene

Regresjonsstatistikk	
Multippel R	0.987700759
R-kvadrat	0.97555279
Justert R-kvadr	0.975123891
Standardfeil	0.020433469
Observasjoner	59

Variansanalyse

	fg	*SK*	*GK*	*F*	*Signifkans-F*
Regresjon	1	0.949687	0.949687	2274.554	1.23545E-47
Residualer	57	0.023799	0.000418		
Totalt	58	0.973486			

	Koeffisienter	*tandardfei*	*t-Stat*	*P-verdi*	*Nederste 95%*	*Øverste 95%*	*Nedre 95.0%*	*Øverste 95.0%*
Skjæringspunk	15.43433492	0.3115	49.54842	1.47E-48	14.81056688	16.05810296	14.81056688	16.05810296
X-variabel 1	-0.01	0.000156	-47.6923	1.24E-47	-0.007762965	-0.007137343	-0.007762965	-0.007137343

The regression shows that the intercept is 15.43, which represents the theoretical CO2 intensity at the starting point of the analyzed period. The slope coefficient for the year variable is -0.01, indicating that CO2 intensity decreases by a constant rate of 0.01 units annually.

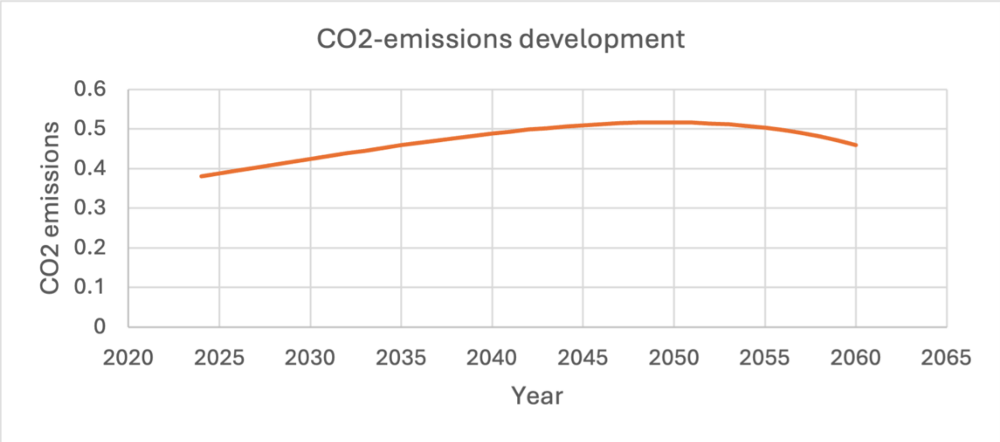
$$CO2\text{-}intensity_t = CO2\text{-}intensity_0 - 0.01 * t$$

Under different scenarios of the annual growth rate of GDP (table 2), emissions – which is a product of the GDP and the CO2-intensity – will peak in 2050 with a growth rate of 4 percent (graph 5).

Growth rate	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**
2048	0.3236	0.4090	0.5157	0.6489	0.8146

2049	0.3179	0.4057	0.5165	0.6561	0.8315
2050	0.3118	0.4018	0.5165	0.6624	0.8475
2051	0.3053	0.3973	0.5157	0.6677	0.8625
2052	0.2984	0.3921	0.5140	0.6719	0.8761

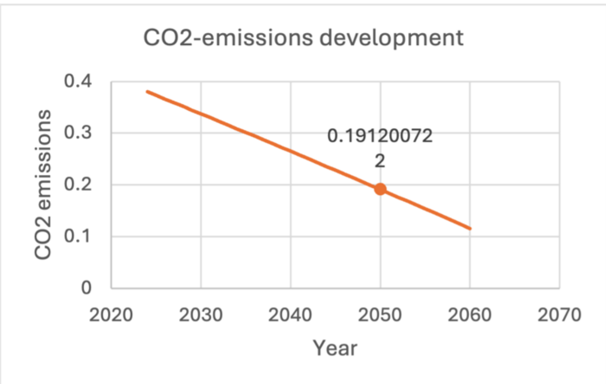
Table 2 – emissions under different scenarios of the annual growth rate of GDP



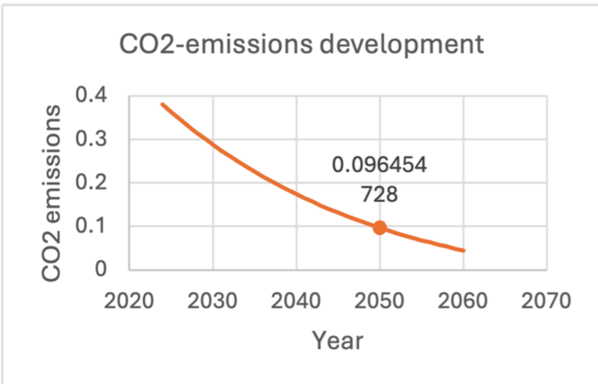
Graph 5 – CO2-intensity declines at a constant rate, and GDP increases with an annual growth rate of 4 percent

With an annual growth rate of 0.001 versus -0.025, we could reduce emissions by 2050 to one-half or a quarter of emissions in 2023.

g	**share2050/share2023**
0.001	0.5032
-0.025	0.2538



Graph 6 – BNP annual growth rate 0.001 (emissions are ½ of 2023)



Graph 7 – BNP annual growth rate -0.025 (emissions are 1/4 of 2023)

Question c)

To plot the CO2-intensity as a function of GDP, we can perform a new regression where the GDP is the new independent variable.

Summary Y = CO2 intensity, og X = GDP, from a starting point of year 2000

Regresjonsstatistikk	
Multippel	0.951167774
R-kvadrat	0.904720134
Justert R-I	0.900389231
Standardf	0.013300954
Observas	24

Variansanalyse

	fg	*SK*	*GK*	*F*	*Signifkans-F*
Regresjor	1	0.036957396	0.036957	208.8987294	1.03434E-12
Residuale	22	0.003892138	0.000177		
Totalt	23	0.040849534			

	Koeffisienter	*Standardfeil*	*t-Stat*	*P-verdi*	*Nederste 95%*	*Øverste 95%*	*Nedre 95.0%*	*Øverste 95.0%*
Skjærings	0.654242944	0.014224367	45.99452	2.3203E-23	0.624743412	0.683742475	0.624743412	0.683742475
X-variabe	-0.002924616	0.000202349	-14.4533	1.03434E-12	-0.003344262	-0.00250497	-0.003344262	-0.00250497

