**Energy Resources, Economics, and Sustainability**


**Prof. Pratham Arora**

**Hydro and Renewable Energy Department**

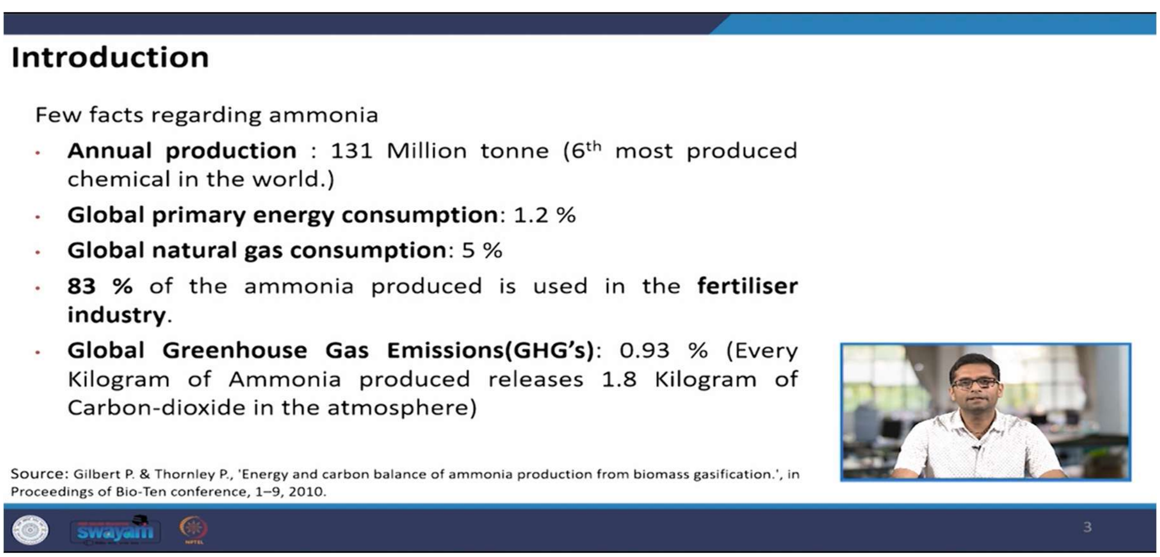
**Indian Institute of Technology Roorkee, Roorkee, India**


**Week – 08**

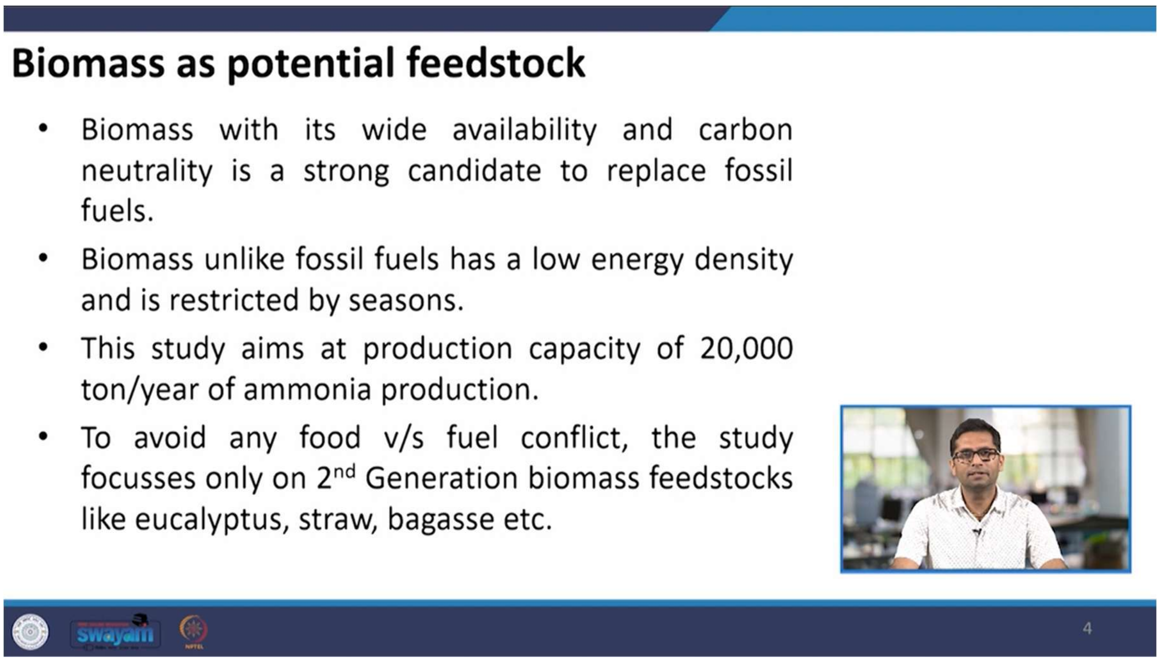
**Lecture – 05**

**Lecture 41 - Case Studies-I**

Hello everyone. Welcome back to the course Energy Resources, Economics and Sustainability. In the past few classes, we have been studying about the basics of life cycle assessment and in the last class, you got an experience how LCA is performed in real life cases using one of the commercial softwares that is Simapro. With this, we have tried to encapsulate the basic concepts of life cycle assessment along with how would you do that in real life. So, in today's class, we will try to spend some time on the different case studies where we have utilized the tools such as life cycle assessment, economic analysis that you have studied in the earlier classes to real life cases to generate some good results which we can help in which we can use to make decisions which can help the policy makers to form future policies and which can also help people in general to get various insights. So what I will take you through a few of the case studies that we ourselves have performed during different time spans and what were the prospective results that we got. So the first case study that we would focus on is the production of ammonia from biomass. So why ammonia? The first question might arise. Now ammonia is one of the largest chemicals that is manufactured across the world and where it is utilized?



