Energy Resources, Economics, and Sustainability

Prof. Pratham Arora

Hydro and Renewable Energy Department

Indian Institute of Technology Roorkee, Roorkee , India

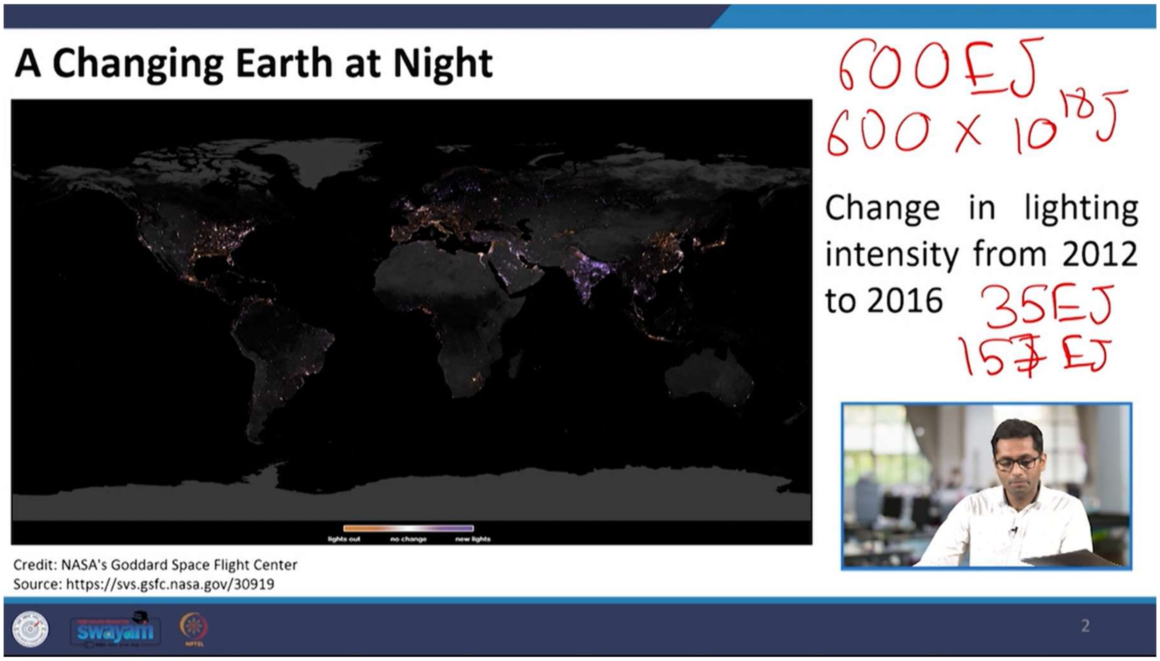
Week – 01

Lecture – 01

Lecture 01 – Introduction

Hello everyone, welcome to the first lecture of the course Energy Resources Economics and Sustainability course. So, today being the first lecture, we will try to get some introduction of the linkages that exist between the use of energy resources in the present moment and its environmental consequences. So, what we are going to do today is, we will do a very simplistic calculation in which we will try to understand if we will keep on progressing with the current use of fossil fuels or conventional fuels, what could be the possible effect on the environment. So, we will embark on a simple calculation where we are going to estimate the amount of CO2 emissions that could be possible if all the energy requirements of today's world were to come from the fossil fuels. Given that, what will be the CO2 emissions and if we keep on with those emissions, what will be the time frame for doubling the amount of CO2 in the atmosphere. Now doubling the amount of any gas in the atmosphere has critical consequences.

Even if you go through literature, many of them would be focusing on what will be the effect of doubling the amount of CO2. Again this would be a very simplistic calculation, but nonetheless it will give us an understanding how the things work and how serious the matter is.



A Changing Earth at Night

600 EJ

$600 \times 10^{18} J$

Change in lighting intensity from 2012 to 2016

35EJ

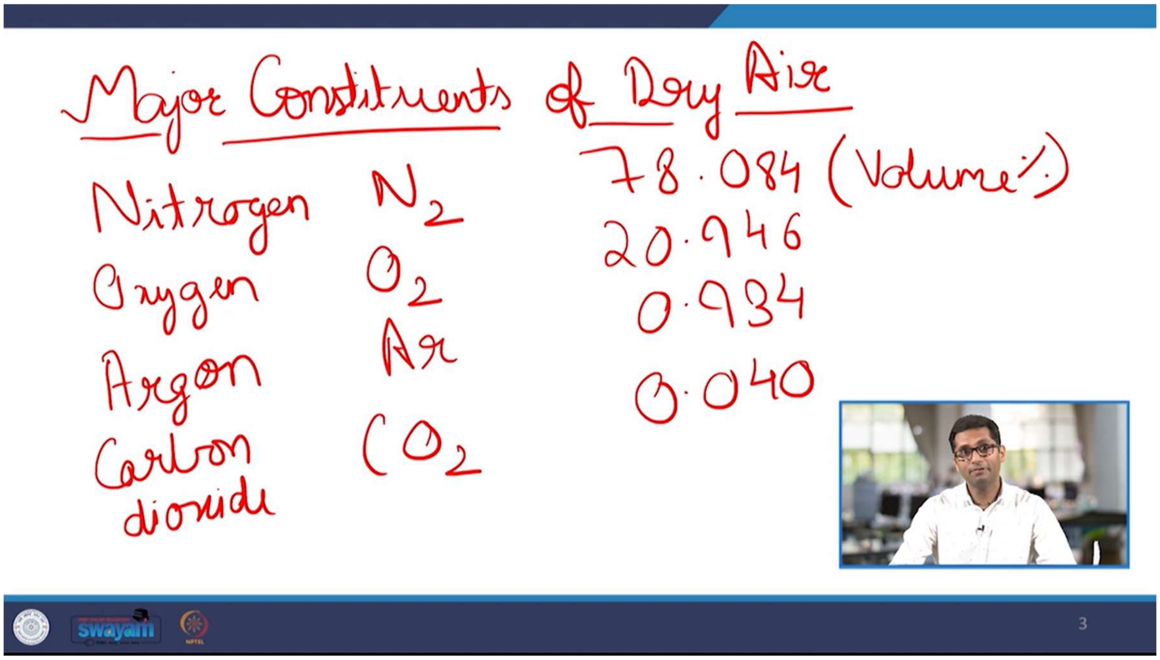
157 EJ

Credit: NASA's Goddard Space Flight Center
Source: https://svs.gsfc.nasa.gov/30919

So, let us try to have a view of the night sky of the earth. So, this image is basically by the NASA, put in a study like how the night sky would look like.So, we can see there are places on the earth which are poorly lit, there are other places which are very nicely lit. And we can also see how the lights have been changing over a span of five years for which the study was done 2012-2016. And we can see the energy use is not very evenly distributed throughout the world. There could be other reasons like not all the places are equally populated, but nonetheless we need to understand that there is a constant change in the energy use throughout the world. So, if I talk about the energy use of the world, so the current energy use stands at around 600 exajoules.

