Energy Resources, Economics, and Sustainability

Prof. Pratham Arora

Hydro and Renewable Energy Department

Indian Institute of Technology Roorkee, Roorkee, India

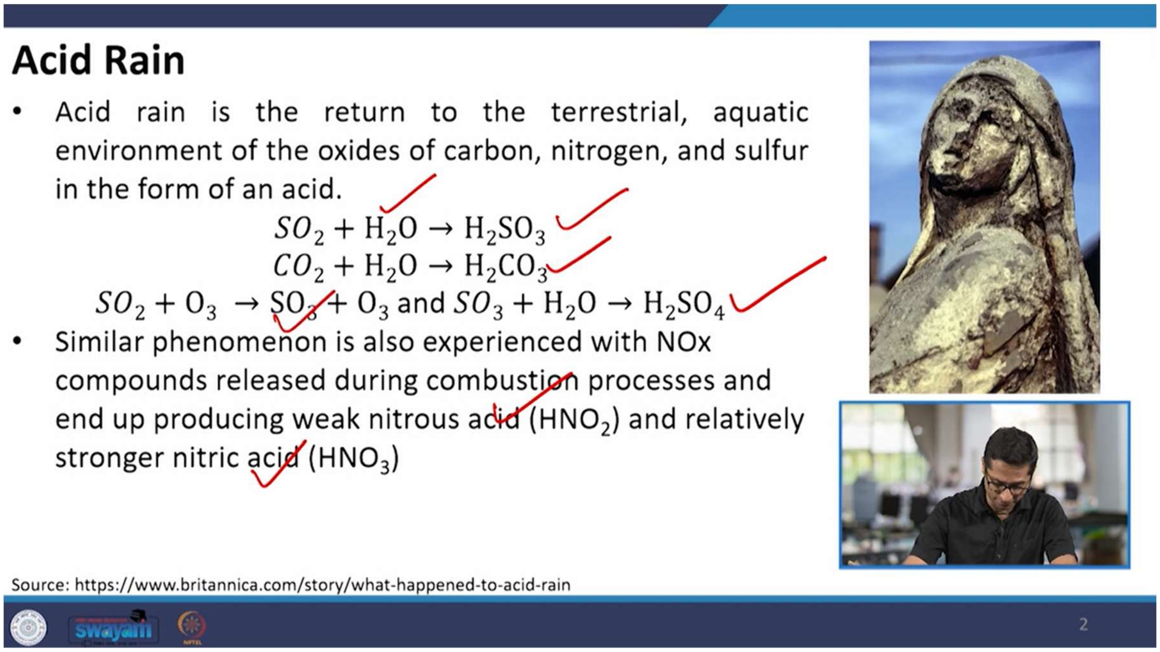
Week – 05

Lecture – 02

Lecture 22 - Recent Successes in Environmental Stewardship-I

Hello everyone, welcome back to the course Energy Resources, Economics and Sustainability. In the past few classes, we have been discussing the environmental impact of different energy production pathways. In the last class through the simple example, we tried to estimate the quantum of emissions in terms of CO2, sulfur oxides and nitrous oxides that went out into the atmosphere from a rather typical coal fired power plant. We estimated the amount of emissions were quite huge. So, we understand that a typical power plant that could be powered by fossil fuels leads to a lot of environmental emissions and they could have a degrading effect on the environment in the long term. But have there been some success stories with respect to some of the emissions in the past, which we can learn from and apply the same principles to the current problem of CO2 emissions. Let us try to look at some of the problems that were seen as major problems in the past resulting mainly from energy production pathways and because of concerted efforts by the scientific communities, signing up of international agreements, proactive role by the different governments, these problems could be solved to a good extent.

So, we will spend today's class as well as the future classes on understanding some of these case studies. So, the first case that we are going to undertake would be that of acid rain.



Acid Rain

- Acid rain is the return to the terrestrial, aquatic environment of the oxides of carbon, nitrogen, and sulfur in the form of an acid.

$$SO_2 + H_2O \rightarrow H_2SO_3$$
$$CO_2 + H_2O \rightarrow H_2CO_3$$
$$SO_2 + O_3 \rightarrow SO_3 + O_3 \text{ and } SO_3 + H_2O \rightarrow H_2SO_4$$

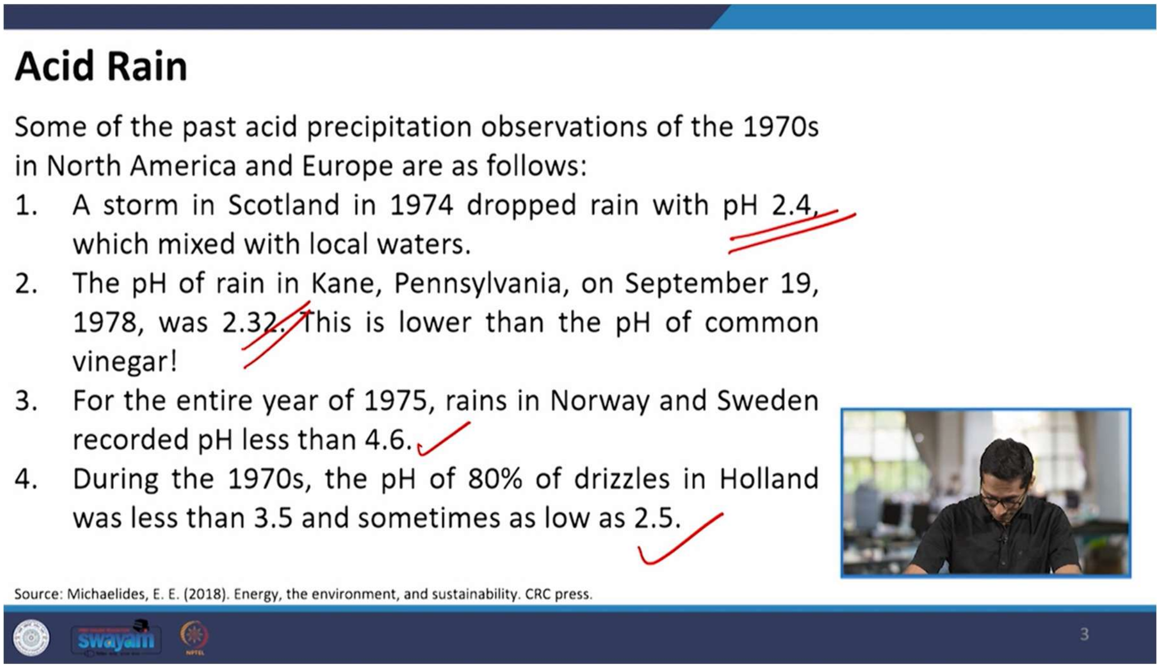
- Similar phenomenon is also experienced with NOx compounds released during combustion processes and end up producing weak nitrous acid (HNO_2) and relatively stronger nitric acid (HNO_3)

Source: https://www.britannica.com/story/what-happened-to-acid-rain

Acid rain entails like or acid precipitation as it is known, like it is the return of emissions that are went to the atmosphere in terms of light acids or even concentrated acids. A typical example could be the different sulphur oxides that went out in the atmosphere.

So we have seen in the last example, in the last class, that a typical power plant would vent out significant amount of sulphur and nitrous oxides into the atmosphere. So these sulphur oxides might combine with the water that is available in the atmosphere and form weak acids like hypersulphuric acid or even the CO2 that is vented on the atmosphere can react with water to form a weak acid like H2CO3. Further, another possible pathway could be this SO2, sulphur dioxide reacting with the ozone and forming SO3 molecules and these SO3 molecules can further combine with water to form sulphuric acid which is a strong acid. Similar phenomena has also been observed in the case of NOx emissions where the nitrous oxides go and react with the water molecules and form light acids or the weak acids like nitrous acids as well as stronger acids in the form of nitric acid. Now these, the major problem with these kinds of particles or precipitation is that the acids that are formed initially are in the form of aerosols which means they have, they are very small particles typically of diameter of few micrometers and they combine with the precipitation that is happening in the form of snow or rain and then enter the water bodies.

Also being light in nature they can easily be transported to hundreds of kilometers. So it means that the emission source could be very far away from the source where the precipitation is occurring which is having an acidic character. Further, a lot of you would understand the acidity of a particular medium is measured by the pH value. A pH value of 7 basically indicates water and is neutral in nature and typically the water bodies around the world are expected to have a pH ranging from 6.8 to 7.4 and this is the normal range in which the marine life also survives and flourishes. What happens when we have an acid rain is the water that comes in contact with the different water bodies or the soil would have a significantly lower pH. Just for an example, vinegar which is used for the cooking applications would have a likely pH of around 2.4. Sulfuric acid would have a pH of around 1. If you are talking about different types of bases they would have a pH of greater than that of 7. So these precipitation which is also called acid precipitation with low pH enter into the water bodies brings down the pH of these water bodies and this becomes not a very conducive environment for the fish or the marine life to thrive. Sometimes leading to endangerment and extinction of species. Also major concern is that this acid rain when this falls on the historical monuments it leads to the spoil. An example you can see on the figure on the right. Further there had been an increasing concern about acid rains spoiling the Taj Mahal in India as well. So this is having a great consequence as well as the historical monuments are also concerned.