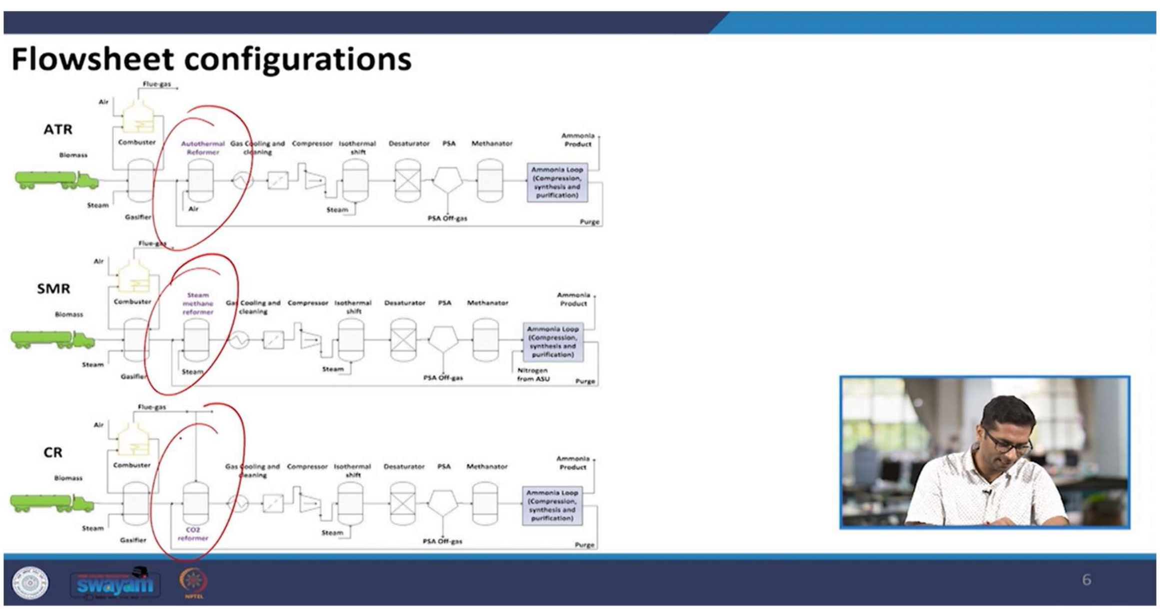
Well, a lot of the fertilizer industry, the urea or the diammonium phosphate that we use for the farming purposes is using ammonia as a precursor and this ammonia is also the biggest user of the hydrogen that is produced. So now everyone is talking about hydrogen economy coming for the future. One of the major applications for the hydrogen is this ammonia industry and further, a majority of this hydrogen that is used for production of ammonia is coming from natural gas. So not to say that for every kg of ammonia produced we are venting out 1.8 kgs of CO2 into the atmosphere. So it is a pretty intensive, CO2 intensive process and we wanted to see if there could be a greener pathway which utilizes biomass.



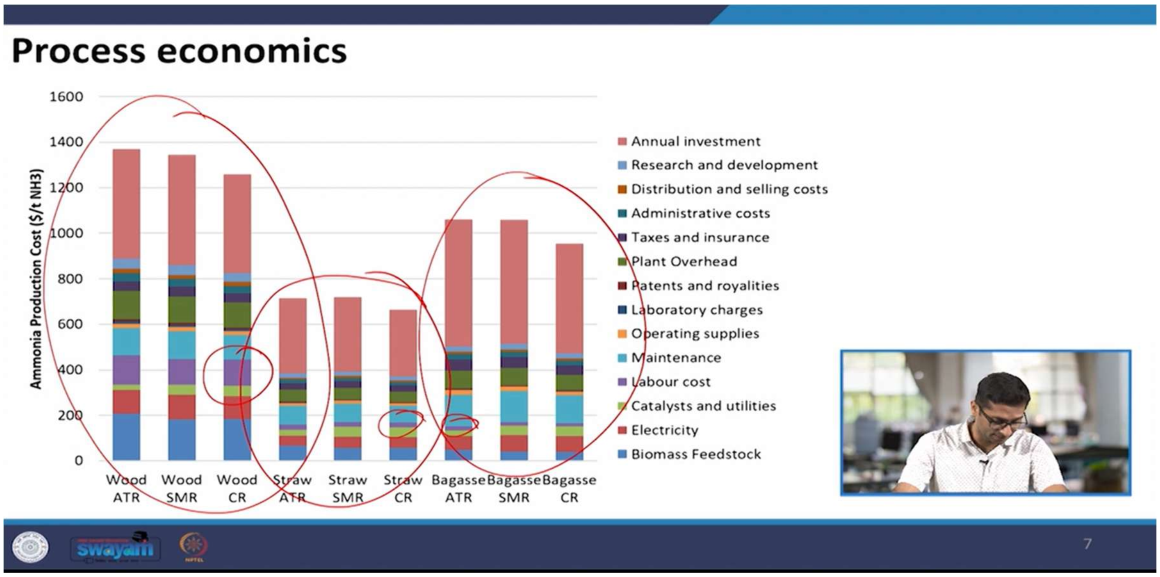

Now biomass if I am using as a potential feedstock, of course it appears to be greener but since the production is quite spread out, we cannot have bigger scale plants.