And 600 exajoule, I mean 600 into 10 to power 18 joules. And this use in itself is huge. And it has been constantly increasing over the years. If I talk about the Indian value, it stands somewhere around 35 exajoules as per the statistics that are given by the International Energy Agency. And if I talk about our neighbors on the north, that is China, their use would be around 157 exajoule.

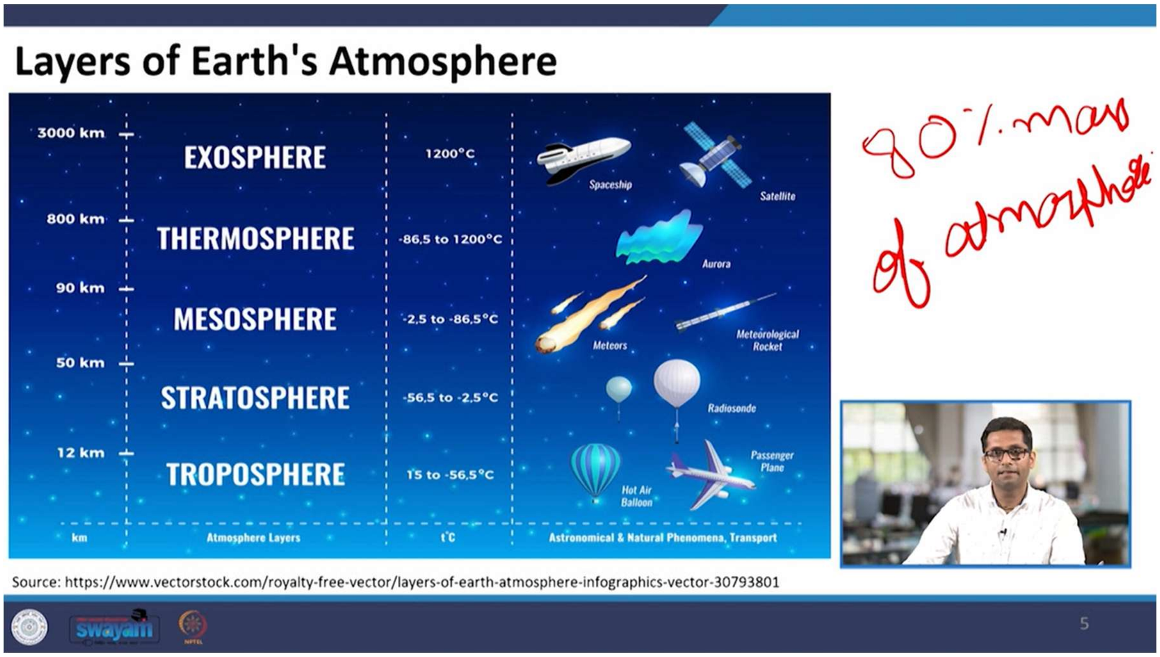
So, it is quite high. Now, we will try to understand if this amount of energy was to come from fossil fuels, what would be the tentative amount of CO2 that we would be emitting. And if we keep on with that use, what will be the time that would be required for doubling that amount of CO2? So, let us embark on this simple but interesting calculation. So, first thing we need to understand is the constituents of dry air over the atmosphere. So, let me write it down for you.



Major Constituents of Dry Air

Nitrogen	N_2	78.084 (Volume%)
Oxygen	O_2	20.946
Argon	Ar	0.934
Carbon dioxide	CO_2	0.040

So, this is the major constituents of dry air. And I hope most of you would be knowing that the major constituent consequence is nitrogen. It is one of the most abundant gas. The percentage of nitrogen is 78.084. And here I am talking about the volume percentage. The next major gas that comes is oxygen. And the percentage is roughly 20.946. The next major gas is argon. You do not hear about that gas much, but still it is the third largest gas. And the percentage is roughly 1%. To be exact, it is 0.934. And then comes the major culprit, which is carbon dioxide. So, this is one of the major gas that everyone talks about nowadays. And the percentage if I talk about is 0.040 or 400 ppm. Just the scale gives us an understanding that it is not a major constituent. But this CO2 is something that we cannot do away with. If there was no CO2 in the atmosphere, possibly Earth would have been a planet like Venus. Lots of cold weather. And if it keeps on increasing, then we have the other consequences of global warming. So, we will try to understand that if we continue with the current consumption of fossil fuels, which nonetheless emits CO2, what will be the time that would be required for doubling this amount of CO2? And some of you might be wondering there is another gas that is present that is water vapor. The constituents or the percentage of water vapor in the atmosphere varies from 0.01 to 5%. But that is a function of the place. And we are going to neglect that in this particular calculation. So, in our case, there would be four major gases, nitrogen, oxygen, argon and carbon dioxide. And what is the focus will be carbon dioxide. So, now let us try to gain quite more understanding of the Earth's atmosphere.