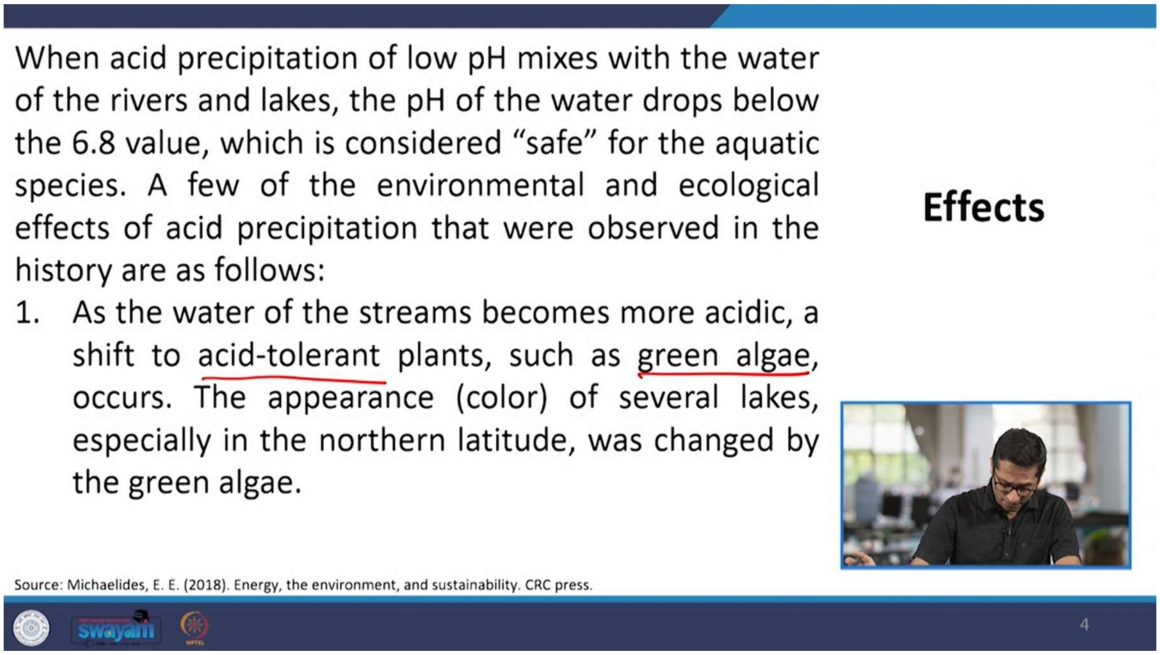
Acid Rain

Some of the past acid precipitation observations of the 1970s in North America and Europe are as follows:

1. A storm in Scotland in 1974 dropped rain with pH 2.4, which mixed with local waters.
2. The pH of rain in Kane, Pennsylvania, on September 19, 1978, was 2.32. This is lower than the pH of common vinegar!
3. For the entire year of 1975, rains in Norway and Sweden recorded pH less than 4.6.
4. During the 1970s, the pH of 80% of drizzles in Holland was less than 3.5 and sometimes as low as 2.5.

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

Further if you look in the history what have been the major instances of extreme acid precipitation in the past we can come across that there was a storm in Scotland in the year 1974 which had a pH of as low as 2.4 and it made a degrading effect on the local water bodies. Then in the state of Pennsylvania in the US in the year 1978 there was again a rain which was having a pH of 2.32 which is lower than the pH of the common vinegar that you use for cooking purposes. Then in Norway and Sweden it was recorded that the rains were having consistently a pH that was less than 4.6. Something similar was also experienced in the country of Holland where like the pH of 80% of the results was less than 3.5 and sometimes as low as 2.5. And a majority of this was basically because of the power production or the energy production pathways which were primarily sourced from coal because a lot of SOx and NOx emissions were going into the atmosphere. And it was also happening that many a times the countries which were suffering from this particular phenomena of acid rain had very little contribution. The actual emissions were happening in a different country which could lie hundreds of kilometers away.



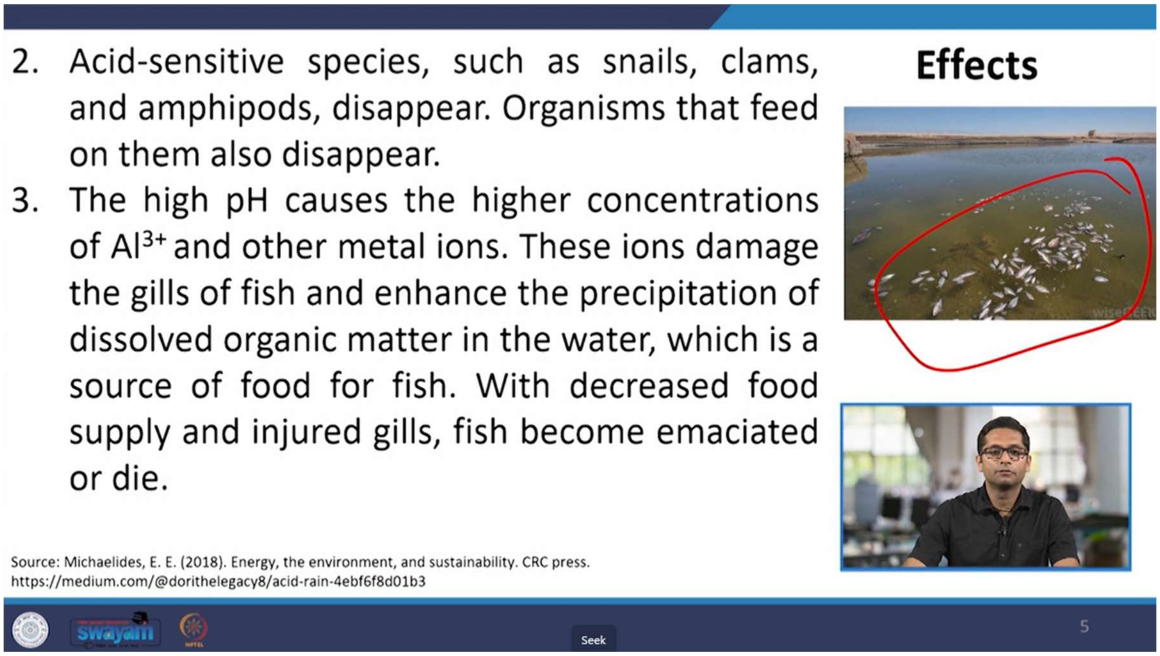
Effects

When acid precipitation of low pH mixes with the water of the rivers and lakes, the pH of the water drops below the 6.8 value, which is considered "safe" for the aquatic species. A few of the environmental and ecological effects of acid precipitation that were observed in the history are as follows:

1. As the water of the streams becomes more acidic, a shift to acid-tolerant plants, such as green algae, occurs. The appearance (color) of several lakes, especially in the northern latitude, was changed by the green algae.

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

So if you try to look at what were the consequences of some of these extreme events we can come across that it had a major degrading effect on the marine life of these countries. So as I have iterated like the normal operating range for lakes and rivers in terms of pH the pH should have value between 6.8 to 7.4 but because of the continuous intake of highly acidic influx in terms of acid rains or acid snow the pH of many of the water bodies in these observed countries fell below the 6.8 level. As a result of this there was a shift in the types of species that existed. It gave way to acid tolerant species which includes the algae and similar species and slowly you would have noticed like a lot of lakes turned green. And this is also a phenomena that we experience in our countries in a lot of places because a lot of acid tolerant species or the species which are not very tolerant to acid would not want to stay here. And it was also like observed that the salmon fish in many of these countries didn't reproduce for a number of years which brought it near endangered or extinction.

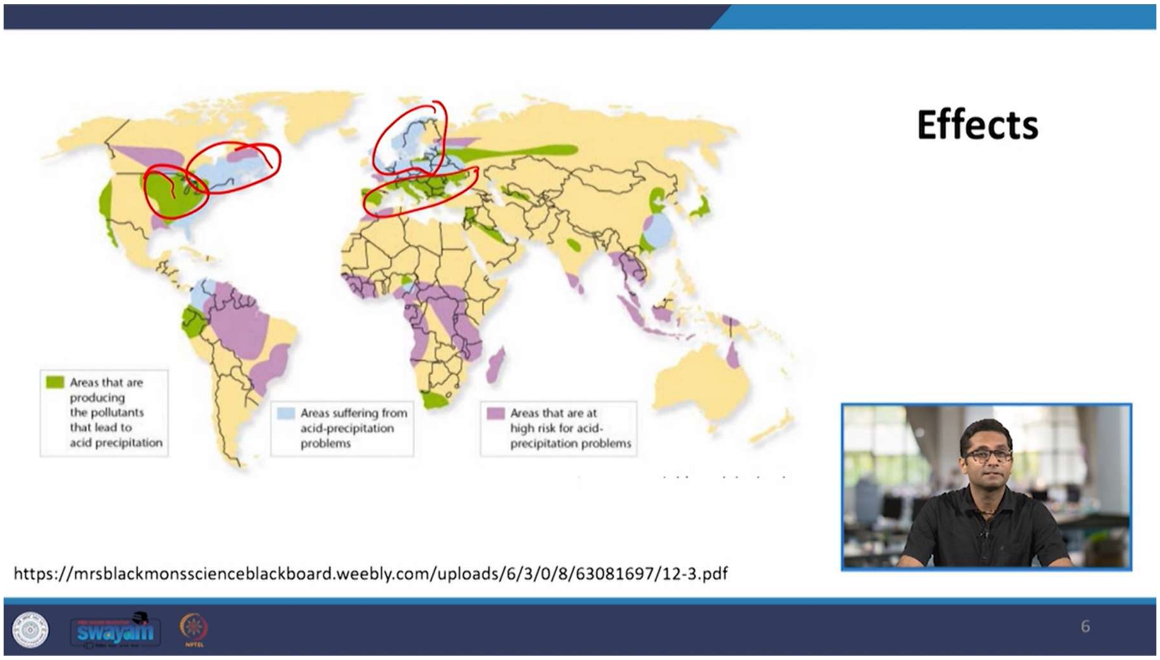


Effects

2. Acid-sensitive species, such as snails, clams, and amphipods, disappear. Organisms that feed on them also disappear.
3. The high pH causes the higher concentrations of Al^{3+} and other metal ions. These ions damage the gills of fish and enhance the precipitation of dissolved organic matter in the water, which is a source of food for fish. With decreased food supply and injured gills, fish become emaciated or die.