So we have to reduce the scale of conventional ammonia plant to the scale of around 2000 tonnes per day but that would not be possible for biomass. Further, biomass also have the food versus fuel conflict. So in this study we are using only the biomass feedstocks, we don't have any food value. Some energy crops like eucalyptus, farm waste like straw or industry waste like bagasse which is coming out from the sugarcane industry and we plan to do an economic analysis as well as LCA to see how does this process figure out as compared to the conventional process and can there be different configurations of these processes. And also we try to understand that if the similar process was employed in different countries would there be different results.

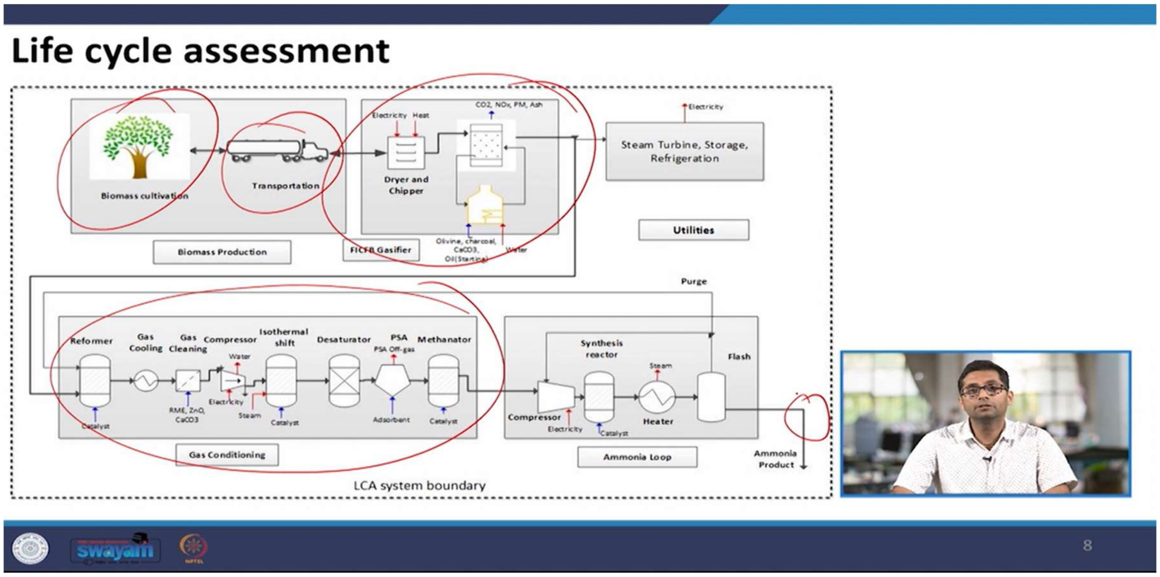

So what we did, we chose three different countries and three different feedstocks. So of course we had India in here. So in India we chose the straw. Now straw is a big problem during the months of October and November specifically in the northern part of the country where it is burned and causes major environmental issues. Then there is another feedstock that is eucalyptus trees in Australia which are grown on purpose to do away the problem of dry land salinity and then we selected bagasse in Brazil. Brazil is one of the major producers of sugarcane and not to say they have a huge production of bagasse as well. So these three feedstocks were available in plenty in these three countries and we wanted to see if they were used for the production of ammonia how would they fare in economic and environmental terms.



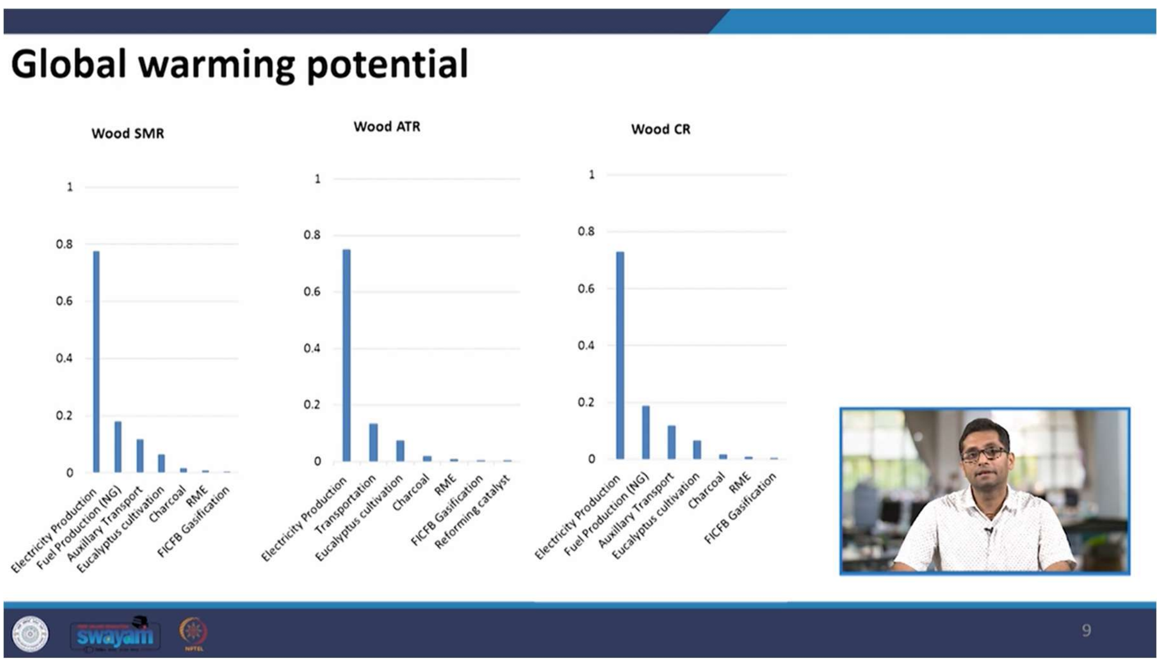
Further we also tried to do three different flow sheet configurations or process configuration on how the hydrogen which is a precursor for ammonia would be produced from biomass. I would not be going into detail but to say like we are gasifying biomass which would produce a syngas that is rich in hydrogen and this gas had to be then conditioned. So the processes differed in how those conditioning was occurring in terms of different kinds of reformers. Again I would not be spending much time on it but like three different process configurations.