Layers of Earth's Atmosphere

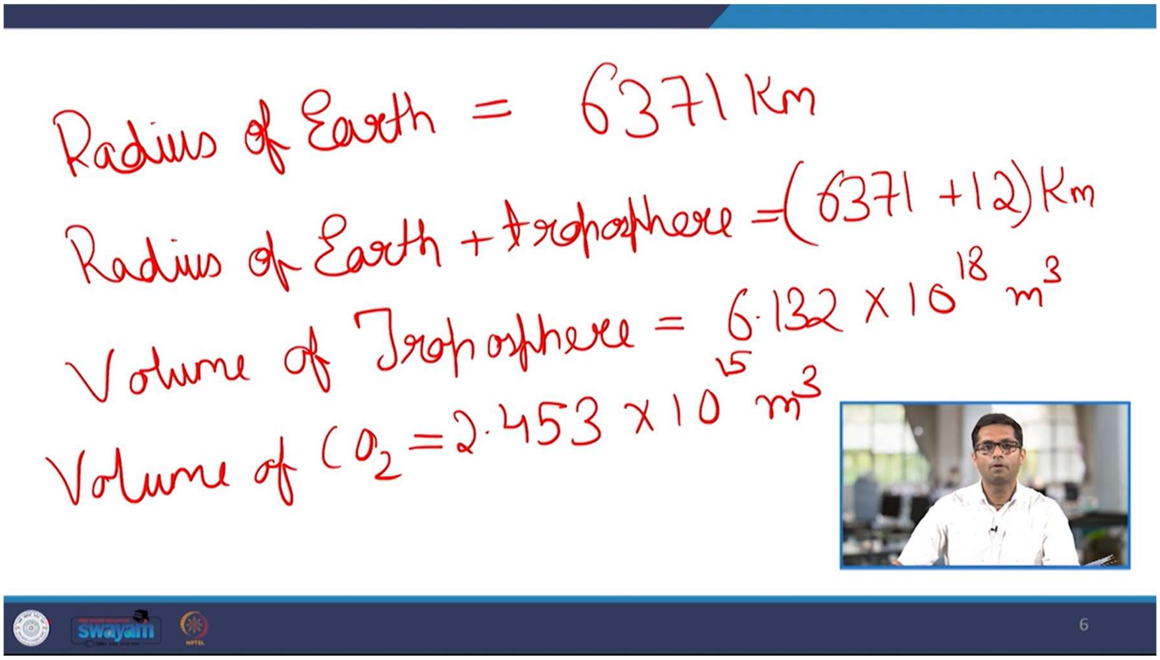
80% mass of atmosphere

Source: https://www.vectorstock.com/royalty-free-vector/layers-of-earth-atmosphere-infographics-vector-30793801

So, if I talk about the Earth's atmosphere, it could be divided into different zones. The bottommost zone could be called the troposphere, which extends from 0 to 12 kilometers. The next zone would be the stratosphere, 12 kilometers to 50 kilometers. Then comes in the mesosphere, extending up to 90 kilometers. Thermosphere from 90 to 800 kilometers. And finally, exosphere, which basically takes the atmosphere into the outer space. And on the right hand side of the graph or the figure, you can also see the amount or the activities that are relevant to that particular sphere. Majority of the world that we interact with or almost 99% of the world that we interact with can be found in the troposphere. A typical flight, if you take a transatlantic flight, would be flying at a height of around 10 kilometers. So, the flight that you might have travelled for, for intercontinental travels would also be in the troposphere.

We know the highest mountain ranges, the Himalayas, as well as the mountain Everest would be in the troposphere. Then comes the stratosphere, where you find much of the weather balloons. Above that comes the mesosphere, where most of the meteors that you see in the night sky could be found that. Then comes the thermosphere, where you have the northern lights, if you are placed in some of the Nordic countries. And finally, we have the spaceships and the satellites in the exosphere.

So, this is how the atmosphere looks like. And again, to repeat, much of the economic activities that we are going to deal with lies in the troposphere. And that's not the only thing. Almost 80% of the Earth's, mass of the Earth's atmosphere is also found in the troposphere. So, for our calculation, we are going to assume that troposphere basically reflects the whole of atmosphere. Because it consists of 80% of the mass of atmosphere.



Radius of Earth = 6371 Km

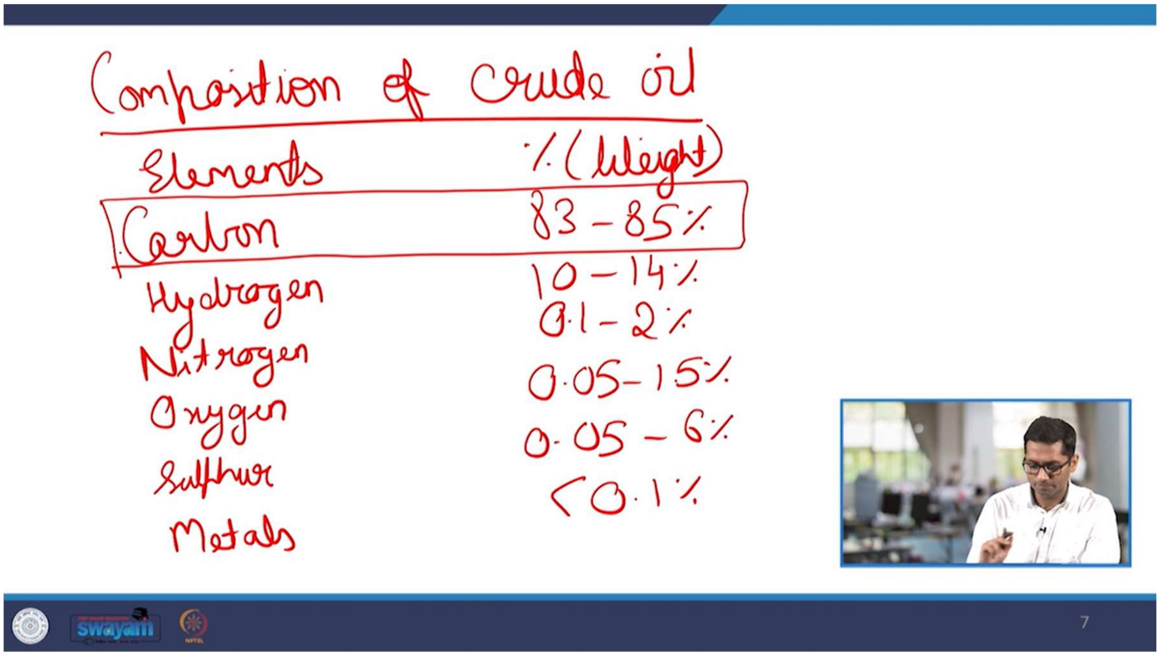
Radius of Earth + troposphere = (6371 + 12) Km

Volume of Troposphere = $6.132 \times 10^{18}\ m^3$

Volume of $CO_2 = 2.453 \times 10^{15}\ m^3$

Now, let us try to understand the constituent or the volume of the Earth's atmosphere. So, every one of us know that the radius of the Earth is 6371 kilometers. I can use this radius to calculate the volume of the Earth. Similarly, I can also calculate the radius of Earth plus troposphere.