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.
https://medium.com/@dorithelegacy8/acid-rain-4ebf6f8d01b3

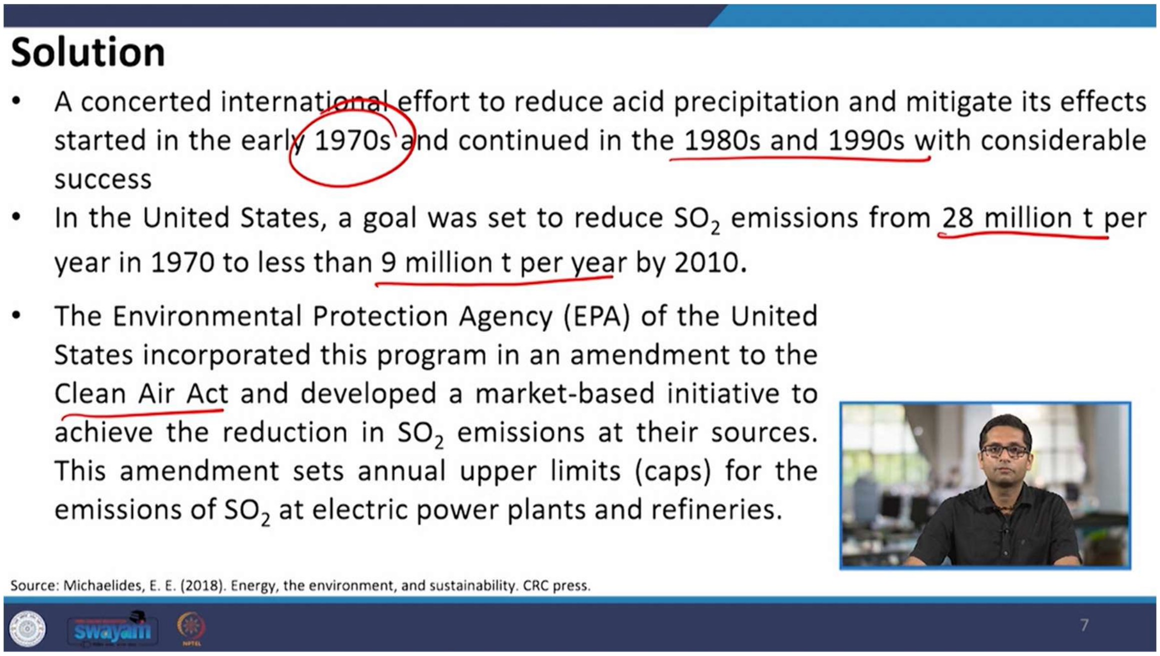
Further it was also noticed that the acid sensitive species like snails or amphipods disappear and these kinds of species also form a major part of the food chain the larger fishes or the larger marine life would feed on them because of the disappearance of their food it also affects the entire food chain leads to the death of fishes. So it was quite common to see like fishes being dying in masse in the lakes. Another major consequence was that a higher pH also causes a higher concentration of aluminium ions and other metallic ions and these ions would damage the gills of the fish which is which they use for their respiration. And once the gills get damaged it also helps like the future propagation of the marine life and also the higher ups like the animals or the different marine animals which will feed upon this fish again causing a degrading effect on the complete food chain and the fishes in return would either become emancipated or they die in the long run. So these effects were felt in a major way in all these countries in the Europe and the Americas and it was there was a big public outrage and the governments wanted to take a specific target to bring down the sulphur additions.



Effects

https://mrsblackmonsscienceblackboard.weebly.com/uploads/6/3/0/8/63081697/12-3.pdf

And also as I have iterated that in many of the cases it so happened that the source of emissions was a different country than the country which was reaping the effects of these kinds of acid rains. So as can be seen in this map the areas marked in green are the areas which led to the which were the source of acid precipitation which were the major sources of sulphur and nitrous oxides so you can see the Americas here and the lower parts of the Europe. And the areas that were suffering from the acid precipitation were different countries like you can see the countries like Norway, Sweden and other Nordic countries as well as Canada was a major sufferer for the emissions that were originating from the US. And this also led to an accelerated effect because there was international politics that was involved the sufferers were not really the originator of the problem and this helped in accelerating the events where the countries came together took up the global targets to reduce the sulphur emissions by so and so amount and to some extent or to a greater extent they were very successful. If you see India the problem is not very much although we have emissions because of the flow or the air pattern and also the studies have not been widely carried out but this problem was widely faced in the developed world as the Europe and the Americas. So what was the solution to this?



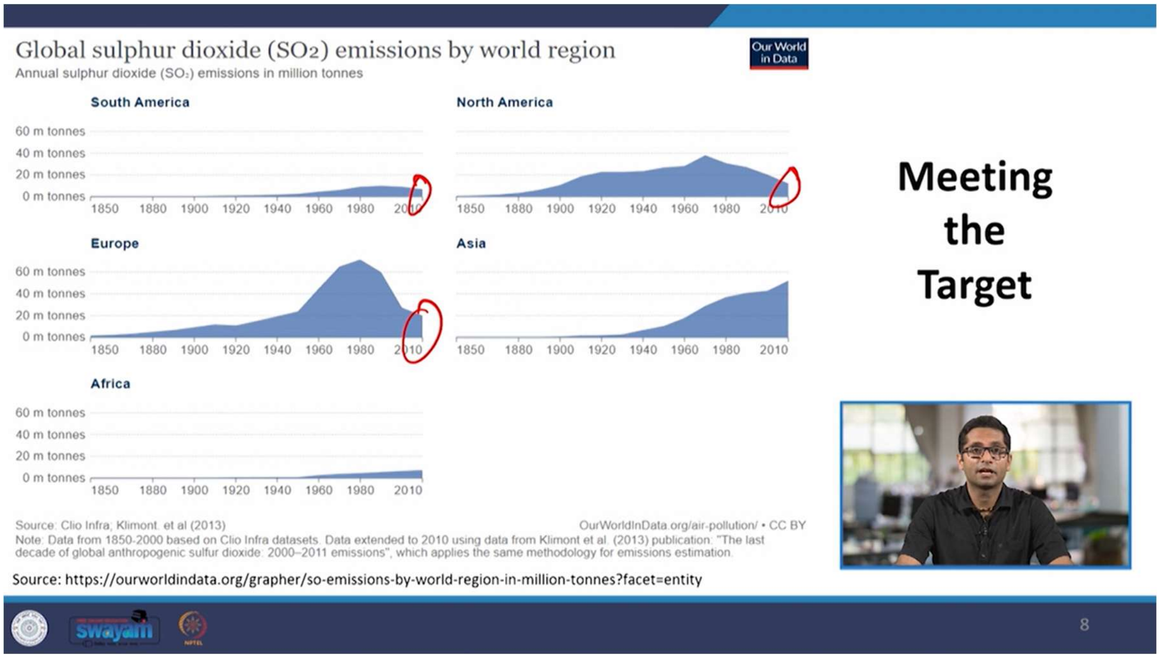
Solution

- A concerted international effort to reduce acid precipitation and mitigate its effects started in the early 1970s and continued in the 1980s and 1990s with considerable success
- In the United States, a goal was set to reduce SO_2 emissions from 28 million t per year in 1970 to less than 9 million t per year by 2010.
- The Environmental Protection Agency (EPA) of the United States incorporated this program in an amendment to the Clean Air Act and developed a market-based initiative to achieve the reduction in SO_2 emissions at their sources. This amendment sets annual upper limits (caps) for the emissions of SO_2 at electric power plants and refineries.

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

So the solution came into being it started in the early 1970s and continued till the 80s and the 90s so it took around 20 to 30 years. In the US they set up a target of reducing the SO2 emissions from the one prevalent at 1970s in the terms of 28 million ton per year to around 9 million ton per year by 2010 almost 3 fold reduction in the total amount of SO2 emissions. Further the environmental protection agencies of the US also came in brought in the Clean Air Act and also developed the market based mechanisms which could help the cap and trade system which means the industries or the different kinds of corporations which were the major reasons behind the sulphur emissions had to cap their emissions by the targets and by the government which were becoming stringent year by year. Further there might be some companies or corporates which were overdoing the target so these companies had the opportunity to sell their further emissions to the corporates or the industries which were unable to meet the target.

So as to incentivize the good performance whereas to penalize the poor performance it also helped bring down the total cumulative emissions the industry which was having or which was out doing its performance in terms of emissions had the ability to make monetary benefits in terms of selling the emissions to a particular industry which was not able to do so because of certain constraints. So people for the companies could realize the capital investment that they made for capturing of the SO2 into the air quite fast and because of these policies we can see the SO2 emissions could drastically reduce in the Americas as well as the Europe.



Global sulphur dioxide (SO2) emissions by world region

Annual sulphur dioxide (SO2) emissions in million tonnes

Meeting the Target

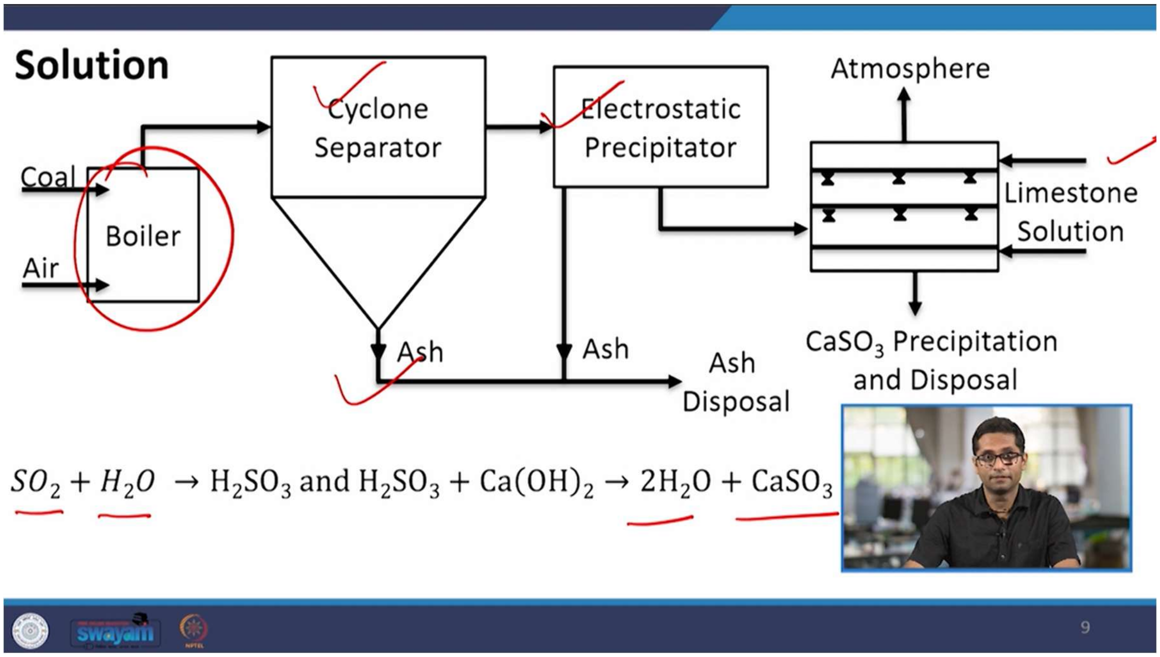
Source: Clio Infra; Klimont. et al (2013)

OurWorldInData.org/air-pollution/ • CC BY

Note: Data from 1850-2000 based on Clio Infra datasets. Data extended to 2010 using data from Klimont et al. (2013) publication: "The last decade of global anthropogenic sulfur dioxide: 2000–2011 emissions", which applies the same methodology for emissions estimation.