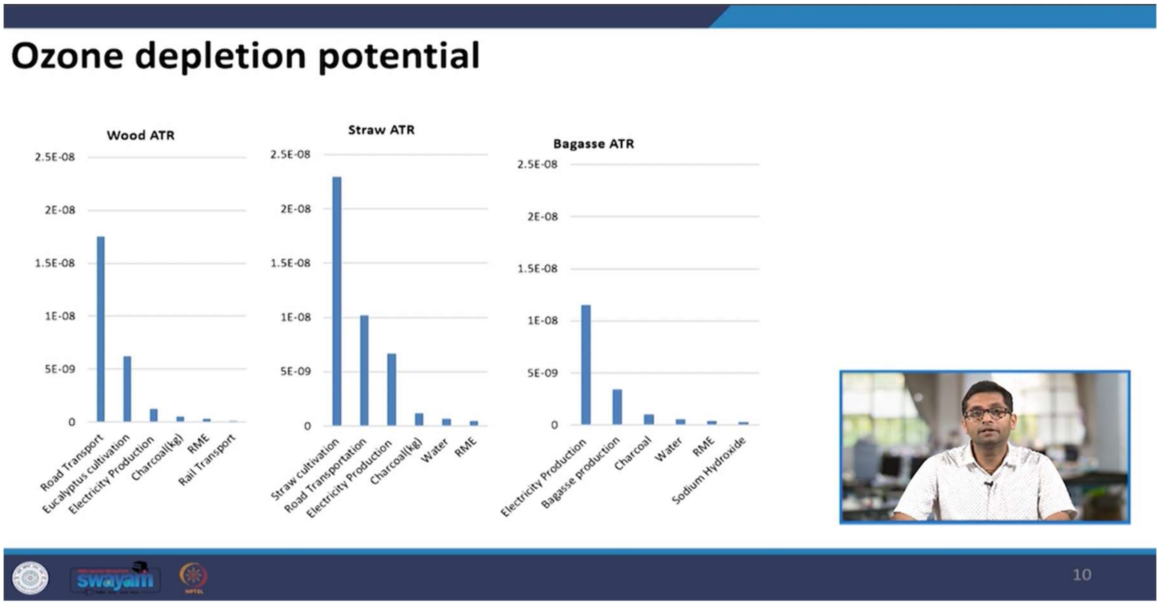

So we did this and we did an economic analysis as we have seen in the earlier classes and economic analysis basically helped provide the data like how the economic value of the ammonia that is produced. So if I talk about the ammonia production cost this would be very different for different countries so it came out to be the least in India. So these are the straw cases in India for the three processes. Somewhat better in Brazil and then the most expensive came in for the case of Australia that is using mode or eucalyptus feedstock. If I talk about the current market value of conventional ammonia that is coming from natural gas feedstock that is nearly around 500 dollars per ton. So India was quite near to that case and of course we can see there are different parameters causing different kinds of impacts. Electricity you can see is quite cheap in India whereas if you see the biomass feedstock is somewhat expensive as compared to Brazil. Then if I talk about the labour cost this is somewhat lesser in India and Brazil but it could be quite high in a country like Australia. So it helped us highlight like there could be different aspects that could affect the economics for the same type of process in different countries. Just to remind you we were using similar kind of scales for these technologies the only difference was the feedstock and of course that differed the quantum of hydrogen and ultimately ammonia that could be derived that was a bit different. But it gave us some meaningful insights like how different countries would fear in terms of economic analysis.