And this would come out to be 3791 plus 12 kilometers. We have the simple formula for volume, which is 4 by 3 pie r cube. We can calculate the volumes and subtract the two to calculate the volume of the troposphere. So, if I do that calculation, which I would expect you guys can do on your own as well. The volume of troposphere would come out to be roughly 6.132 into 10 to power 18 meter cube. This is the volume of the troposphere that we get. Again, let me reiterate that we are assuming that much of the Earth's atmosphere to be reflected by the toposphere, which extends from the mean sea level till 12 kilometers of height. Now, we are also aware that the percentage of CO2 in this volume of troposphere would be almost 400 ppm or 0.04%. We can multiply that to get the volume of CO2. The volume of CO2 would be nothing but volume of the troposphere as calculated above multiplied by 0.04%. And this would come around to be 2.453 into 10 to power 15 meter cube. So this is the present amount of volume of CO2 in the troposphere. So this is basically the first part of the calculation where we have tried to estimate the amount of CO2 that we have in the toposphere. Now let us try to go to the next part of the calculation. The next part of the calculation basically entails the use of fossil fuels. So one of the major fossil fuels that we use in the present world is the crude oil.



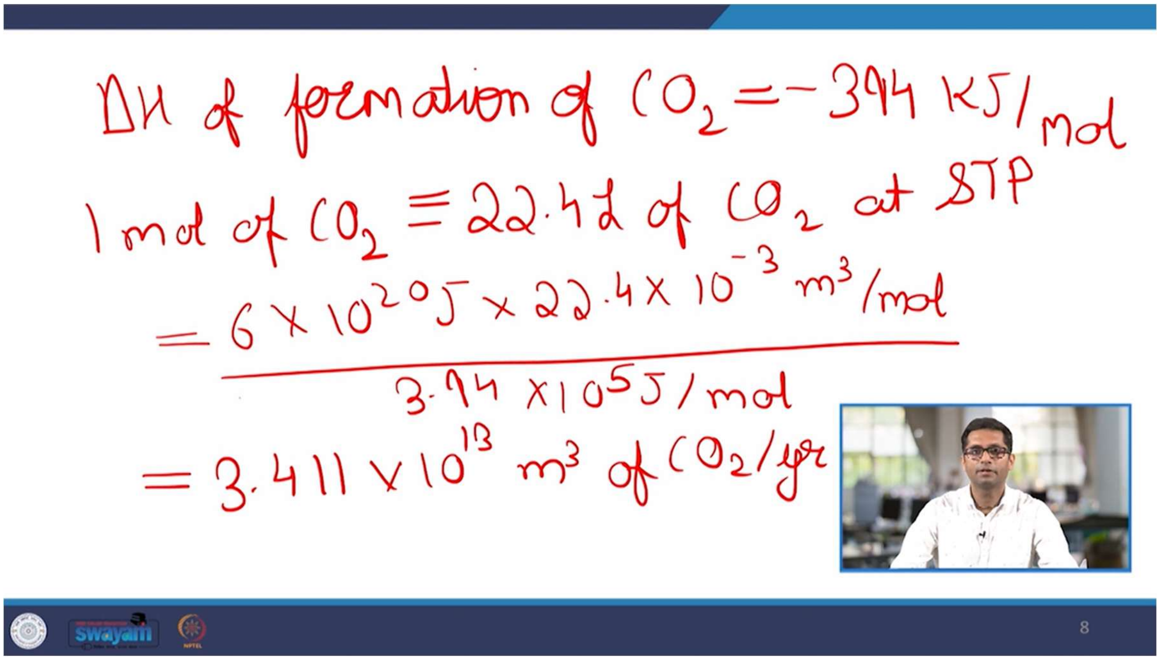
Composition of crude oil

Elements	% (Weight)
Carbon	83 – 85%
Hydrogen	10 – 14%
Nitrogen	0.1 – 2%
Oxygen	0.05 – 15%
Sulfhur	0.05 – 6%
Metals	< 0.1%

Now if I go with the composition of crude oil, it looks something like this. So we would have the elements and then we would have the percentage in terms of weight. The earlier percentages that I have given you were in terms of volume whereas this is in weight. The major constituent of any fossil fuel would be carbon. And this in a crude oil, carbon will vary between 83 to 85%.

Then comes in hydrogen which would vary between 10 to 14%. Then nitrogen which could vary between 0.1 to 2%. All this is a function of where the crude oil is coming from. Then we also have some amount of oxygen in here which could vary from 0.05 to 1.5%. Also Sulphur could again vary from 0.05 to 6%. And there could be some trace metals which could normally be less than 0.1%. So this would be the basic composition of the crude oil which is again one of the major fossil fuel that is used for providing energy for different end uses.

We see here that the majority of the energy is coming from the carbon and we also have energy from the combustion of hydrogen and the remaining elements that we have would not be a source of energy per se. So for this calculation what we are going to assume that the 100% of the energy by the combustion of the crude is coming from the carbon. So this is again a simplistic assumption that we are trying to make given that the crude oil is already 85% carbon let me assume that 100% of the energy that would be coming from the combustion of a crude oil would be because of the combustion of the carbon and I am assuming crude oil to be consisting of 100% carbon. Now whenever we have the combustion, the energy released is nothing but the enthalpy of formation and we know that the enthalpy of formation or the delta H. So next part of the calculation would be to relate the energy that is evolved by the combustion of carbon which would inevitably lead to the formation of CO2.