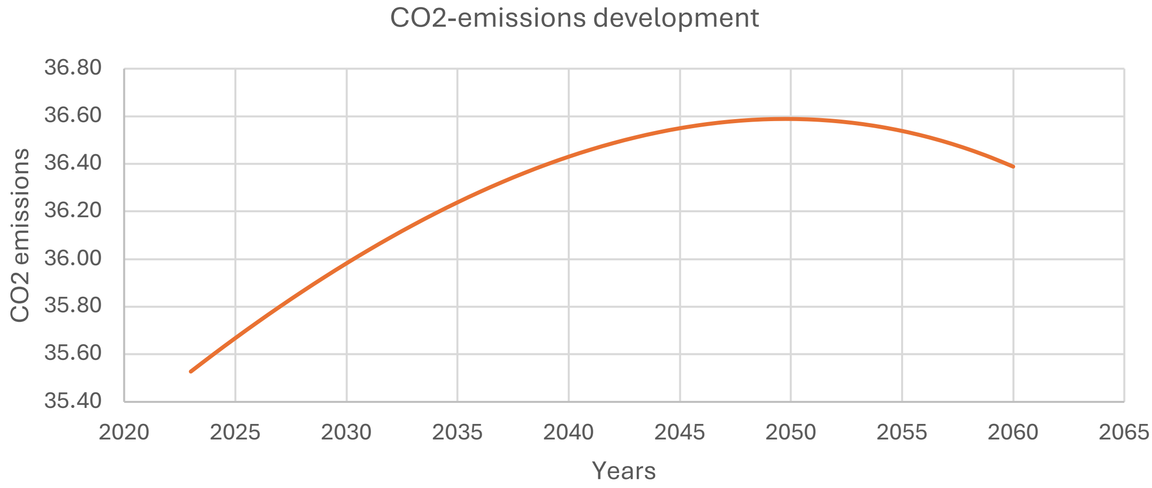
When the CO2-intensity is expressed as a linear function of GDP_t at time t, it depicts that as GDP increases, CO_2 intensity decreases at a constant rate

$$CO_2 - intensity_t = 0.654243 - 0.002925 * GDP_t$$

Under different scenarios of the growth rate for GDP, we found that emissions would peek in 2050 with a growth rate of 0.7 percent.

Growth rate	**0.005**	**0.006**	**0.007**	**0.008**	**0.009**
2048	36.4565	36.5402	36.5834	36.5831	36.5361
2049	36.4764	36.5544	36.5878	36.5733	36.5070
2050	36.4947	36.5662	36.5888	36.5585	36.4711
2051	36.5115	36.5756	36.5862	36.5386	36.4283
2052	36.5268	36.5826	36.5799	36.5136	36.3784

Table 3 – emissions under different scenarios of the annual growth rate of GDP

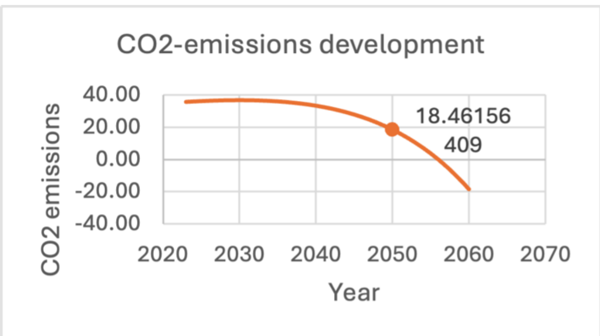


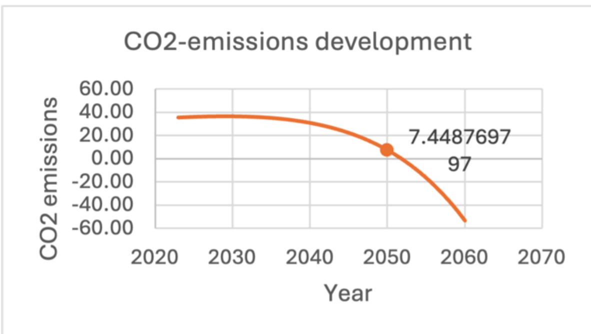
Graph 6 – CO2-intensity as a function of GDP, and GDP increases with an annual growth rate of 0.7 percent.

By increasing the growth rate to 2.7 versus 3.1 percent we could reduce emissions by 2050 to one-half or a quarter of emissions in 2023. This means that the faster the world grows, the faster it reduces emissions. However, the assumption that this relationship will remain over time is questionable. Given how it changed as the world GDP passed the 50 trillion-dollar mark in 2000, it is likely that decarbonization trends may slow or change. In this scenario, CO2 emissions depend on an increasing GDP, and emissions will stabilize when GDP grows at a lower rate.

In scenario b), the growth rate of GDP has an opposite effect on CO2-emissions. It suggests that a low growth rate would lead to emission reductions, and that achieving net zero would only be possible with a negative (declining) growth rate. That means that if the relationship found in c) is the true representation, the negative growth rate we found would reduce emissions to a quarter of emissions in 2023, in reality would increase emissions.

g	**share2050/share2023**
0.027	0.5263
0.031	0.2120





Question d)

In part (b), we assumed a linear relationship between GDP and CO2 intensity, meaning that CO2 intensity continues to decrease at a constant rate. This simplified approach does not account for the diminishing effect of GDP growth on CO2 intensity over time. On the other hand, in part (c), the fitted equation reflects a diminishing return as GDP increases, meaning that the reduction in CO2 intensity slows down as the economy grows.

Furthermore, reducing GDP to cut emissions is unlikely to be a viable long-term strategy. This would likely result in reduced living standards, especially in developing economies. Instead, it is crucial to focus on technological progress and structural changes in the economy to achieve CO2 emission reductions without sacrificing economic growth. The fitted model in part (c) supports this by demonstrating that a combination of cleaner energy adoption, more efficient use of resources, and innovative technologies is essential for reducing CO2 emissions over time while allowing continued economic development. This approach provides a more sustainable solution than relying solely on reduction of GDP growth.