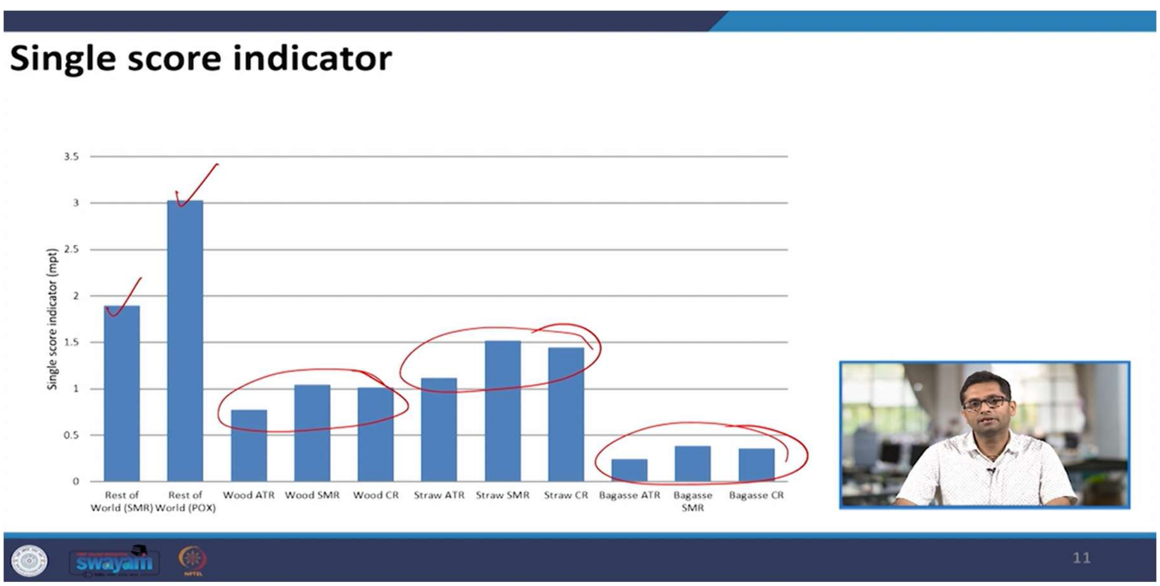

Taking the study further we also did the LCA for the complete like cradle to grave sorry cradle to gate process for the ammonia production which had the biomass cultivation, transportation, the conversion using gasification, gas conditioning and finally ammonia is produced at the gate. Further this would also use a lot of utilities in terms of steam production, refrigeration and that whole was taken into account as well.



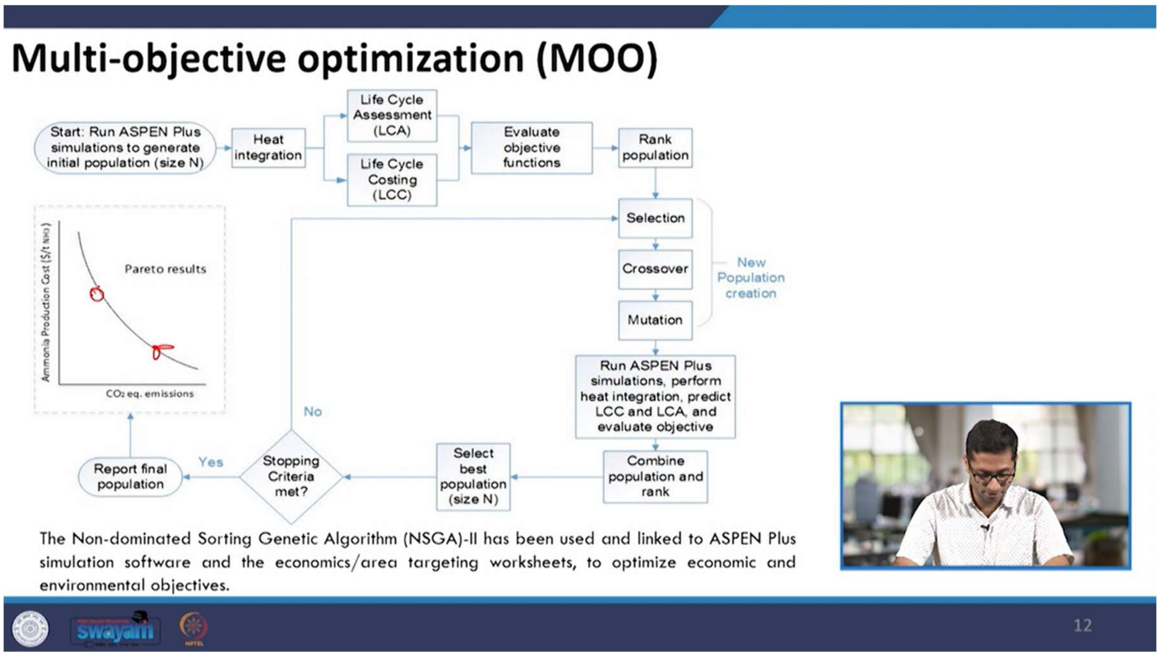

And we got the results in terms of global warming potential in which we can see that all the 3 processes had somewhat of a different but we can different CO2 equivalent emissions per kg of ammonia production and we can also see where the emissions are coming from. So the impact of the emission was basically from the input electricity that we would have to take for running the compressors.




Again if you do an analysis for the 3 different countries we can see there could be different places where the impact could be coming. So if I talk about ozone depletion potential in the case of Australia road transportation was a leading cause of ozone depletion whereas in India it was a straw cultivation and if I talk about Brazil it was the electricity production. So there could be different reasons that could be causing different impacts in different countries. It all depends on the like how the different like what are the inventories, how they have been formed, what are the causing impacts, how the electricity is produced in that particular country what insecticides or pesticides are being used for the cultivation of biomass that makes a lot of difference.