ΔH of formation of $CO_2 = -394\ \mathrm{KJ/mol}$

1 mol of $CO_2 \equiv 22.4\,l$ of CO_2 at STP

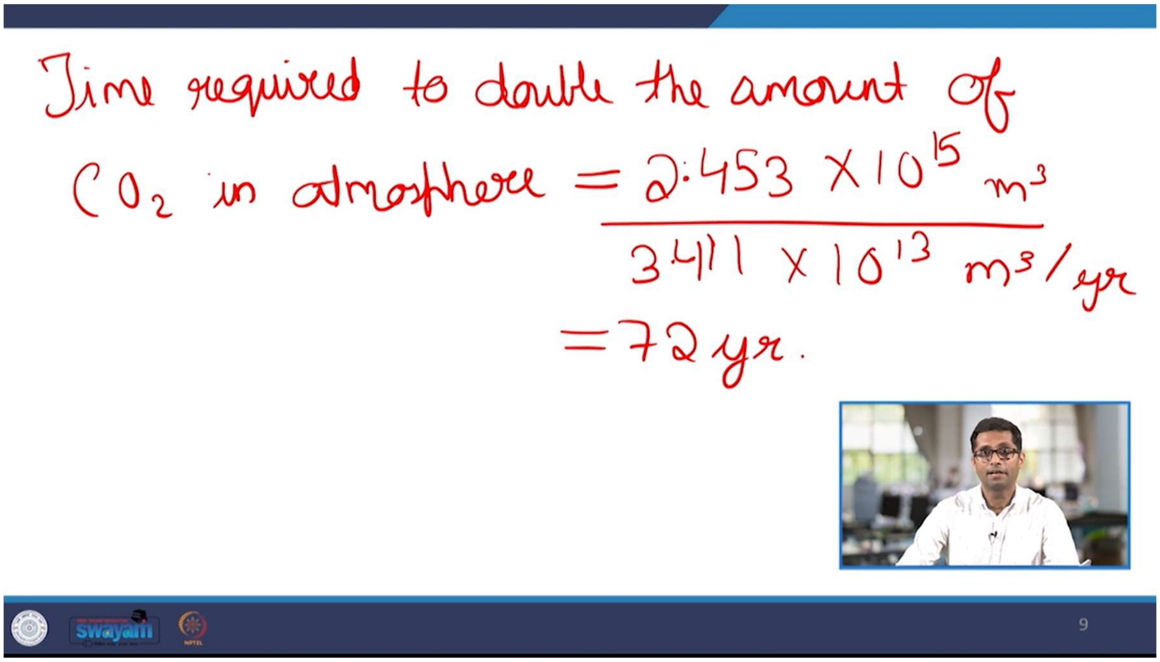
$$= \frac{6\times10^{20}\,\mathrm{J} \times 22.4\times10^{-3}\ \mathrm{m^3/mol}}{3.94\times10^{5}\,\mathrm{J/mol}}$$

$$= 3.411\times10^{13}\ \mathrm{m^3}\ \text{of}\ CO_2/\mathrm{yr}$$

So the basic reaction would be carbon combining with oxygen and producing CO2. We are aware that the delta H or the enthalpy of formation of CO2 and this value is equal to minus 394 kilojoules per mole. So for the production of 1 mole of CO2 we would be releasing minus 394 kilojoules of energy. The minus sign basically reflects that the energy is evolved in this reaction and this reaction basically forms the basics of energy production from any fossil fuel which is carbon based. So most of the fossil fuels we know are carbon based and this is the final reaction that would be happening carbon combining with oxygen producing CO2 and this would lead to the release of energy.

We are also aware that 1 mole of CO2 would be equivalent to 22.4 liters of CO2 at STP. So when I say STP I basically refer to 0 degree temperature and 1 bar of pressure but this is only applicable at 0 degree of temperature and 1 bar of pressure. So if we look back at the different layers of atmosphere we also notice that there is a huge variation in the temperature in the different zones. So if we look at the troposphere the temperature varies from 15 degrees to minus 56 degrees and we also know that majority of the mass of the atmosphere is concentrated in the troposphere. So I will make again a simplistic assumption here that the average temperature of the troposphere is 0 degree Celsius so that I can take this conversion factor. Again this is a very simplistic assumption. So if that was the case I would be producing almost 22.4 liters of CO2 from 1 mole at STP. Now given this case if all my energy was to come from the consumption of crude which is reflected in the form of carbon how much energy I would be releasing? I can calculate that by a simple calculation in which we have the energy that is getting consumed which is 6 into 10 to power 20 joules.

The conversion factor which is 22.4 into 10 to power minus 3 is for the meter cube per mole and I divide that with energy released by the production of 1 mole of CO2 which is 3.94 into 10 to power 5 joule per mole. I cancel the units and what I finally get is 3.411 into 10 to power 13 meter cube of CO2 per year. So this would be the amount of CO2 that I will be releasing into the atmosphere if all the energy consumption was to come from crude and the crude is assumed to be almost 100 percent carbon. Let me repeat I have made many simplistic assumptions in this calculation I have assumed that the troposphere as such is at STP. I have also assumed that 100 percent of the mass of the atmosphere is located in the troposphere. I have assumed earth to be a perfect sphere which it is not. I am also assuming that there is no moisture in the atmosphere but again the aim here is not to get the exact answer but to get an understanding of the effect of the energy use of the earth. So now I have two numbers one is the volume of the CO2 that is already there in the atmosphere and the second is the CO2 that is released into atmosphere because of the anthropogenic activities and that is primarily attributed to the use of energy by the humans.



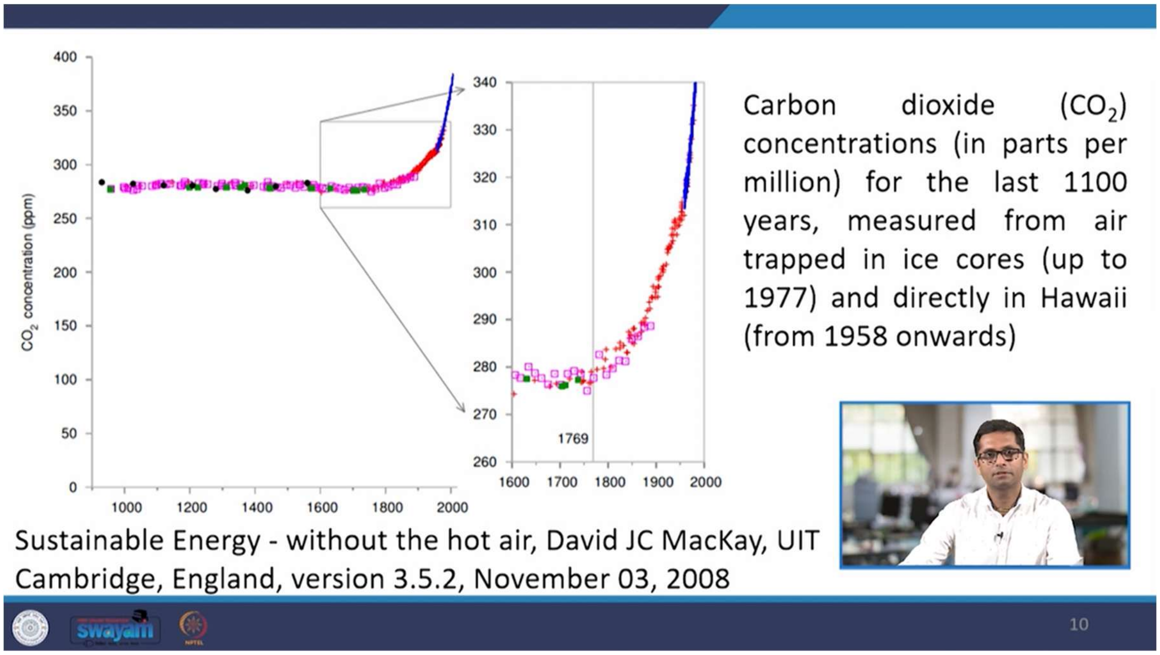
Time required to double the amount of CO_2 in atmosphere $= \frac{2.453 \times 10^{15} \, m^3}{3.411 \times 10^{13} \, m^3/yr}$