Assignment 3

Question a)

Norway's consumption is 2.7 TWh per week. Over 52 weeks, this requires:

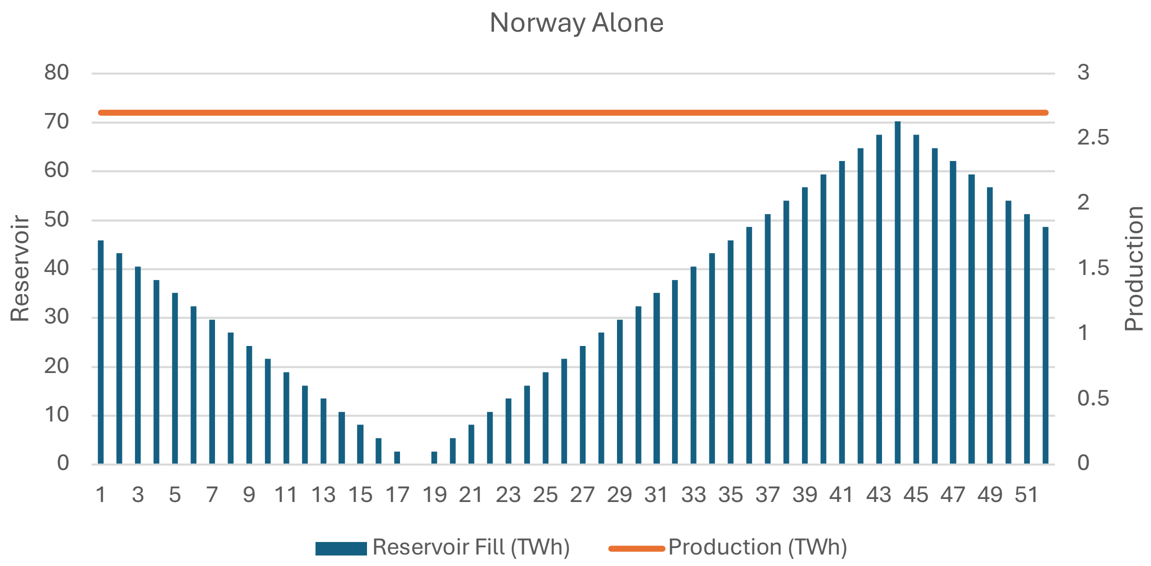
2.7 TWh/week * 52 weeks = 140.4 TWh

However, production is only feasible for 26 weeks due to rainfall replenishment equivalent to 5.4 TWh weekly. Therefore, the total replenishment for the wet season is:

26 weeks * 5.4 TWh/week = 140.4 TWh

This matches the demand, but reservoir capacity for balancing production during dry weeks. To sustain constant production during the 26 dry weeks (no inflow), the reservoir must hold enough water to produce:

26 weeks * 2.7 TWh/week = 70.2 TWh



The chart depicts the reservoir fill levels and weekly production. The orange line represents production capacity. It starts at a maximum reservoir capacity of 70.2 TWh in week 44. Then, it gradually depletes during the dry season (weeks 1-17 and 44-52) and is replenished during the wet season (weeks 18-43) by the inflow of 5.4 TWh per week.

This reflects fundamental hydropower principles, such as balancing inflow and outflow to meet consumption. The deterministic inflow assumption simplifies calculations but may not capture variability, as highlighted in the lecture notes. A stochastic analysis could adjust for variance inflow, as noted in the extension of the problem.

Question b)
Norwegian hydropower plays a crucial role in meeting energy demand, especially during periods of wind energy shortfalls in Europe. To model this, we use a stochastic variable where 1 = wind and 0 = no wind, representing the variability of wind energy. The calculations provided consider the weeks when there is no wind and no replenishment of reservoirs, alongside the need for reservoir storage to sustain production.

During weeks with wind, surplus energy is stored in reservoirs. The energy balance is given by:

Where x represents the surplus energy stored in

$$22.7 - x = 10.8$$
$$x = 22{,}7 - 10{,}8 = 11{,}9$$

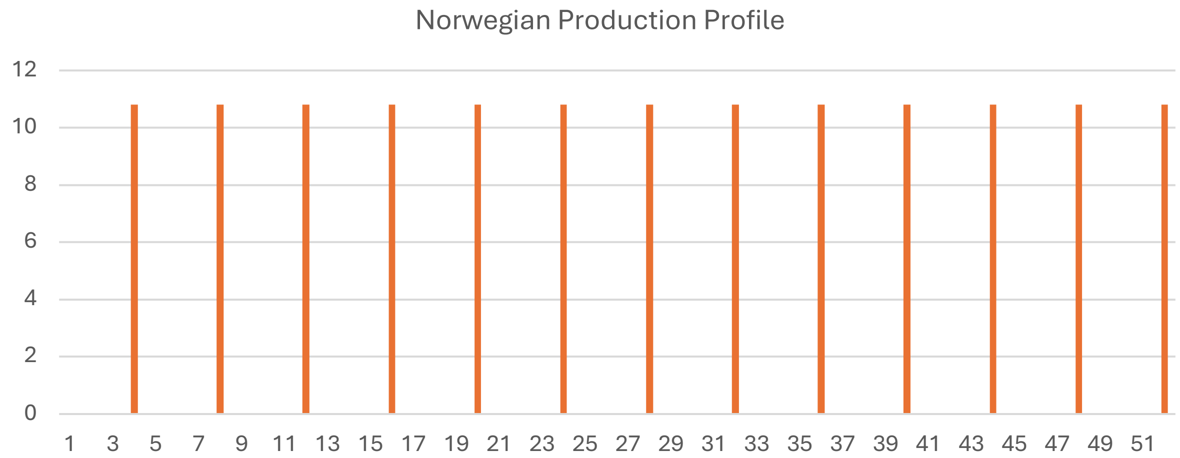
This means that during weeks with wind, 11.9 TWh is stored in reservoirs to prepare for periods without wind.

In the 7 weeks without wind and no inflow, the reservoirs must provide for both Norwegian consumption (2.7 TWh/week) and demand from wind-reliant countries (20 TWh/week):

Total weekly demand = 2.7 + 20 – 11.9 = 10.8 TWh/week

For 7 consecutive windless weeks, the total production requirement is:

$$10.8 * 7 = 75.6$$



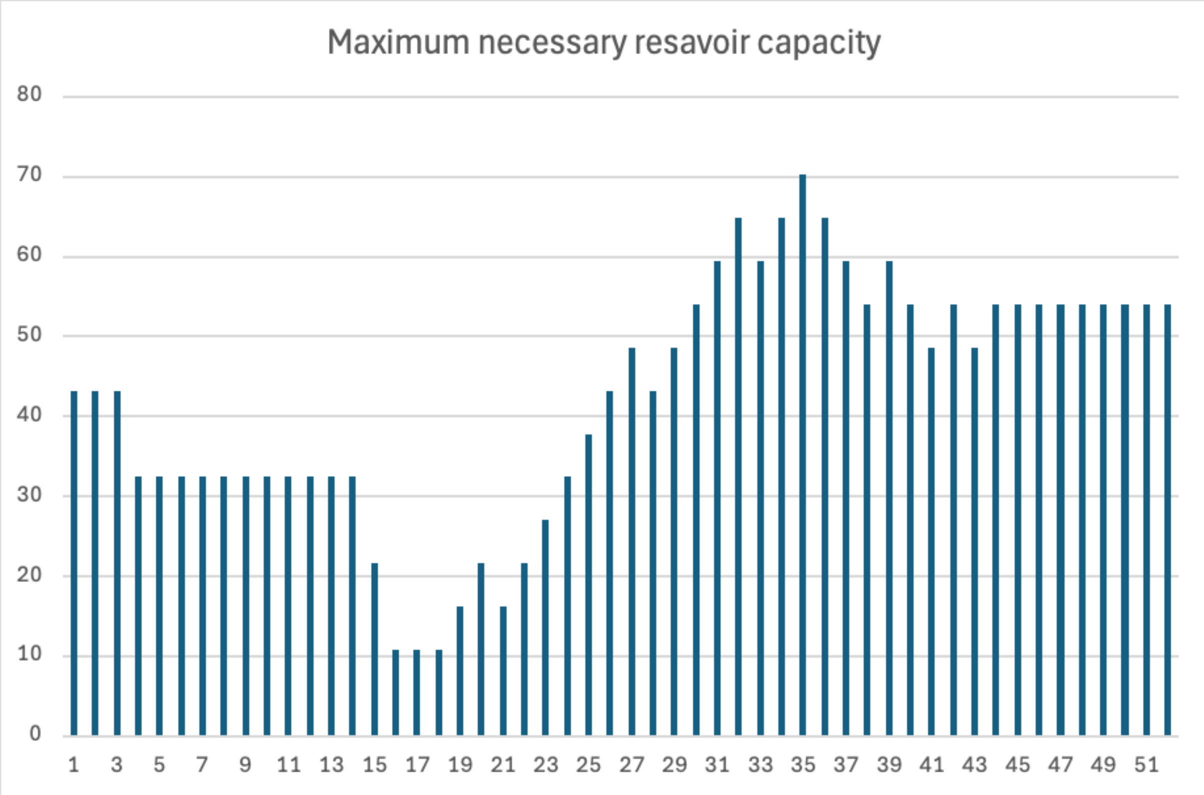
The production profile chart reflects a consistent hydropower output of 10.8 Twh/week, which is necessary to meet demand throughout the year. The flat production line demonstrates the role of Norwegian hydropower in stabilizing energy supply across wind reliant countries. The consistent production every fourth week reflects Norway's ability to maintain a reliable output under variable conditions.

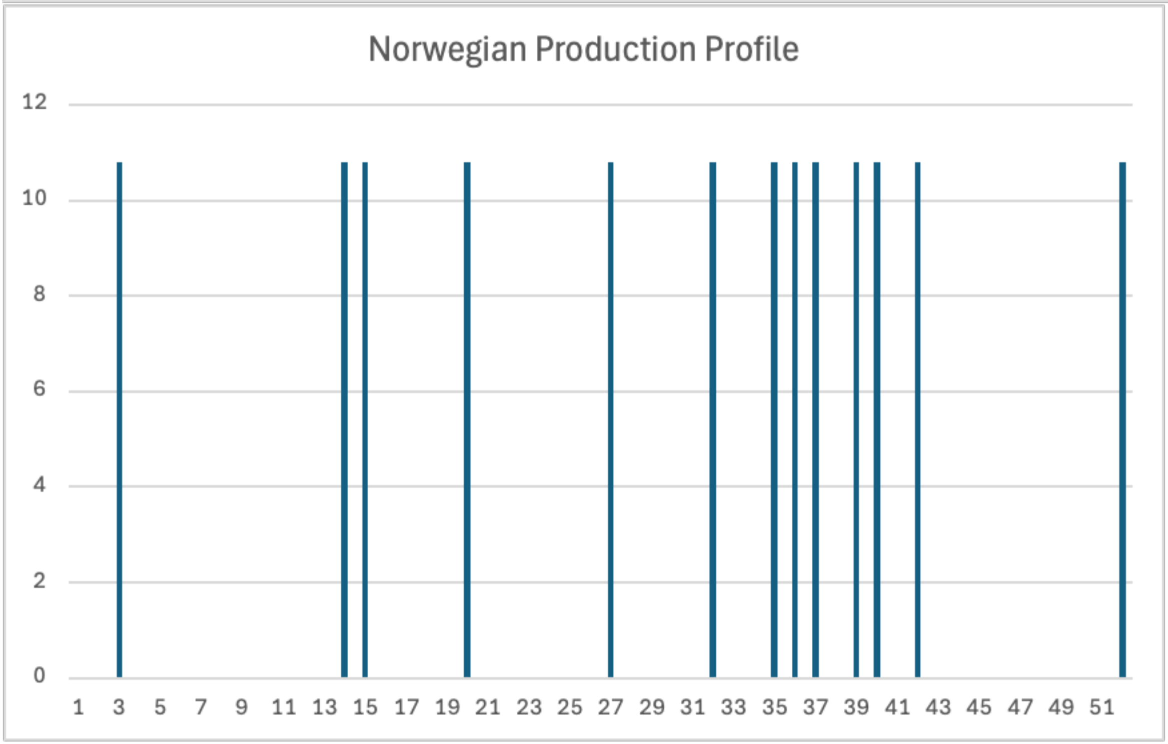
The reservoir capacity chart shows the dynamics of reservoir levels over the year. At the beginning of the year, the reservoir starts with a capacity of 75.6 TWh to support production during the 7 dry weeks. The chart illustrates that reservoir levels gradually deplete during wet weeks when surplus energy is 11.9 TWh/week is stored. By week 43, the reservoirs reach their maximum capacity of 75.6 TWh, fully replenished and prepared for the subsequent dry weeks.

This emphasizes the importance of effective reservoir management and surplus storage during wet weeks. The deterministic inflow model simplifies the calculations, but the inclusion of stochastic variable for wind energy accounts for the real-world variability, highlighting Norwegian hydropower's critical role as a buffer in Europe renewable energy system. By ensuring adequate reservoir capacity and maintaining consistent production, Norwegian hydropower effectively balances supply and demand during periods of wind energy shortages.

Question c)

The scenario with a 25% probability of no wind in Denmark, Germany, the Netherlands, and the UK introduces stochastic variability to wind availability. This requires Norwegian hydropower to adjust dynamically to compensate for the random occurrence of wind shortfalls while relying on deterministic inflows of 5.4 TWh/week during weeks 18 to 43.