Source: https://ourworldindata.org/grapher/so-emissions-by-world-region-in-million-tonnes?facet=entity

So this is the data how the SO2 emissions have been increasing so we see with the influx of the industrial revolution there has been a great increase in these emissions particularly in the Americas and the Europe and it peaked around somewhere around 1970s or 1980s and beyond which because of the efforts by the different government agencies as well as the public perception there was a drastic reduction in the amount of SO2 emissions in terms of million tons and we can see how the reduction took place in the year 2010 in the different Americas as well as the Europe. Whereas a part of concern would be that in India or China or a majority of Asia the SOX emissions still tend to rise and this means that we should be following some similar policies that the Americas and Europe have followed almost 30 years back and bring down the levels of SO2. So this is something that we should learn there have been policies which have worked from them and they have been successfully been able to achieve the set targets and many of those targets were achieved well beyond the deadline.



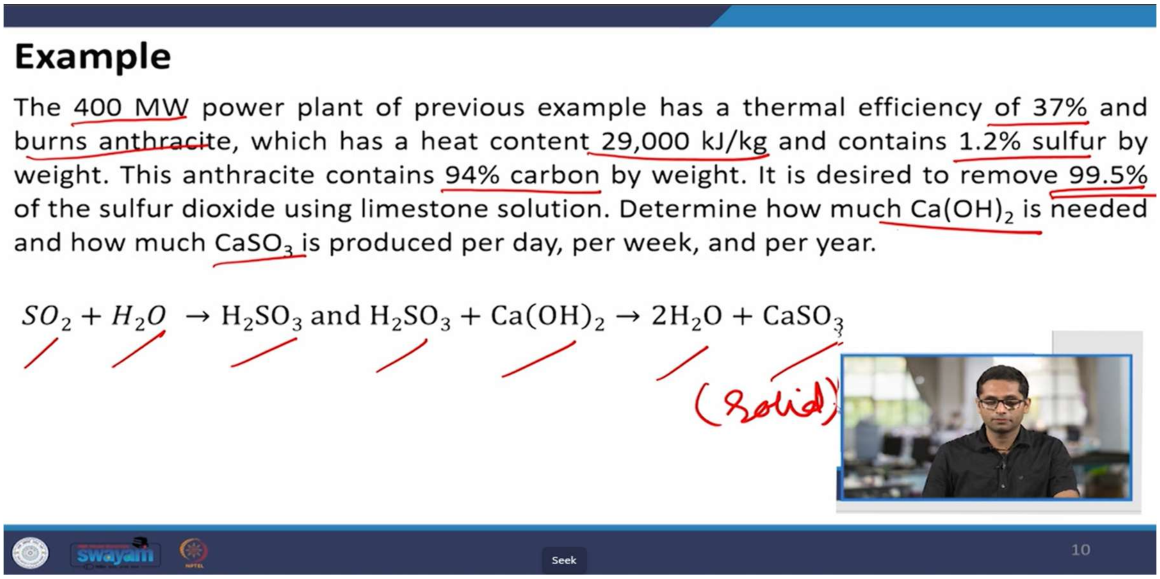
Solution

Coal
Air
Boiler
Cyclone Separator
Electrostatic Precipitator
Atmosphere
Limestone Solution
Ash
Ash
Ash Disposal
$CaSO_3$ Precipitation and Disposal

$SO_2 + H_2O \rightarrow H_2SO_3$ and $H_2SO_3 + Ca(OH)_2 \rightarrow 2H_2O + CaSO_3$

So the solution one of the major solution that was employed in particularly the coal power power plant was the use of calcium sulphate for the capture of the SO2 this is also called the flue gas desulphurization. So normally you would have the coal and the air entering the boiler which would be combusting the coal and providing in the heat for raising the steam and this steam is then used in the steam turbines for the production of electricity. The flue gas from these boilers would normally go to a cyclone separator for the removal of ash and further particulate metals get removed in the electrostatic precipitator. What is left in the flue gas is a majority of nitrogen, carbon dioxide and the sulphur dioxides and that sulphur dioxide is made to react with water. So what is sprayed on this flue gas is the limestone solution which is limestone dissolved in water.

So first the water reacts with the sulphur gas to produce hydrogen sulphite and this hydrogen sulphite is then made to react with calcium hydroxide which is nothing but lime to produce calcium sulphate as well as water two molecules of water and this is precipitate this is in the form of solid and quite easy to separate. So this is one of the method methodology that was adopted in the developed world for capturing the excess amount or the capturing a majority of sulphur dioxide that was coming from the coal based production of electricity. Further we have also seen a lot of industries as well as the power plants also shifted from coal to natural gas that again in turn helped in bringing down those emissions because a majority of these emissions came from either coal based power plants or the use of crude in the refineries. So let us try to understand the application of this kind of process with the help of an example. Let us consider the power plant that we have considered in the previous class.



Example

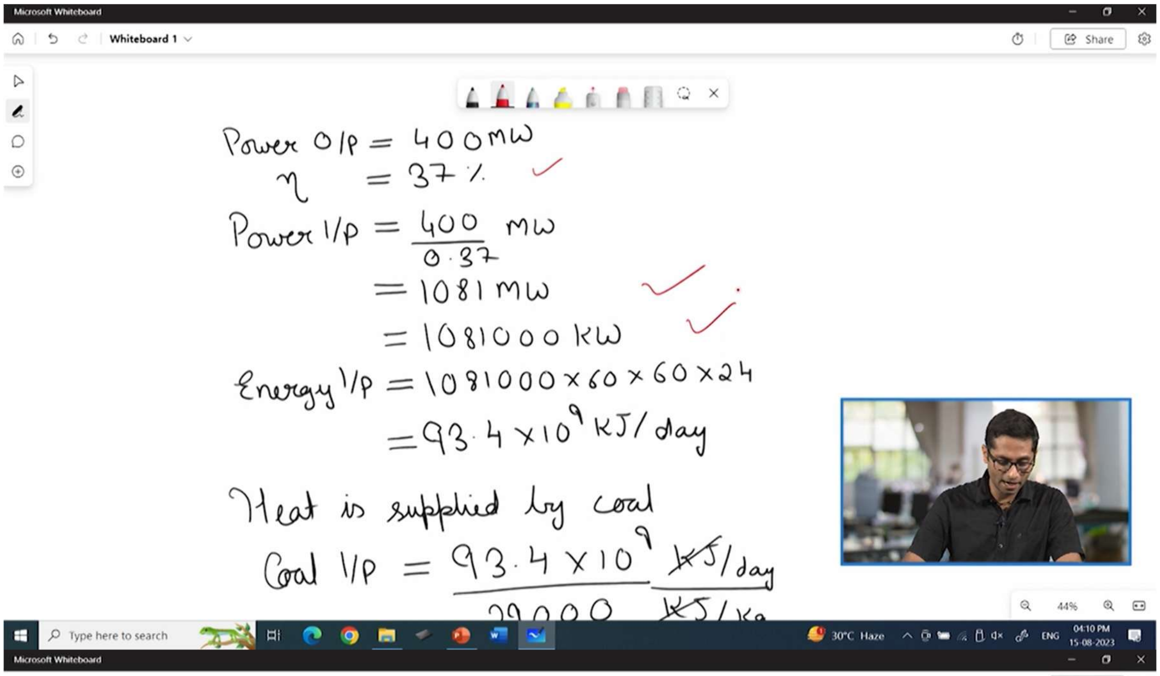
The 400 MW power plant of previous example has a thermal efficiency of 37% and burns anthracite, which has a heat content 29,000 kJ/kg and contains 1.2% sulfur by weight. This anthracite contains 94% carbon by weight. It is desired to remove 99.5% of the sulfur dioxide using limestone solution. Determine how much $Ca(OH)_2$ is needed and how much $CaSO_3$ is produced per day, per week, and per year.

$SO_2 + H_2O \rightarrow H_2SO_3$ and $H_2SO_3 + Ca(OH)_2 \rightarrow 2H_2O + CaSO_3$

(Solid)

The power plant had a nominal capacity of around 400 megawatt of production and the thermal efficiency that was taken was around 37% it was burning on anthracite which is a high grade coal and the calorific value is quite good in terms of 29000 kilojoules per kg. We approximated that the coal would have around 1.2% of sulphur and this sulphur is by weight. The anthracite is all again expected to have almost 94% of carbon and it is desired that we use the lime stoll solution for in the flue gas desulphurization unit and it is also expected that this particular solution or this particular methodology is able to extract almost 99.5% of the sulphur dioxide from the flue gas.

Now let us try to determine the amount of calcium hydroxide and the calcium sulphide that would be formed on a per day or a per year level if we were to use the same process. The underlying equations would be SO2 reacting with H2O providing in H2SO3 and further this H2SO3 reacting with sodium sorry calcium hydroxide to produce 2 molecules of water and 1 molecule of calcium sulphide and this is a solid in nature and could be easily separated. So let us move to white board to gain a better understanding. So this was the calculation that we undertook so just for a sake of revision we had the power plant producing almost 400 megawatt of electricity. The efficiency was 37% which is here.