$= 72 \, yr.$

So if I have to calculate the amount of years that would be required to double the amount of CO2 in the atmosphere I would be just dividing the first number by the second number. So if I have to calculate the time required to double the amount of CO2 in the atmosphere this would be nothing but the CO2 that is already there that is 2.453 into 10 to power 15 meter cube divided by the CO2 that I am producing every year 3.411 into 10 to power 13 meter cube per year and this gives me an answer of 72 years. Now whether this number of years is too high or too small is something that is a matter of debate but if I take a general opinion this is not a very large time scale this is basically the average span of life of a human being.

So within our lifespan we can see that if we keep on continuing with the present rates of the consumption of fossil fuels we can see the doubling of the CO2 to happen and this doubling or doubling of the carbon dioxide could have serious consequences. As we have been reading in the scientific literature this is one of the primary cause of the global warming which is causing extreme weather events like sea level rise we might lose many of the coastal areas many of the countries might cease to exist and this number is again a very simple number that is coming from simple calculation. A major catch again here is that the energy consumption that has been used to calculate this number is not constant it is constantly rising. We know that the population is on a constant rise specifically in India and if I look at the energy consumption of India it is also increasing at a very fast rate. So given these assumptions this number of year could be even lesser if we keep or we have a linear rise in the energy or exponential rise in the energy consumption this number could be even shorter.

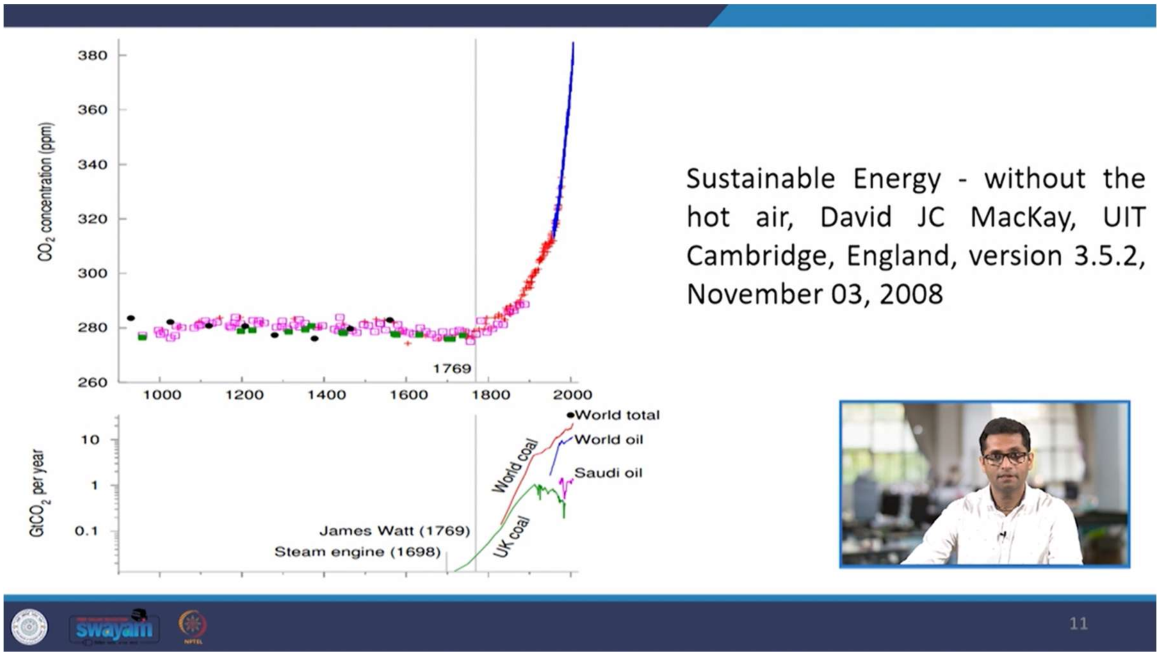
If we are doubling the energy consumption this number might even come to half 30 years maybe 20 years so this can this doubling of the CO2 could be reached in much lesser time than we can assume. Again this was a very simple calculation to make you understand that the use of energy by the humans could have serious consequences and this consequence is nothing is not that it is for our future generations will face even we people can face it in our own lifetimes.



Carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards)

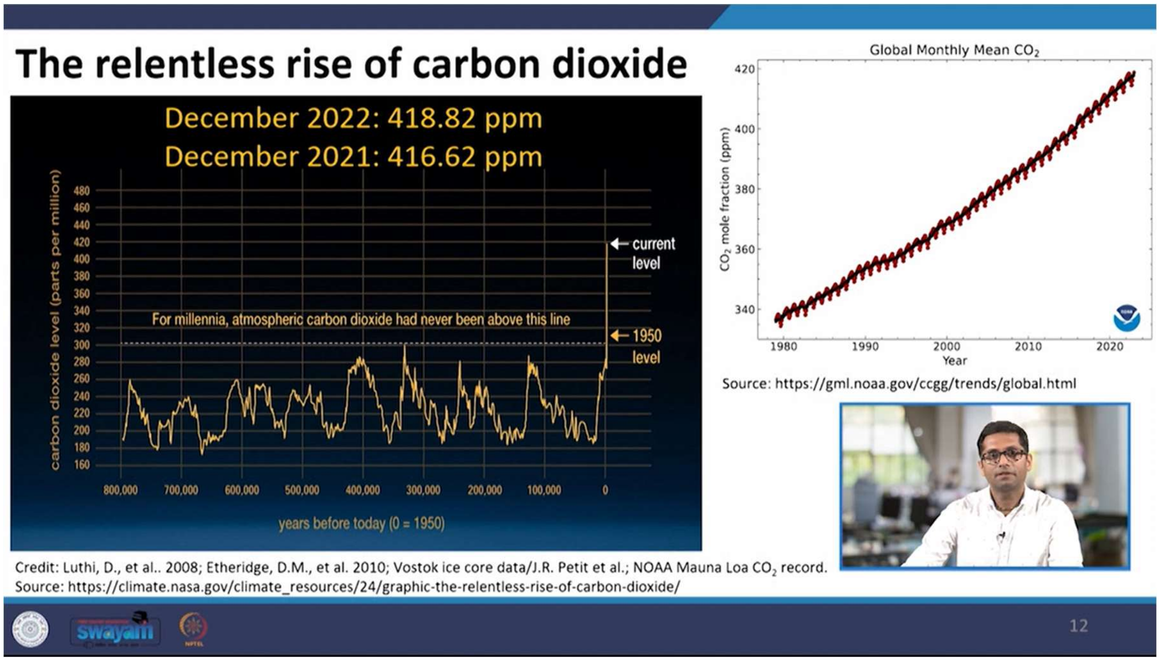
Sustainable Energy - without the hot air, David JC MacKay, UIT Cambridge, England, version 3.5.2, November 03, 2008