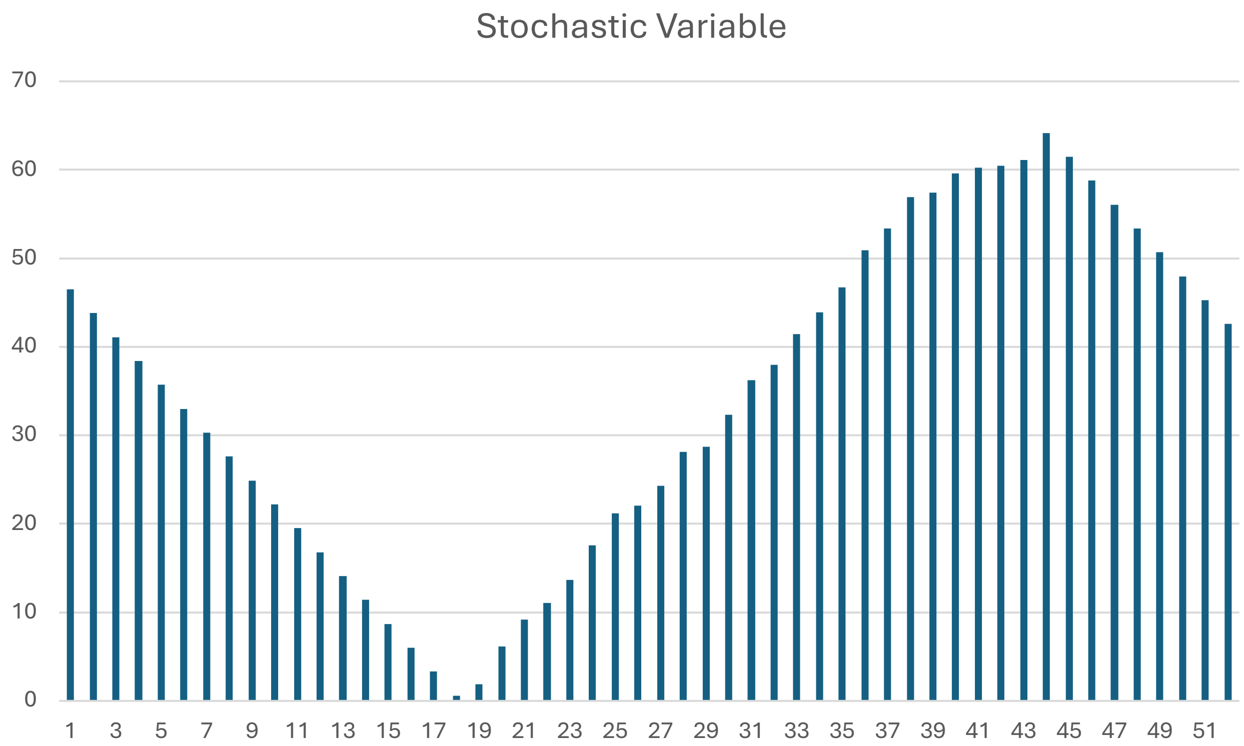


The Maximum Necessary Reservoir capacity chart demonstrates how this increased unpredictability impacts reservoir levels. Although the maximum capacity of 75.6 TWh remains the same as in scenario B, the drawdowns in this scenario occur irregularly due to the random timing of windless weeks. In scenario B, the reservoirs experienced predictable depletion and replenishment cycles tied to the fixed pattern of wind production, making managing more straightforward. In contrast, this scenario forces the system to handle more frequent drawdowns depending on the random sequence of windless weeks, highlighting the increased complexity of reservoir usage.

The Norwegian Production Profile chart reinforces the greater unpredictability of this scenario. Production spikes are distributed randomly throughout the year, reflecting stochastic nature of wind shortfalls. Unlike the regular production spikes in scenario B, which occurred every fourth week, this irregular pattern requires Norwegian hydropower to maintain a higher level of flexibility in its response to meet energy demand. The system must react dynamically to periods of high demand, ensuring that reservoir is sufficiently replenished during wet weeks to sustain production during random windless weeks.

The lecture notes emphasize the challenges posed by the variability and intermittency of renewable energy sources like wind. This scenario exemplifies those challenges, as the random nature of wind shortfalls increases the strain on Norwegian hydropower's ability to act as Europe's "green battery". By storing surplus energy during wet weeks and dynamically adjusting production during windless periods, Norwegian hydropower ensures energy stability despite the unpredictability of this scenario.

Question d)
In this scenario, the water replenishment in Norwegian reservoir is modeled as a stochastic variable with a mean of 5.4 TWh/week and a variance of 1. The chart below illustrates the impact of this variability:



When water replenishment changes each week, with an average of 5.4 and some randomness, the reservoir levels and energy production become less stable. The reservoirs might fill too much in some weeks or run low in others, making production unpredictable. This would require better planning to keep energy output steady and avoid problems.

Assignment 4

Question 1
a)

The formula $r = \eta \frac{dc/dt}{c} + \rho$ represents the social discount rate.

- ρ: The utility discount rate (a high ρ favours present generations over future ones).
- η: The elasticity of marginal utility (reflects inequality aversion; a high
- η makes us less willing to increase future generations' consumption).
- $\frac{dc/dt}{c}$: The consumption growth rate (high growth reduces the need for current investment).

The formula implies that a higher ρ or η leads to lower investment for future generations. This makes sense as it balances present and future consumption by incorporating ethical considerations (ρ and η) and economic growth ($\frac{dc/dt}{c}$), but its validity depends on normative assumptions about intergenerational equity.
b)

For ρ = 0.001, $\eta = 2$, and consumption growth from 0 to 0.05, the expected discount rate $E[r] = 0.051$ is determined by averaging r across this range. This value reflects a combination of ethical considerations and economic projections, as outlined in the lecture. A higher discount rate, r, reduces attractiveness of long-term investments, such as climate initiatives, by assigning less value to future benefits. Conversely, a lower r promotes policies that prioritize the well-being of future generations by increasing the present value of those benefits.

The calculated $E[r]$ provides a moderate approach, balancing the need for present-day investments with ethical responsibility to account for intergenerational equity. This approach acknowledges the uncertainty in future economic growth while supporting sustainable decision-making that carefully considers both present and future generations.

c)

Using the expected discount rate $E[r] = 0.051$, the present value (PV) of a future benefit of 100 at T = 20, T = 50, and T = 100 is calculated as follows:

$$PV = 100 * (1 + E[r])^{-T}$$

The table below shows present values for different values of T.