Power O/P = 400 MW

$\eta = 37\,\%$ ✓

Power I/P $= \frac{400}{0.37}$ MW

= 1081 MW ✓

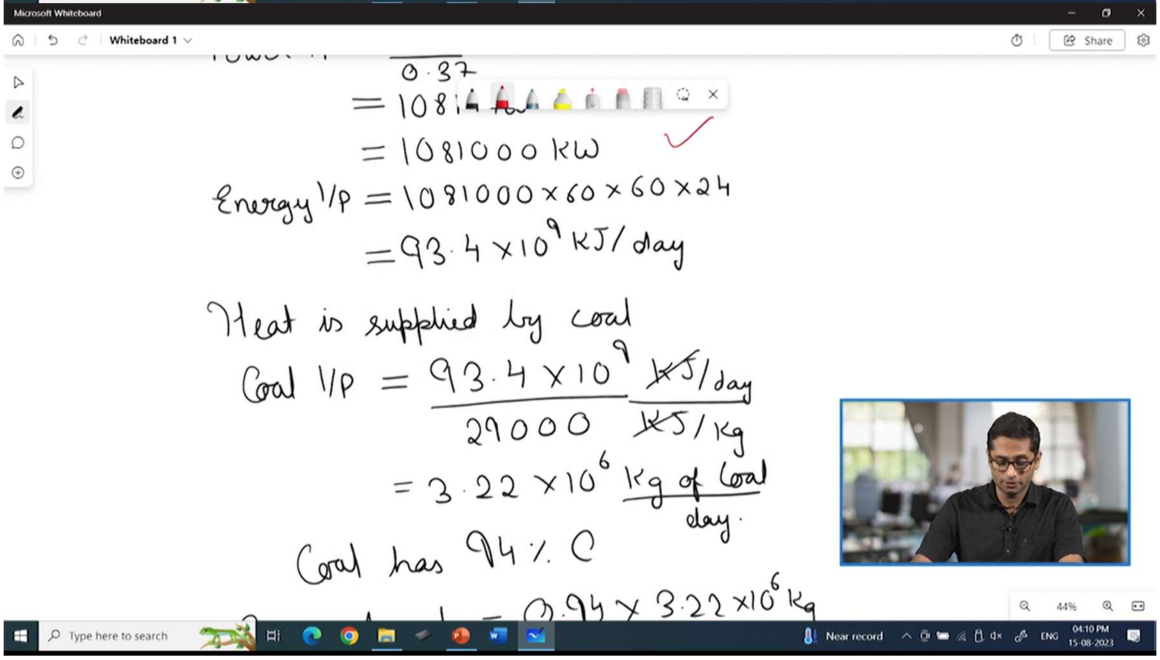
= 1081000 KW ✓

Energy I/P = 1081000 × 60 × 60 × 24

$= 93.4 \times 10^{9}$ KJ/day

Heat is supplied by coal

$\text{Coal I/P} = \dfrac{93.4 \times 10^{9}\ \cancel{KJ}/day}{29000\ \cancel{KJ}/kg}$



0.37

= 1081 MW

= 1081000 KW ✓

Energy I/P = 1081000 × 60 × 60 × 24

$= 93.4 \times 10^{9}$ KJ/day

Heat is supplied by coal

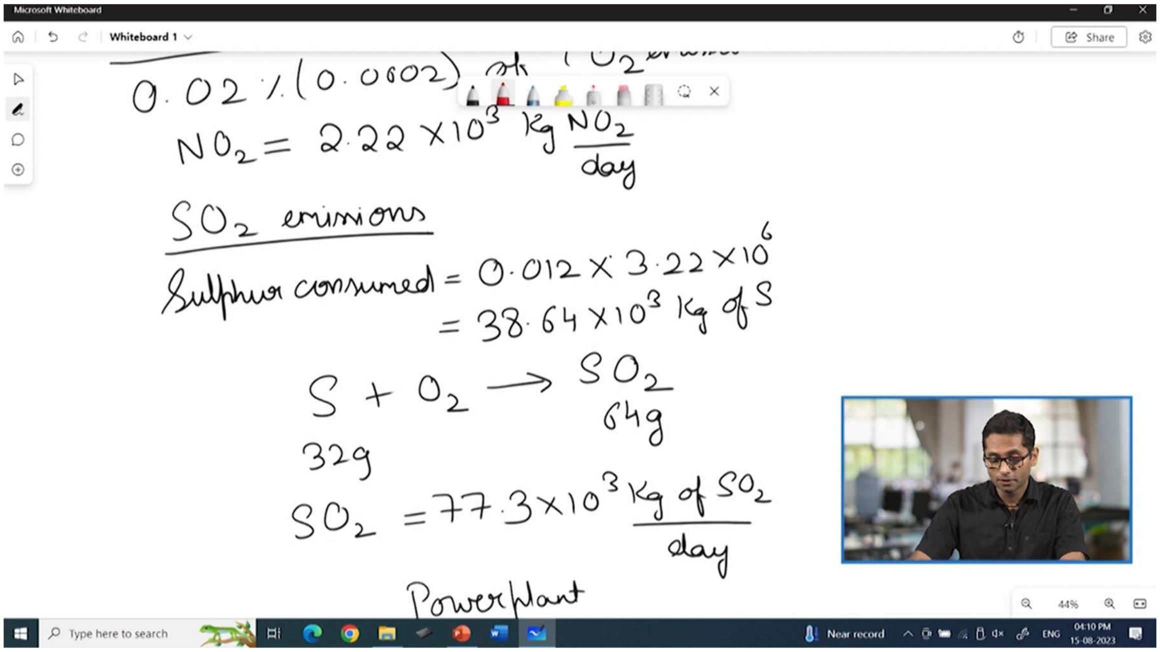
$\text{Coal I/P} = \dfrac{93.4 \times 10^{9}\ \cancel{KJ}/day}{29000\ \cancel{KJ}/kg}$

$= 3.22 \times 10^{6}\ \dfrac{\text{kg of coal}}{\text{day}}$

Coal has 94 % C

$= 0.94 \times 3.22 \times 10^{6}$ kg

The power input that would be required would be almost 1081 megawatt or 1081000 kilowatt. This was the power input and if we would have to look at the energy input I would multiply this with 60 minutes into 24 hours. So this gives me the energy input on a per day basis and this heat would primarily be supplied by coal for which I know the calorific value to be around 29000 kilojoules per kg. I divide the total energy input by the calorific value of the coal to give me the consumption of coal in terms of kgs of coal per day.



0.02 % (0.0002) of

$NO_2 = 2.22 \times 10^3 \frac{Kg\ NO_2}{day}$

SO2 emissions

Sulphur consumed $= 0.012 \times 3.22 \times 10^6$

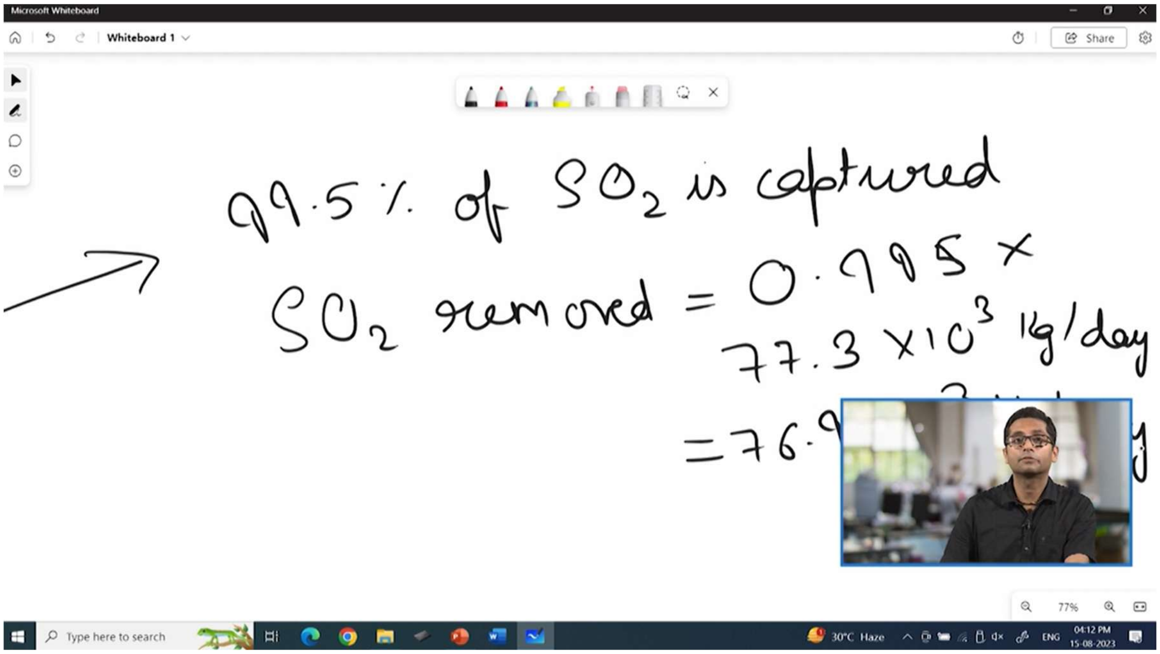
$= 38.64 \times 10^3$ Kg of S

$$\underset{32g}{S} + O_2 \rightarrow \underset{64g}{SO_2}$$

$SO_2 = 77.3 \times 10^3 \frac{Kg\ of\ SO_2}{day}$

Powerplant

Further we also estimated the SO2 emissions in terms of 0.012 into 3.22 into 10 to power 6. 0.012 basically refers to the 1.2% of sulphur being the component of coal and 3.22 into 10 to power 6 is the amount of coal that was being used on a daily basis. So further my emissions were around 38.61 into 10 to power 3 kgs of sulphur that was that this was the emission of sulphur and further this reacted with oxygen to give in a sulphur dioxide and the sulphur emission that came were finally 77.3 into 10 to power 3 or 77.3 tons of sulphur dioxide on a daily basis.