We can also see the validation of these numbers so if I look at the CO2 concentration for the last 1000 years or so this is how the concentration looks like. So the earlier the graph that we have seen on the left hand side shows you the concentration of the air in the bubbles that have been trapped in the polar regions. What you see in the blue is the CO2 measurement that has been taken place taking at the an observatory at Mauna Loa in Hawaii and we see that the CO2 concentration has been more or less constant for the last 1000 years but there was something that happened in the year 1769 and after that there has been an exponential rise in the CO2. Most of you must have guessed it right this year 1769 was the year when James Watt discovered the steam engine and that is what catalyzed the industrial revolution. Industrial revolution meant large scale use of the energy usage to have industrial processes, use of coal, fossil fuels and there has been a great increase in the CO2 since then.



Sustainable Energy - without the hot air, David JC MacKay, UIT Cambridge, England, version 3.5.2, November 03, 2008

We can also correlate this with the increase in the consumption of the CO2 of the fossil fuels. We can see that on the graph on the bottom that this is how the consumption of coal which was spearheaded by UK in the start and then the different countries of the world started with the discovery of the steam engine and it is nicely correlated with the increase of CO2. So the increase in the CO2 of the atmosphere has been in line with the increase in the use of fossil fuels which has been increasing exponentially since the onset of the industrial revolution.



The relentless rise of carbon dioxide

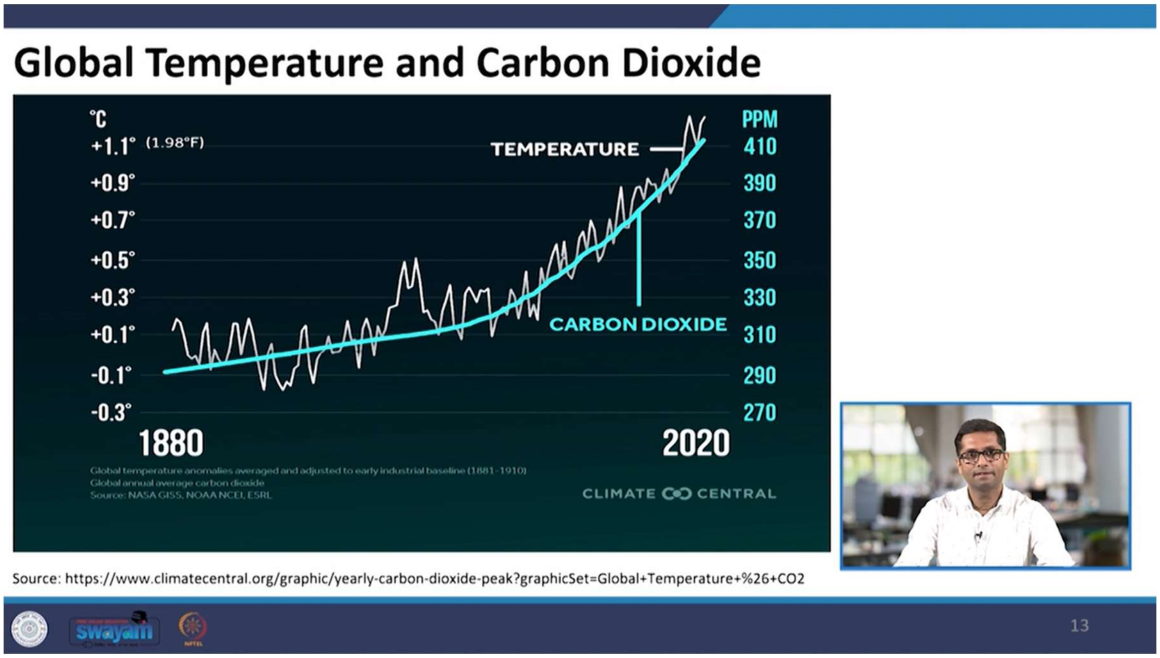
December 2022: 418.82 ppm

December 2021: 416.62 ppm

Source: https://gml.noaa.gov/ccgg/trends/global.html

Credit: Luthi, D., et al.. 2008; Etheridge, D.M., et al. 2010; Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record.
Source: https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide/

Now this CO2 that was produced again has been questioned like people have been saying that the CO2 levels have been going up and down in the last million years or so. So even if you look at that of course there have been fluctuations in the level of CO2 but it has not never risen to the levels that we are currently facing. There was an equilibrium around which the fluctuations were taking place for the few million years. These fluctuations were due to different reasons like maybe precision of the earth and the seasonal changes but present increase in the CO2 which is constantly rising has an anthropogenic angle to it which is basically the consumption of fossil fuels. And this consumption of fossil fuels and the subsequent release of CO2 is again leading to the rise in temperature which again are very nicely correlated.