T	**20**	**50**	**100**
PV	36.9782	8.3150	0.6914

These results show a significant decline in the present value as the time horizon extends, reflecting the effect of compounding the discount rate over time. As highlighted in the lecture notes, this approach aligns with the normative methods of discounting, where the expected discount rate reflects a balance between ethical considerations (ρ and η) and economic growth ($\frac{dc/dt}{c}$). The high discounting effect for longer horizons demonstrates the reduced weights assigned to benefit that occur far in the future, which can discourage long-term investments unless the discount rate is adjusted for uncertainty.

d)

Discounting by the expected discount factor instead of the expected discount rate changes how the present value (PV) is calculated. The table below shows present values for different values of T.

T	20	50	100
PV	45.8396	25.3235	17.5197

When discounting by the expected discount factor, the calculation accounts for the probabilistic distribution of discount rates over time rather than assuming a single average rate. This method results in higher present values for long-term benefits because it effectively applies a lower equivalent discount rate as time increases, consistent with the Weitzman's argument that lower discount rates should apply further into the future due to uncertainty. This adjustment emphasizes the importance of distant future benefits, making policies with long-term payoffs, such as climate change mitigation, more attractive.

Question 2

a)

Since the emission quotas require each firm to abate half their emissions ($a_1 + a_2 = 100$), we solve as follows:

$$mc_1 = 2 * 50 = 100$$

$$mc_2 = 3 * 50 = 150$$

$$2 * a_1 = 3 * a_2 \rightarrow a_2 = \frac{2}{3}a_1$$

Which gives us two equations:

$$a_{1+} \frac{2}{3}a_2 = 100 \rightarrow \frac{5}{3}a_1 = 100 \rightarrow a_1 = \frac{100}{5} * 3 = 60$$

$$a_2 = 40$$

Thus, firm 1 abates 60 units, and firm 2 abates 40 units. The marginal costs are $mc_1 = 120$ and $mc_2 = 120$, confirming equilibrium since both firms face the same marginal costs.

b)

Transferable quotas allow firms to equalize their marginal abatement cost, minimizing the total cost of reducing emissions, which is more efficient. By ensuring that $mc_1 = mc_2 = 120$, the allocation of abatement is cost-effective, meeting the emission reducing target at the lowest possible economic cost.

$$mc = 2 * 60 = 120$$

c)

If a tax of 60 is imposed:

For Firm 1: $60 = 2a_1$, so $a_1 = 30$
For Firm 2: $60 = 3a_2$, so $a_2 = 20$

This solution is identical to the transferable quota solution

d)

Derivation of the marginal cost curve of aggregate abatement:

$$mc_1 = 2 * a_1 \rightarrow \ a_1 = \frac{1}{2}mc$$

$$mc_2 = 3 * a_2 \rightarrow \ a_2 = \frac{1}{3}mc$$

$$a_1 + \ a_2 = mc\left[\frac{1}{2} + \frac{1}{3}\right] \ = \ mc * \frac{5}{6}$$

Since $a_1 + \ a_2 = q \rightarrow \ \ mc = \frac{6}{5} * q$

e)

When marginal benefit curve = $220 - q$

The optimum abatement is mb = mc:

$$220 - q = \frac{6}{5}q$$

$$220 = \frac{11}{5}q$$

$$q = 100$$

Optimal reduction is 100 units, with marginal cost:

$$mc = \frac{6}{5} * 100 = 120$$

f)

With tax of 96:

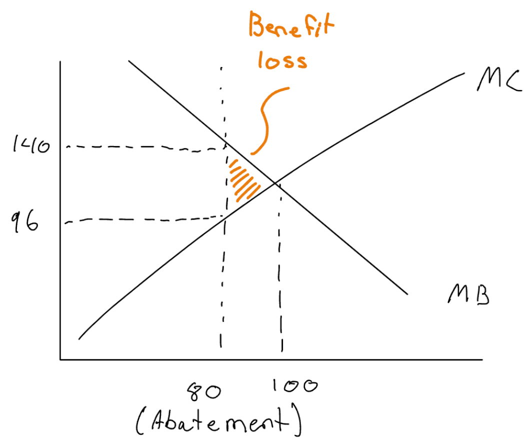
$$q = \frac{5}{6} * 96 = 80 \text{ (abatement)}$$

The result is a reduction of 80 units.

Benefit loss:

$$Loss = \frac{1}{2} * (100 - 80) * (140 - 96) = 440$$

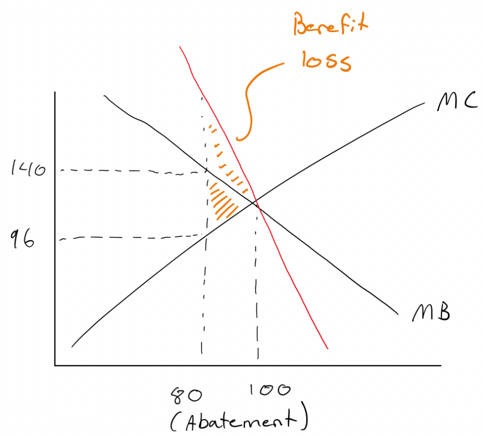
Illustration:



g)

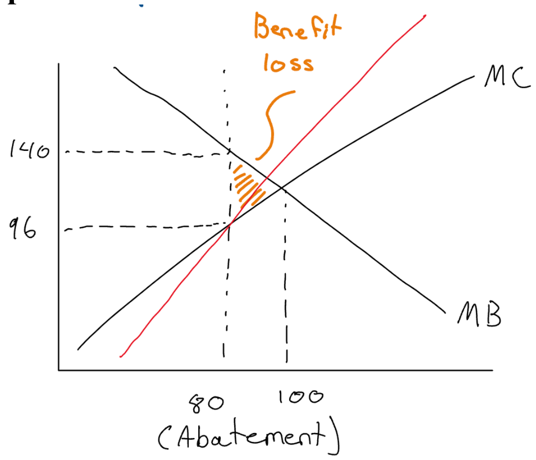
If the marginal benefit curve were steeper, the loss would be greater because the difference between optimal and actual reduction would have a large impact on benefits.

Steeper MB:



If the marginal cost curve were steeper, the loss would be smaller because a given error in the tax rate would lead to a smaller deviation in reduction.

Steeper MC:



Assignment 5

Question 1

Suppose that the US, EU, the UK, Japan, Korea and Canada all evaluate the benefits of abating CO_2 emissions in proportion to their own emissions. The necessary information is given in a table presented in Lecture 5, except for the UK, which had a share of world emissions of 0.9 percent in 2023.

a) On this assumption, which country would be most willing to unilaterally eliminate its CO_2 emissions? What would the cost have to be to make this worthwhile for the country in question?