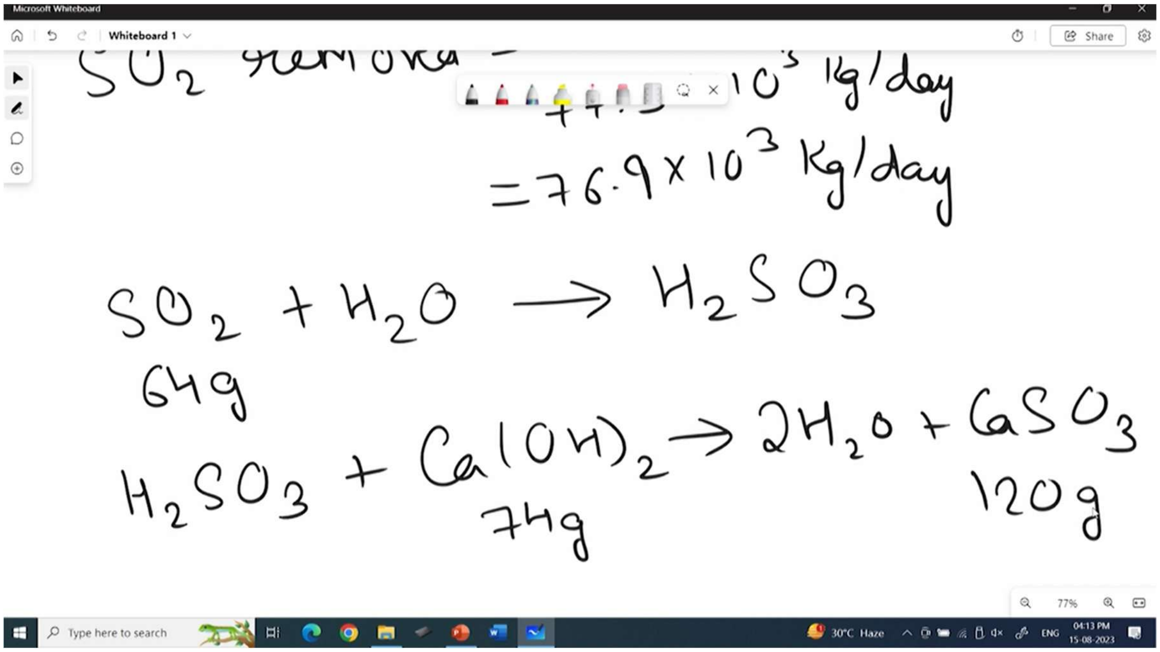


99.5% of SO_2 is captured

SO_2 removed $= 0.995 \times 77.3 \times 10^3$ kg/day

$= 76.9$

So let us start our calculation from this very point wherein the SO produced is available to us and now I would want 99.5% of sulphur dioxide is captured this is assumption that I am undertaking. So SO2 removed specifically would be 0.995 sorry into the amount of sulphur dioxide that was used that was around 77.3 into 10 to power 3 kgs per day and this value would come around to be 76.9 into 10 to power 3 kgs per day. So this is the amount of sulphur dioxide that what I would expect to be removed on a daily basis.



SO_2 removed = 77. $\times 10^3$ Kg/day

$= 76.9 \times 10^3$ Kg/day

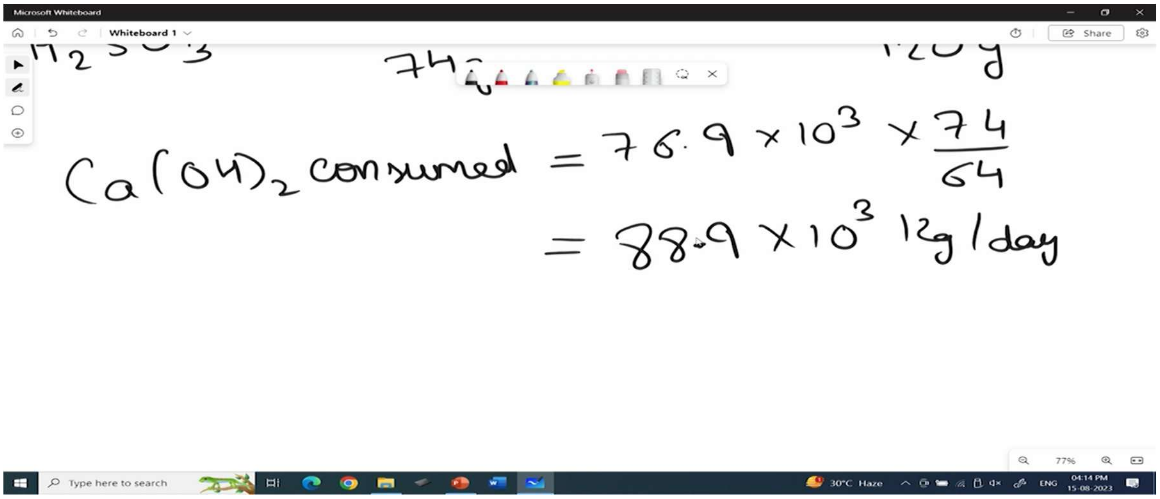
$SO_2 + H_2O \rightarrow H_2SO_3$

64g

$H_2SO_3 + Ca(OH)_2 \rightarrow 2H_2O + CaSO_3$

74g 120g

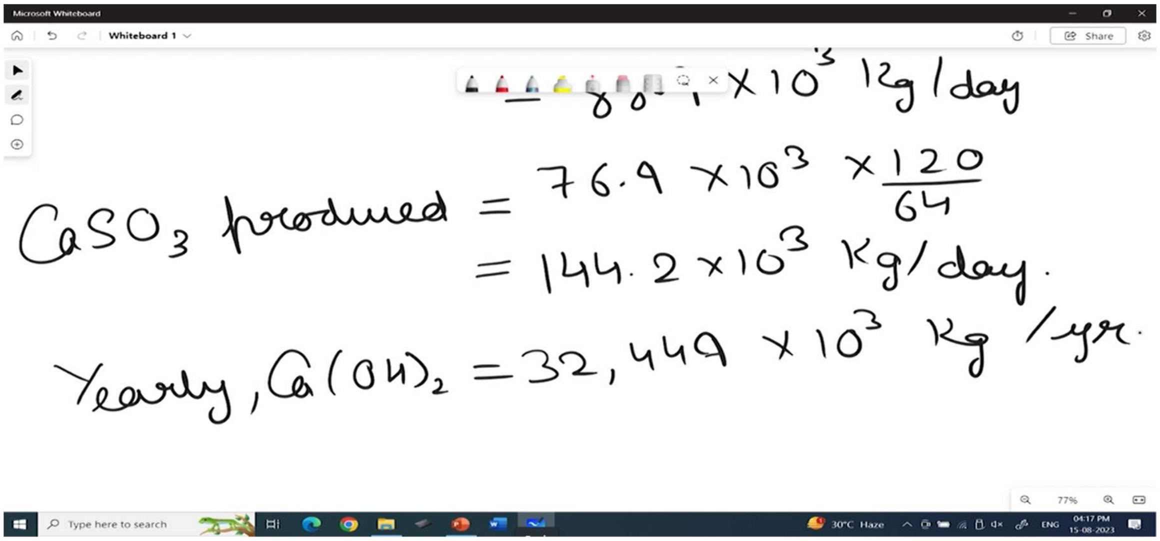
The underlying equation would be the sulphur dioxide reacting with water and this gives me H2SO3 and this H2SO3 then reacts with calcium hydroxide to give us two molecules of water plus one molecule of calcium sulphate SO3. So I would have almost 64 grams of SO2 this reacts with water and would produce H2SO3 and this H2SO3 one molecule again would react with calcium hydroxide which the molecular weight would be 74 grams and would produce two molecules of water as well as one molecule of CaSO3 with a molecular weight of 120 grams. So all in all 164 grams of SO2 to be captured would require almost 74 grams of calcium hydroxide and would produce 120 grams of final product.



H_2SO_3 74 120 g

$$Ca(OH)_2 \text{ consumed} = 76.9 \times 10^3 \times \frac{74}{64}$$
$$= 88.9 \times 10^3 \text{ kg/day}$$

So if I would have to estimate and the amount of calcium hydroxide that is consumed this would be equal to 76.9 into 10 to power 3 into 74 divided by 64 this value would roughly come out to be 88.9 into 10 to power 3 kgs per day. So this is the amount of calcium hydroxide that would be consumed on a daily level so it would be around 88 tons per day which is again a huge amount.

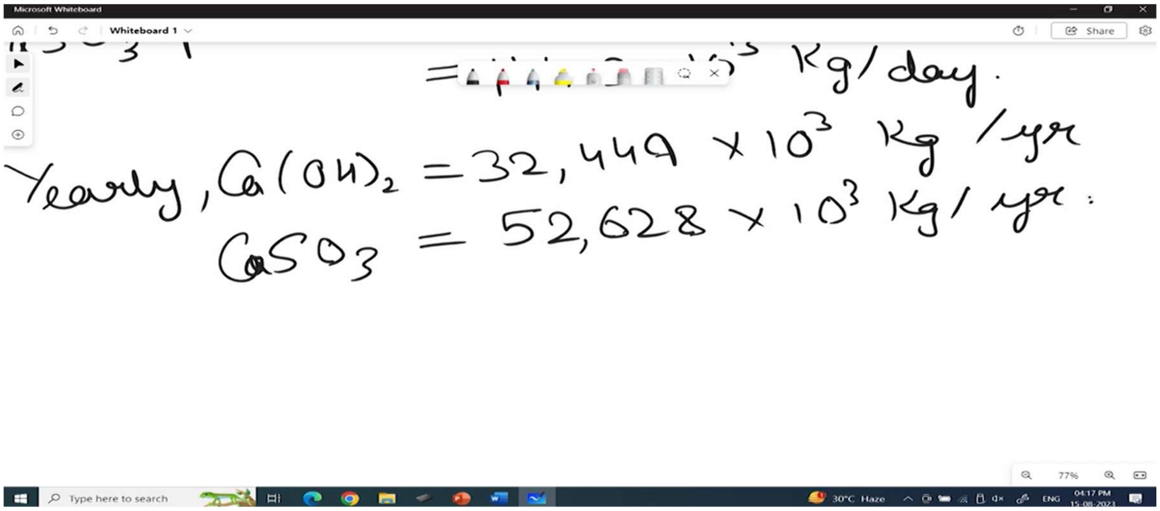


$$= 88.9 \times 10^3 \text{ kg/day}$$

$$CaSO_3 \text{ produced} = 76.9 \times 10^3 \times \frac{120}{64}$$
$$= 144.2 \times 10^3 \text{ Kg/day.}$$

$$\text{Yearly}, Ca(OH)_2 = 32,449 \times 10^3 \text{ Kg/yr.}$$

Also if we want to have a look at the production of CaSO3 we can write a similar equation when we have 76.9 into 10 to power 3 into 120 divided by 64 so this is the amount of CaSO3 that would be produced if I solve it this would come around to be 144.2 into 10 to power 3 kgs per day. If I look at the yearly values for the production so the value of calcium hydroxide so if I look at the yearly production of calcium hydroxide this would come around to be around 32,449 into 10 to power 3 kgs or 32,000 tons on an yearly basis and if I go towards the production of CaSO3 and this would be roughly 52,628 into 10 to power 3 kgs per year.