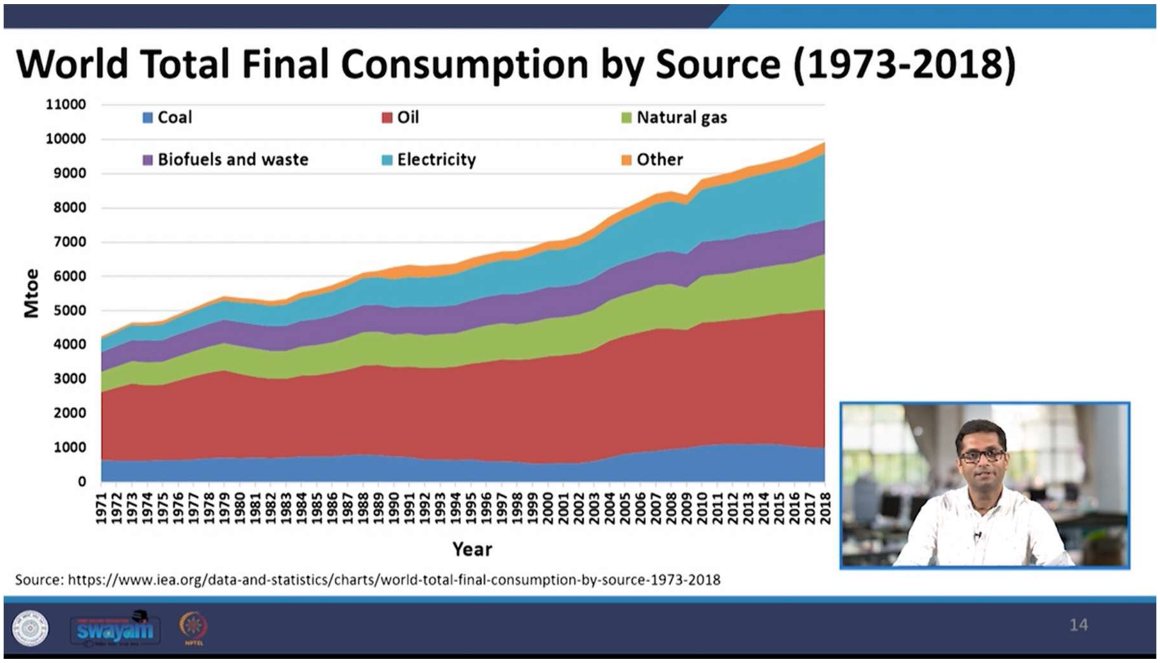


Global Temperature and Carbon Dioxide

Global temperature anomalies averaged and adjusted to early industrial baseline (1881-1910)
Global annual average carbon dioxide
Source: NASA GISS, NOAA NCEI, ESRL

Source: https://www.climatecentral.org/graphic/yearly-carbon-dioxide-peak?graphicSet=Global+Temperature+%26+CO2

The increase in CO2 is leading to rise in temperature. We can see how the mean temperature of the globe has been rising and it has risen by almost 1 degree Celsius since the industrial revolution. So this energy consumption is very closely linked or the energy use is closely linked to the release of energy and this energy is linked to the release of CO2 which can have drastic consequences for the earth in the future.

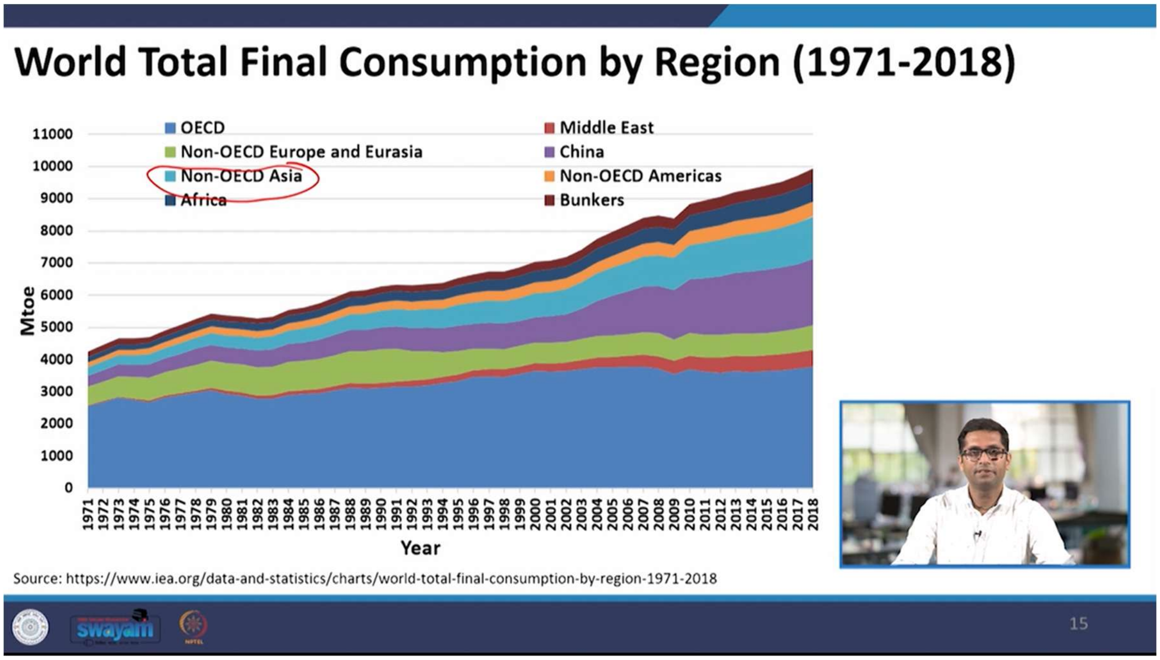


World Total Final Consumption by Source (1973-2018)

Source: https://www.iea.org/data-and-statistics/charts/world-total-final-consumption-by-source-1973-2018

And again the last point that I would want to make the energy consumption is not constant. It has been rising drastically. So if I look at the different fossil fuels we can see that oil consumes on majority of the energy consumption and this is why we have also assumed that majority of the energy was to come from oil.

Again we had done a simple calculation in which we have assumed all the energy was to come from oil which is not the case. We also have coal, we have the natural gas, all the three being the major constituents of energy production. So if we take all the three together they would be more than 80%. In this graph in the electricity section we would have much of the electricity coming from fossil fuels as well. And as we can see it has been steadily rising and this will rise at even a faster pace for a country like India where much of the population is energy poor. Much of the population is utilizing the energy which is much less than the world average.



World Total Final Consumption by Region (1971-2018)

Source: https://www.iea.org/data-and-statistics/charts/world-total-final-consumption-by-region-1971-2018

And again we can see how the different regions have been behaving. We can see much of the rise in the future to be expected in the known OECD Asia of which India is also a part. So just to recapitulate we did a simple calculation in which we tried to understand the consequences of the energy use of humans and how much time will it take to double the amount of CO2 if we continue with the same amount of energy that is today and if we keep on using the energy from fossil fuels.

So this was to make us understand that this is a serious issue. Again this was a simplistic calculation and I would like to attribute Professor Pratap Haridas who did this calculation and I have adopted this calculation from his lectures. And from today's results we make two conclusions that there could be significant effects of the energy consumption of humans and this effect could be realized by the human race in a pretty short amount of time. Thank you.