   The EU and UK would be the most likely countries to join the US in a coalition. The EU would join if the cost (c) is less than 0.495, and the UK would join if c is less than 0.481. If the cost exceeds these thresholds, additional countries will need to join to make the coalition viable. This coalition formation reflects the countries' relative economic strengths and their perceived benefits from emissions reduction, with the EU and UK showing the strongest alignment with US interests in climate action.

b) If the cost is higher than you found in a), which countries would be willing to join the country you found in a) in a coalition? What would the cost have to be to make it worthwhile for a country to join? How many countries would join?

   To assess which country would be most willing to unilaterally eliminate its CO_2 emissions, we examine the associated costs and potential coalitions. Specifically, we consider the scenario where the cost exceeds 0.132, identifying countries that might align with the US to form a climate coalition.

   The column labeled q(US) + q(j) represents the combined emissions of the US and the respective country j. This value indicates the critical cost threshold, beyond which a given country would find it beneficial to join the US in a coalition, while others remain free riders. If the cost is greater than 0.132 but does not surpass 0.204, the EU would find it beneficial to join a coalition with the US, while other nations would prefer to act as free riders. Similarly, if the cost is greater than 0.132 but does not exceed 0.161, Japan would align with the US, while the rest would refrain from joining. The table in question a) continues with this logic, with Korea at 0.148, Canada at 0.148 and UK at 0.150.

	q	q(US)+q(j)
US	0.132	
EU	0.072	0.204
Japan	0.029	0.161
Korea	0.016	0.148
Canada	0.015	0.147
UK	0.009	0.141

To explore the scenario where the US and the EU have already formed a coalition, we examine whether additional countries would have an incentive to join. The EU is motivated to collaborate with the US when the cost lies between 0.132 and 0.204. However, at this cost level, other countries would find it more advantageous to remain free riders. For additional countries to find it worthwhile to join, the cost must exceed 0.204.

If the cost rises above 0.204, the US and the EU would no longer find it advantageous to maintain their coalition. However, if the cost falls within the range of 0.204 and 0.233, Japan might be incentivized to join the coalition with the US and the EU, while it would still be more beneficial for other countries to remain outside the coalition. Similarly, Canada would find it advantageous to join if the cost lies between 0.204 and 0.219, while other nations would continue to opt out.

For the UK and Korea, whose critical costs are 0.213 and 0.220 respectively, only one of them would likely join the coalition, as the cost would have to specifically align with their critical thresholds. For other countries not mentioned, it would remain more favorable to act as free riders at these cost levels. This analysis highlights that while additional members may join the US-EU coalition under specific costs threshold, the potential for full participation remains limited.

c) What are the main simplifications of this model? What are the general results that this model is meant to illustrate? Are the conclusions from this model confirmed by reality?

This model simplifies the complexities of emission reduction by assuming a linear relationship between costs and benefits, which leads to the binary choice of either taking no action or fully eliminating emissions. However, in reality, climate coalitions typically results in partial, rather than complete, emission reduction by member countries due to the non-linear nature of costs and benefits. Similarly, non-member countries that opt to free-ride may still undertake some level of emission reduction. This nuance is well captured in the Scott Barett model. Despite these oversimplifications, the primary aim of this is to emphasize the strong incentives for countries to free-ride, highlighting the challenges in achieving full cooperation.

Question 2

a) In the Excel sheet Assignment 3 is a solution to Scott Barrett's model of the climate mitigation game with parameter values $a = 1$, $b = 2$, $c = 0.1$, and $N = 10$. Find the size of the stable coalition in this case.

In Scott Barett's climate mitigation game, we analyze the optimal coalition size for maximum profit using the parameters $a = 1$, $b = 2$, $c = 0.1$, and $N = 10$ potential coalition members.

M	Pi(i)	Pi(j)	Gain from leaving	Gain from joining
1		6.16		
2	6.17997	6.34038	-0.01997	0.02473
3	6.36511	6.96838	-0.02473	-0.27234
4	6.69604	7.71779	0.27234	-0.62102

5	7.09677	8.40166	0.62102	-0.89889
6	7.50277	8.93274	0.89889	-1.05739
7	7.87535	9.30663	1.05739	-1.10807
8	8.19856	9.55538	1.10807	-1.08496
9	8.47043	9.71606	1.08496	-1.02041
10	8.69565	9.81853	1.02041	-9.81853

The gain from leaving a coalition is calculated by subtracting the profit per coalition member at m from the profit per free rider at m-1. For a coalition of two members, this would result in 6.16 – 6.17997 = -0.01997.

Similarly the gain from joining is determined by subtracting the profit per free rider at m from the profit per coalition member at m+1. For a coalition of two members, this calculation yields 6.36511 – 6.34038 = 0.02473.

A coalition of three members is the most stable. This conclusions is supported by the table, where at this coalition size, countries experience both a negative gain from leaving and a negative gain from joining ensuring stability.

b) What is the main difference between this model and the one we looked at in Question 1?

The main difference between this model and the one in Question 1 lies in its treatment of costs, benefits, and mitigation behavior. This model assumes non-linear abatement costs, leading to a scenario where all countries engage in mitigation efforts, albeit at a lower rate for non-coalition members compared to those within coalition. Unlike the earlier model, which assumes either full cooperation or no action, this model allows for partial mitigation by free riders.

Furthermore, this model does not assume a collective strategy among non-coalition members, treating their responses as independent reactions to the coalition's actions. This contrasts with individual mitigation efforts. As a result, this model highlights the strategic behavior of countries in forming self-enforcing coalitions, where internal and external stability are ensured by balancing the gains from joining or leaving.

Finally, the most stable coalition size under this model is larger (e.g. three members), reflecting the non-linear dynamics of cooperation and free riding. Both models address the free rider problem, but this one captures a more nuanced and realistic representation of climate coalition behavior, emphasizing the challenges of achieving optimal collective action.

Question 3

In her book «Climate Uncertainty and Risk," Judith Curry comes up with the following scenarios for global temperature by 2050:

1. Forcing from climate gasses: (i) 1.6, (ii) 2, (iii) 2.5 degrees Celsius from baseline of 1850-1900.
2. Volcanoes: (i) 0, (ii) -0.17, (iii) -0.4 degrees of cooling.
3. Solar irradiation: (i) 0, (ii) -0.2, (iii) -0.5 degrees of cooling.
4. Internal model variability: (i) 0, (ii) -0.2, (iii) -0.3 degrees of cooling.

a) How many scenarios are there altogether?

There are three possibilities for greenhouse gas impacts, three scenarios for volcanic activity, three scenarios for volcanic activity, three scenarios for solar irradiation, and three variations in internal model variability. Combined, these factors result in $3^4 = 81$ distinct scenarios for global temperature outcomes by 2050.