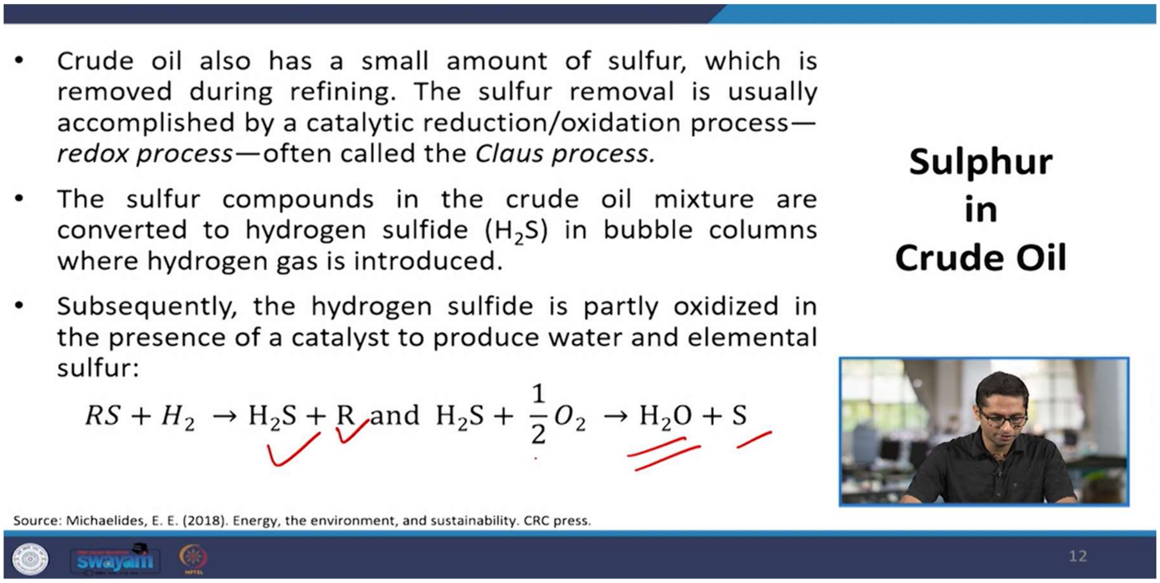


10^3 Kg/day.

Yearly, $Ca(OH)_2 = 32,449 \times 10^3$ Kg/yr

$CaSO_3 = 52,628 \times 10^3$ Kg/yr.

So often it was noticed that the production level of this precipitate like in terms of CaSO3 could be quite huge on a yearly level and this required a specific landfills because the production was around 50,000 tons per year so you would need a dedicated landfill for the disposal of a product like this. So it also turned out like sometimes the solution to one of the problems also led to other problems in terms of disposal and it also need a good amount of feedstocks in the form of calcium hydroxide which was needed to the tune of around 32,000 tons a year. So let us go back to the slides. We have tried to estimate like how this problem was solved in the energy industry where coal was used for as a source of energy. Another major source of the sulphur emissions was also the refineries.



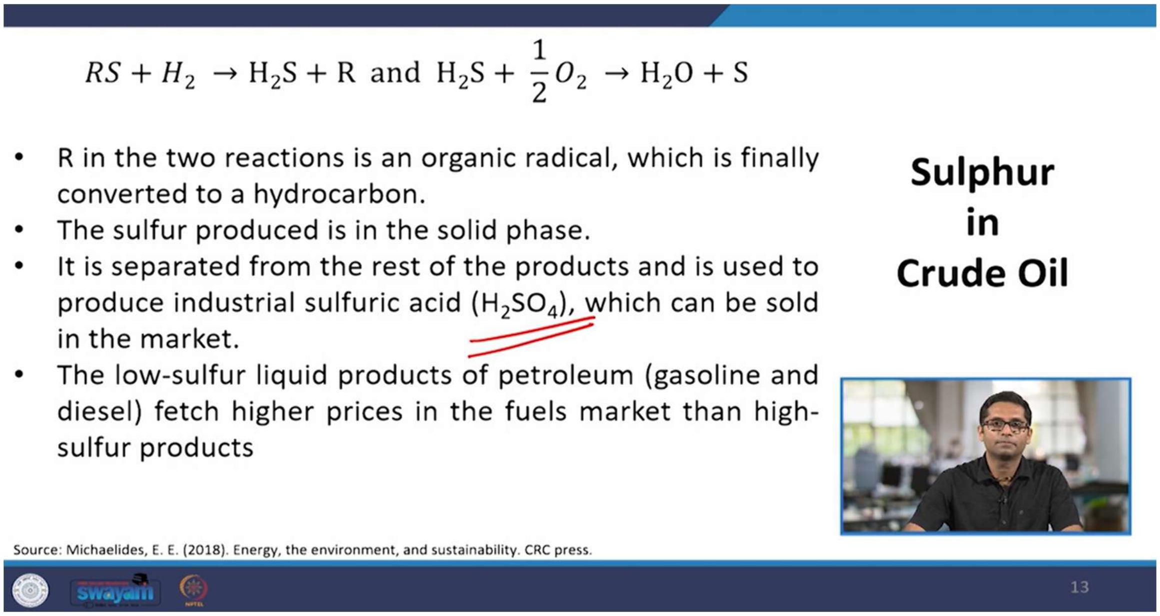
Sulphur in Crude Oil

- Crude oil also has a small amount of sulfur, which is removed during refining. The sulfur removal is usually accomplished by a catalytic reduction/oxidation process—*redox process*—often called the *Claus process.*
- The sulfur compounds in the crude oil mixture are converted to hydrogen sulfide (H_2S) in bubble columns where hydrogen gas is introduced.
- Subsequently, the hydrogen sulfide is partly oxidized in the presence of a catalyst to produce water and elemental sulfur:

$$RS + H_2 \rightarrow H_2S + R \text{ and } H_2S + \frac{1}{2}O_2 \rightarrow H_2O + S$$

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

So refineries were also consuming crude and this crude was having some amount of sulphur which was vented out to the atmosphere. And so the industries took in different pathways for that and one of the pathways that was adopted was the close process or the oxidation reduction process. It is a redox process and the major aim was to capture the sulphur. So the sulphur was first made to react or the sulphur bearing compounds in terms of these R refers to the hydrocarbon chain and we have the sulphur attached to it was made to react with hydrogen by bubbling the hydrogen through a column and the result was the H2S gas as well as the hydrocarbon. Once the H2S gas or the hydrogen sulphide gas was formed it was made to react with oxygen to form one molecule of water and then sulphur in the form of solid and this sulphur was later on used for the production of sulphuric acid which could fetch the company's market value. So the major pathways that was adopted in the form of close process was the reaction of the hydrocarbon chains with hydrogen to produce H2S and the hydrocarbon and because hydrogen was involved this was the reduction process and this H2S gas was later on made to react with oxygen forming water as well as sulphur and sulphur that was produced had another market value and this is the oxidation taking place and that is why it is also called the redox process.



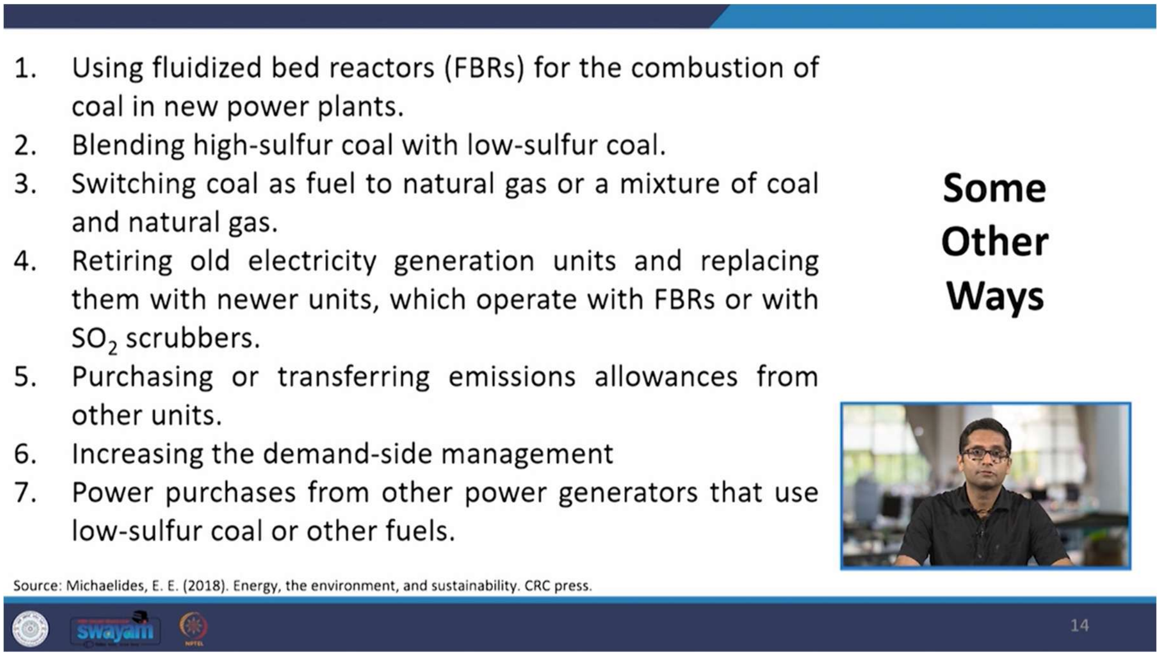
$$RS + H_2 \rightarrow \mathrm{H_2S} + \mathrm{R} \text{ and } \mathrm{H_2S} + \frac{1}{2}O_2 \rightarrow \mathrm{H_2O} + \mathrm{S}$$

Sulphur in Crude Oil

- R in the two reactions is an organic radical, which is finally converted to a hydrocarbon.
- The sulfur produced is in the solid phase.
- It is separated from the rest of the products and is used to produce industrial sulfuric acid (H_2SO_4), which can be sold in the market.
- The low-sulfur liquid products of petroleum (gasoline and diesel) fetch higher prices in the fuels market than high-sulfur products

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

The other pathways that was adopted also included the use of fluidized bed reactors which could make the reactions in the fluidized bed itself. The sulphur that was produced as I have said was in the solid phase and it was normally used in the production of industrial sulphuric acid and the low sulphur liquid products of petroleum in the form of gasoline and diesel were often found to have a market value higher than the high sulphur products and this was another incentive for the fuel companies to go for the low sulphur fuels because it could help get a good market share as well.