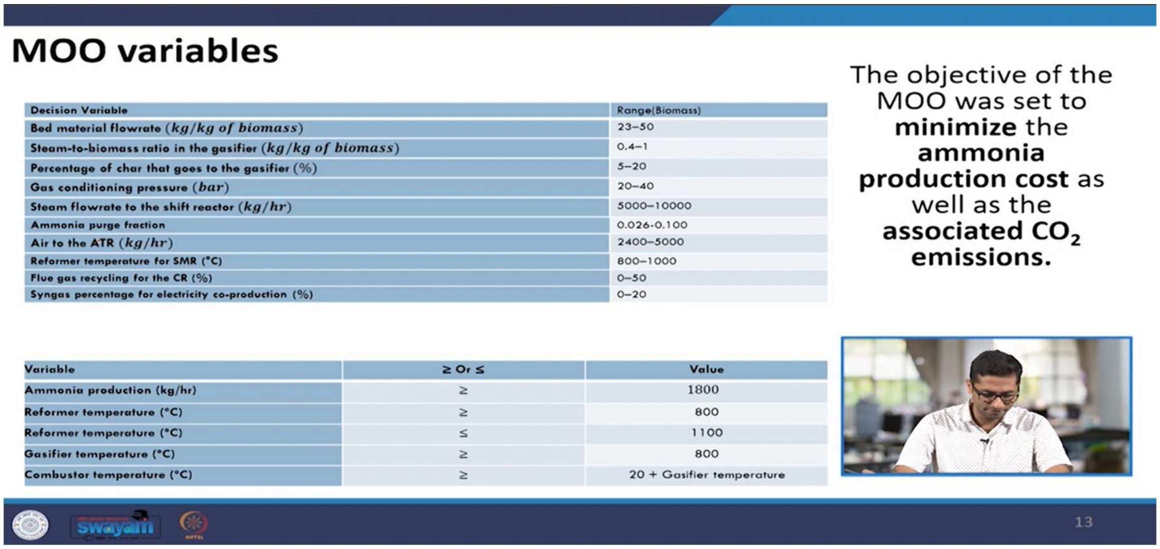



And we can also see if I talk about the single score or the single end point indicator that we have seen. So the first one are the end point indicators for conventional ammonia produced and whereas the remaining ones are for the 3 processes for the 3 countries or the line processes. So we can see the bagasse production or bagasse to ammonia process in Brazil came out to be the best one. Straw to ammonia was not so good and Australia one was somewhat better. So even the end point we can see that there was a considerable reduction in all the emissions but if I talk about the individual emissions there might not be that much reduction.




And we took the study a step further where we are also doing a multi-objective optimization. So in multi-objective optimization I am using genetic algorithms where I am changing the process parameters for the running of the plant and trying to analyze the output and the output was then dictating the LCA and the TEA. And this calculation goes on till I get a smooth curve like this which tries to optimize both the economics and the environmental emissions. So in this case I have just taken the CO2 equivalent emissions whereas I can also work with single point indicators but for the sake of easiness I have just adopted CO2 equivalent emissions and just to mention that all the points on this Pareto front are considered to be optimal. So there is not one point that I can say could be better together.

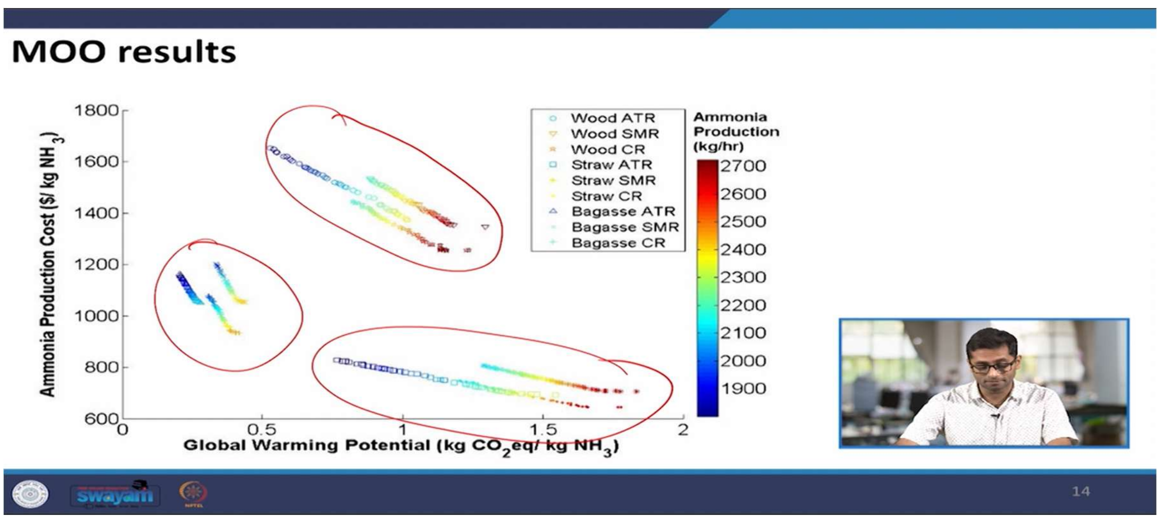
So if there is we have one point here that has like a sort of CO2 equivalent and ammonia production course and I compare with another point say above here. So the other point might have lesser emissions but it again has a greater cost. So it is for us to see the tradeoffs. So all the points are equally good from the point of policy maker and then it he or she has to choose the best operating point for this particular operation.




| Decision Variable | Range(Biomass) |
|---|---|
| Bed material flowrate $(kg/kg\ of\ biomass)$ | 23–50 |
| Steam-to-biomass ratio in the gasifier $(kg/kg\ of\ biomass)$ | 0.4–1 |
| Percentage of char that goes to the gasifier (%) | 5–20 |
| Gas conditioning pressure $(bar)$ | 20–40 |
| Steam flowrate to the shift reactor $(kg/hr)$ | 5000–10000 |
| Ammonia purge fraction | 0.026-0.100 |
| Air to the ATR $(kg/hr)$ | 2400–5000 |
| Reformer temperature for SMR (°C) | 800–1000 |
| Flue gas recycling for the CR (%) | 0–50 |
| Syngas percentage for electricity co-production (%) | 0–20 |