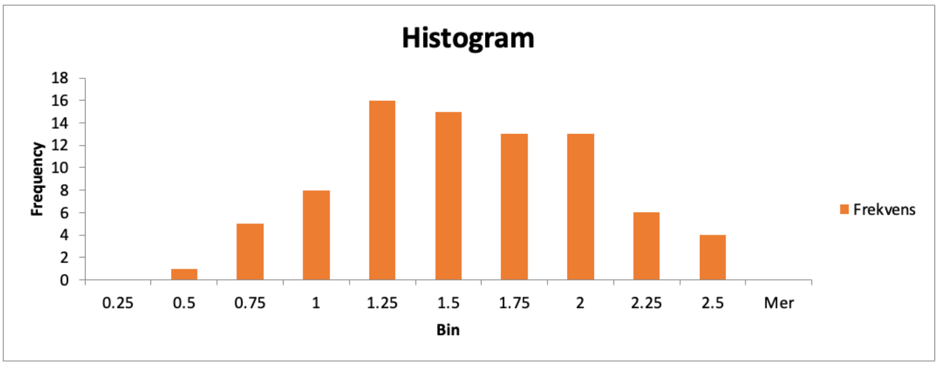
b) Tabulate the outcome for all the scenarios in an Excel sheet.

forcing from climate gases	volcanos	solar irradiation	internal model variability	outcome
1.6	0	0	0	1.6
1.6	0	0	-0.2	1.4
1.6	0	0	-0.3	1.3
1.6	0	-0.2	0	1.4
1.6	0	-0.2	-0.2	1.2
1.6	0	-0.2	-0.3	1.1
1.6	0	-0.5	0	1.1
1.6	0	-0.5	-0.2	0.9
1.6	0	-0.5	-0.3	0.8
1.6	-0.17	0	0	1.43
1.6	-0.17	0	-0.2	1.23
1.6	-0.17	0	-0.3	1.13
1.6	-0.17	-0.2	0	1.23
1.6	-0.17	-0.2	-0.2	1.03
1.6	-0.17	-0.2	-0.3	0.93
1.6	-0.17	-0.5	0	0.93
1.6	-0.17	-0.5	-0.2	0.73
1.6	-0.17	-0.5	-0.3	0.63
1.6	-0.4	0	0	1.2
1.6	-0.4	0	-0.2	1
1.6	-0.4	0	-0.3	0.9
1.6	-0.4	-0.2	0	1
1.6	-0.4	-0.2	-0.2	0.8
1.6	-0.4	-0.2	-0.3	0.7
1.6	-0.4	-0.5	0	0.7
1.6	-0.4	-0.5	-0.2	0.5
1.6	-0.4	-0.5	-0.3	0.4
2	0	0	0	2
2	0	0	-0.2	1.8
2	0	0	-0.3	1.7
2	0	-0.2	0	1.8
2	0	-0.2	-0.2	1.6
2	0	-0.2	-0.3	1.5
2	0	-0.5	0	1.5
2	0	-0.5	-0.2	1.3
2	0	-0.5	-0.3	1.2
2	-0.17	0	0	1.83

2	-0.17	0	-0.2	1.63
2	-0.17	0	-0.3	1.53
2	-0.17	-0.2	0	1.63
2	-0.17	-0.2	-0.2	1.43
2	-0.17	-0.2	-0.3	1.33
2	-0.17	-0.5	0	1.33
2	-0.17	-0.5	-0.2	1.13
2	-0.17	-0.5	-0.3	1.03
2	-0.4	0	0	1.6
2	-0.4	0	-0.2	1.4
2	-0.4	0	-0.3	1.3
2	-0.4	-0.2	0	1.4
2	-0.4	-0.2	-0.2	1.2
2	-0.4	-0.2	-0.3	1.1
2	-0.4	-0.5	0	1.1
2	-0.4	-0.5	-0.2	0.9
2	-0.4	-0.5	-0.3	0.8
2.5	0	0	0	2.5
2.5	0	0	-0.2	2.3
2.5	0	0	-0.3	2.2
2.5	0	-0.2	0	2.3
2.5	0	-0.2	-0.2	2.1
2.5	0	-0.2	-0.3	2
2.5	0	-0.5	0	2
2.5	0	-0.5	-0.2	1.8
2.5	0	-0.5	-0.3	1.7
2.5	-0.17	0	0	2.33
2.5	-0.17	0	-0.2	2.13
2.5	-0.17	0	-0.3	2.03
2.5	-0.17	-0.2	0	2.13
2.5	-0.17	-0.2	-0.2	1.93
2.5	-0.17	-0.2	-0.3	1.83
2.5	-0.17	-0.5	0	1.83
2.5	-0.17	-0.5	-0.2	1.63
2.5	-0.17	-0.5	-0.3	1.53
2.5	-0.4	0	0	2.1
2.5	-0.4	0	-0.2	1.9
2.5	-0.4	0	-0.3	1.8
2.5	-0.4	-0.2	0	1.9
2.5	-0.4	-0.2	-0.2	1.7
2.5	-0.4	-0.2	-0.3	1.6
2.5	-0.4	-0.5	0	1.6
2.5	-0.4	-0.5	-0.2	1.4
2.5	-0.4	-0.5	-0.3	1.3
			MAX	2.5
			MIN	0.4

c) Create a histogram for the outcomes of the scenarios.

Bin	*Frequency*
0.25	0
0.5	1
0.75	5
1	8
1.25	16
1.5	15
1.75	13
2	13
2.25	6
2.5	4
Mer	0



d) What do you have to assume to interpret the frequency table for the outcomes of the scenarios as probabilities?

To analyze the scenarios, we must assume that each variable operates independently. This means that variables such as solar irradiation, volcanic activity, and internal model variability do not influence one another. Additionally, we assume that each scenario has an equal likelihood of occurring, with each outcome – such as 0, -0.2, or -0.5 for solar irradiation – having an equal probability.

The same assumption applies to all variables. To interpret the frequency table for the outcomes of these scenarios as probabilities, it is essential to assume the independence of events, that the sample is representative of the population, and that past observed relative frequencies accurately reflect the probabilities of future occurrences.

e) What is the expected warming by 2050 according to this?

What is the probability that the warming by 2050 will not exceed 1.5 degrees, according to the frequency table?

The expected warming by 2050 is approximately 1.56 degrees. This value is calculated as the weighted average of all temperature bins using their respective frequencies.
The probability that the warming will not exceed 1.5 degrees by 2050 is approximately 0.37, or 37%. This means there is a 37% chance that the warming will stay at or below 1.5 degrees, while there is a 63% chance it will exceed this threshold.