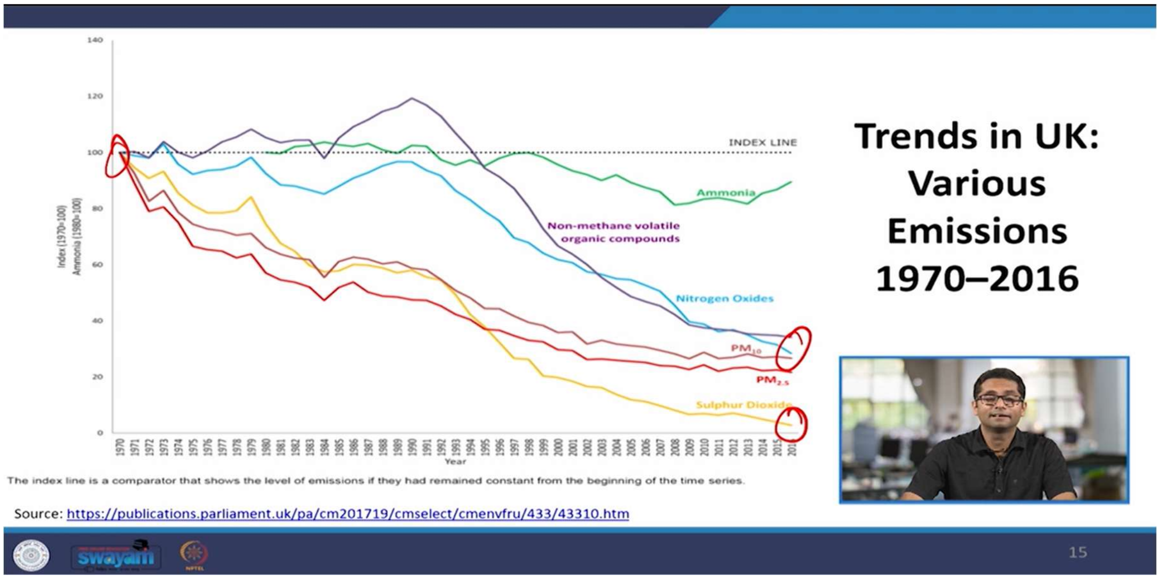
Some Other Ways

1. Using fluidized bed reactors (FBRs) for the combustion of coal in new power plants.
2. Blending high-sulfur coal with low-sulfur coal.
3. Switching coal as fuel to natural gas or a mixture of coal and natural gas.
4. Retiring old electricity generation units and replacing them with newer units, which operate with FBRs or with SO_2 scrubbers.
5. Purchasing or transferring emissions allowances from other units.
6. Increasing the demand-side management
7. Power purchases from other power generators that use low-sulfur coal or other fuels.

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

Some other ways which was used for the removal of sulphur was the use of fluidized bed reactors in the coal based power plants. So in a fluidized bed reactors we have the whole bed acting like a fluid because of the huge influx and in that fluidized bed the calcium hydroxide was mixed so as to capture the sulphur in the bed itself.

And there was also a switch from using low sulphur coals from high sulphur coals. Then companies have also been switching to using natural gas as an energy source or a mixture of coal and natural gas. Then the old coal fired power plants which were not very efficient again as well as had a good amount of emissions of sulphur were either retired or they were retrofitted with new SO2 scrubbers. There was an increased demand side management as well and also the companies were encouraged to purchase power for power generation which were using low sulphur coal or other fuels which were not causing as much emissions.

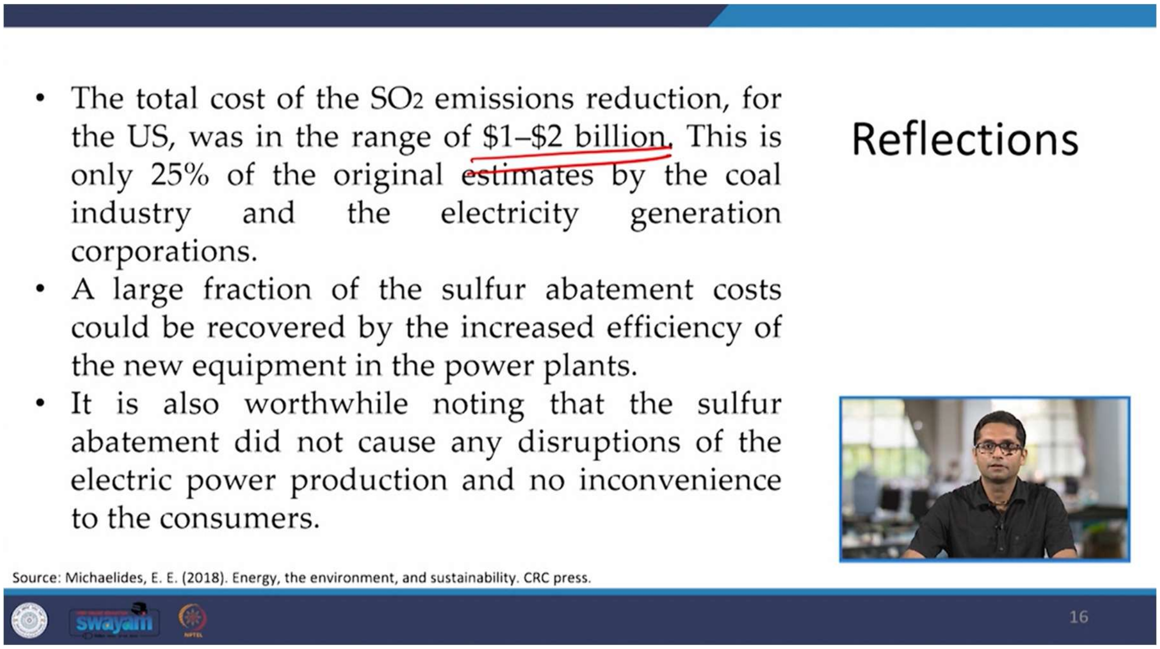


Trends in UK: Various Emissions 1970–2016

The index line is a comparator that shows the level of emissions if they had remained constant from the beginning of the time series.

Source: https://publications.parliament.uk/pa/cm201719/cmselect/cmenvfru/433/43310.htm

So if we see the trends in different countries, let me show you the trend how the sulphur content or the sulphur dioxide have been decreasing in the country of UK we can see there was a significant decrease so the reduction could be almost 90% as compared to 1970 levels so there has been a huge reduction in the sulphur dioxide levels. And these levels were also a lot of time coupled with other emissions in terms of the NOx emissions because these are the source of these kinds of emissions remains similar. So we also saw that similar methodologies and similar kind of pathways also led to a similar decrease in the NOx emissions and the NOx were again a major source of acid rains as well and the efforts that were taken in for the removal of sulphur also acting or a complementary effect was that there was a remove, there was a decay in the nitrous oxide emissions as well.



Reflections

- The total cost of the SO_2 emissions reduction, for the US, was in the range of \$1–\$2 billion. This is only 25% of the original estimates by the coal industry and the electricity generation corporations.
- A large fraction of the sulfur abatement costs could be recovered by the increased efficiency of the new equipment in the power plants.
- It is also worthwhile noting that the sulfur abatement did not cause any disruptions of the electric power production and no inconvenience to the consumers.

Source: Michaelides, E. E. (2018). Energy, the environment, and sustainability. CRC press.

So to sum up or the particular examples is that like the SO2 emission reduction happened quite fast in the major countries of the world and further the industry at the onset were not very keen on adopting the methodologies because it came in the form of the different capex investments so it was estimated in the US that the companies might have to incur somewhere between 1 to 2 billion dollars of investment which the companies were not willing to make and as we have understood in the previous classes as well the error before 1980s was in which companies would see the environmental regulations in a negative tone and they would not want to spend much for the betterment of the environment but further because of the government policies the targets were set and the companies were made to adopt the emission targets further it was realized that the companies ended up spending only 25% of the original estimates so all the savings or the drastic reduction in the SO2 emissions came at one fourth of the cost that was initially estimated and a large part of the abatement cost also helped in increasing the efficiency of the process because new equipments were put in the power plants which were much more efficient and were good for the overall economics of the power plant which helped the power plant owners make profit. Further it was also expected that there would be some major disruptions in the power sector that might occur because of the change of the earlier equipment with the new one but nothing of those sort was felt and the inconvenience that was put to the consumers were also almost negligible. So this brings us to the example that we have seen in the last class that the change in the business perspective with the coming up of new and innovative ideas like major environmental problems could be averted, the emission targets could be met and of course there were the capital expenditures but they could be vastly reduced and a lot of it expenditure also helped in increasing the profits in the future.

So this is one of the case studies with respect to SO2 emissions which is seen as an environmental case study or the case study of environmental emissions which is a success story and that could be adopted in countries like India and China because we still are growing the sulfur emissions as the country is concerned and we can adopt these kinds of methodology for further reduction and similar kind of methodology is also seen as a worthwhile case study for the future implementation of CO2 abatement. With that we end today's lecture. Thank you.