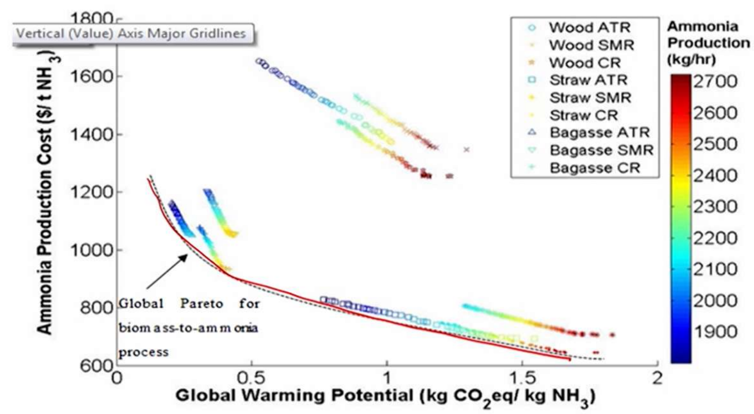
| Variable | ≥ Or ≤ | Value |
|---|---|---|
| Ammonia production (kg/hr) | ≥ | 1800 |
| Reformer temperature (°C) | ≥ | 800 |
| Reformer temperature (°C) | ≤ | 1100 |
| Gasifier temperature (°C) | ≥ | 800 |
| Combustor temperature (°C) | ≥ | 20 + Gasifier temperature |

So I tried to vary a lot of features in this. So these are all technical features with respect to the plant operation in respect to the temperatures, temperatures and other parameters that dictate the flow patterns and I would not be discussing that but these are some of the parameters that were decided and some of the constraints that were put in.




And the final results that we got was Pareto in this front. So on the x axis what you have is the carbon footprint in terms of kgs of CO2 equivalent per kg of ammonia that is produced and on the y axis you have the ammonia production cost in terms of dollars per kg of ammonia and we have the results for the 3 cases in the 3 countries. So if I talk about India, so these are the results for India. These are the results for Brazil and finally we have the results for Australia. So we can see both in terms of economics as well as in terms of emissions the 3 countries would fare very differently and this has to be do with the different inventories that are there and even the slopes of the Pareto fronts could be very different. So if I would want to produce ammonia cheaply and CO2 reduction is not much of a concern probably I will go for India. If I am going want to go for maximum amount of CO2 reduction probably I would want to set up a facility in Brazil where like I can have massive CO2 footprint reduction but economics I would have to pay in a fine. Again Australia does not have the characteristics of either one of its not good in economics and somewhere middle in terms of global warming potential.

## MOO results



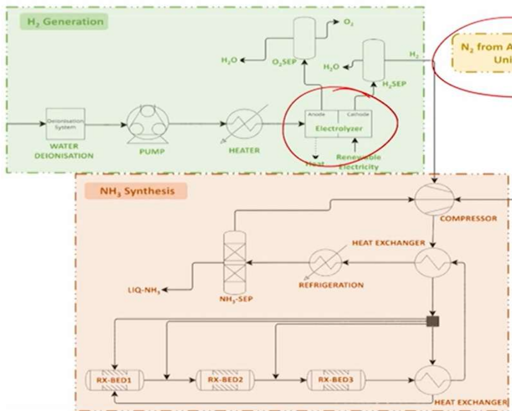



Further such kind of analysis can also help us set a global Pareto in which I can have a Pareto like this which helps me dictate if I want to set up a plant somewhere in the world with so and so CO2 footprint and so and so cost probably I can choose a country based upon this. So if CO2 footprint reduction is a concern for me maybe I will go for a plant setting up in Brazil if economics is much of a concern probably India would be a better choice. So this is how we can benefit from doing a techno-economic analysis or economic analysis and couple it with LCA to get some meaningful insights like how the different plants, different process configurations would vary for different countries for the same process. So these kinds of analysis are now used to see or estimate the sustainability of the processes or energy processes that might be used in the future.

## Case Study II: Economic and Emission Analysis of Decentralized Green Ammonia Production Plant

Further given the recent push on green hydrogen through electrolyzers we also did a recent study where we try to estimate the economic and emission analysis for again decentralized green ammonia production but through water splitting or electrolysis route.

## Flow Process Diagram




**Major Equipment**

**$N_2$ Production**
1. ASU

**$H_2$ Production**
2. Deionisation system
3. Pump
4. Heater
5. PEMe

**$NH_3$ Synthesis**
6. Reactor (Bed 1, 2, & 3)
7. Compressor
8 Ref - Compressor
9. Heat Exchangers 1
10. $NH_3$ Separator

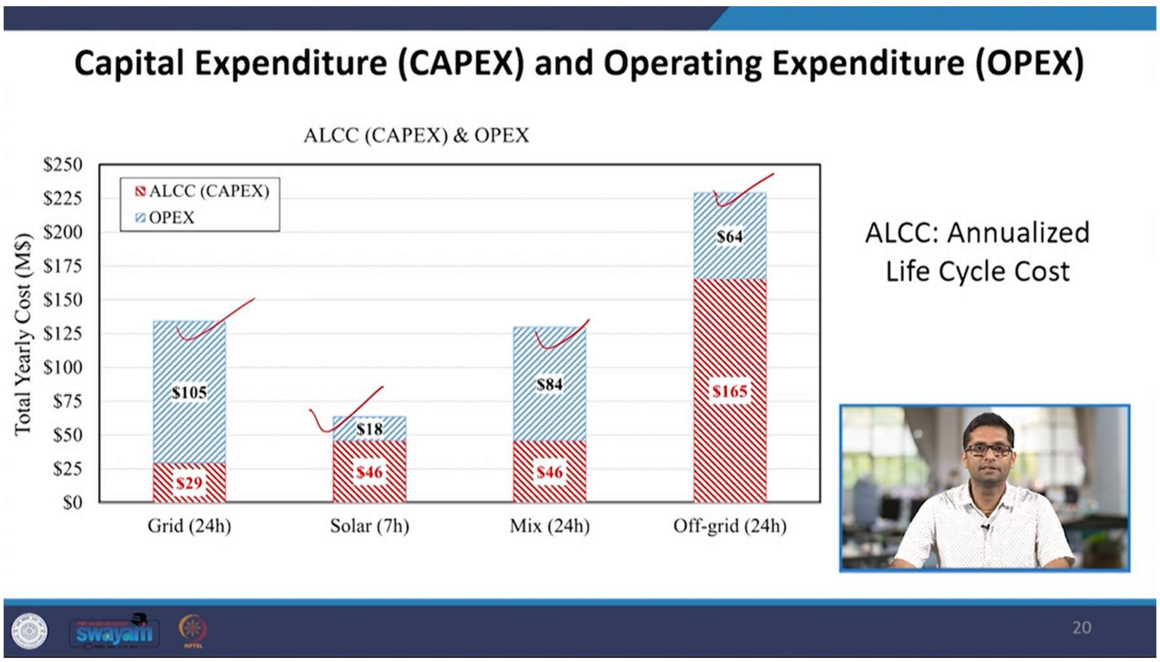


So what is happening in here is we have PEM electrolyzer which is polymer electrolyte membrane electrolyzer which is considered to be like a leading technology as of now which is expected to come up at a good rate in the future and that would be used for production of hydrogen. We can get nitrogen from a simple air separation unit they get and they combine together enter a conventional Haber-Bosch process which is working at a slightly lower pressures and producing ammonia or so called green ammonia and we wanted to analyze how this ammonia what is the economics and the emission trajectories of this ammonia production that is coming from a green hydrogen route.

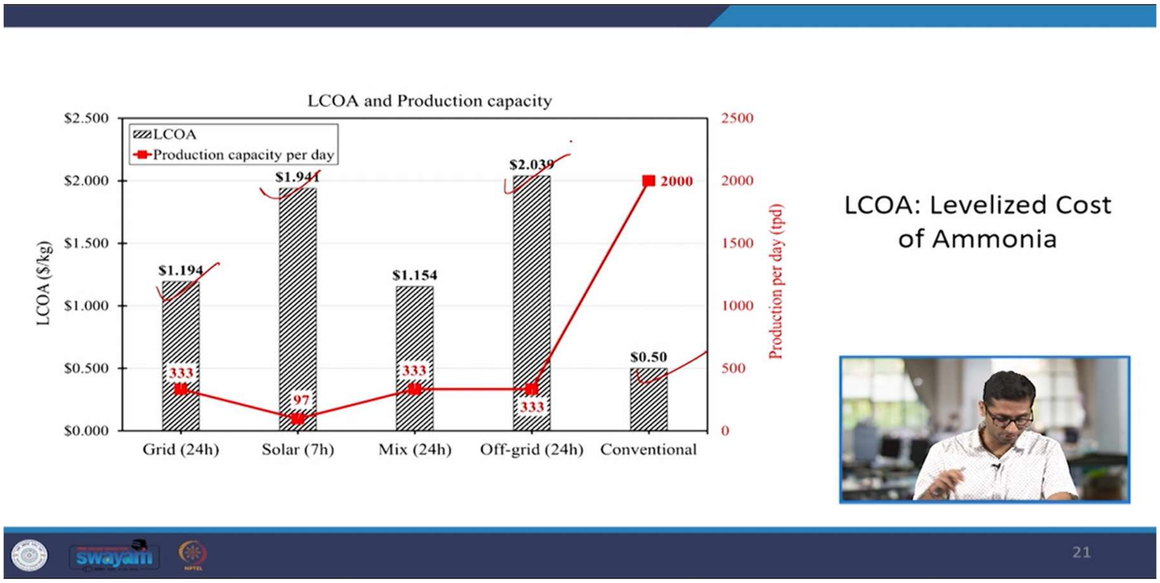
## Scenarios

| Energy Supply from | Operating hours per day | Energy supply distribution |
|---|---|---|
| GRID | 24 hours | |
| Dedicated Solar Plant | 7 hours | |
| MIXED-GRID | 24 hours | 7h from Solar & 17h from Grid |
| OFF-GRID Solar Plant | 24 hours | 7h from direct BES system ch dedicated sola |

So wherein we took four different scenarios. So in the first scenario we have the electricity that is used for running the electrolyzers. So electrolyzers I believe all of you understand intakes electricity and uses this electricity to break down water molecule into oxygen and hydrogen. So this electricity can come from different sources it can come from grid. So the first option was that the electricity will be coming from grid and India the grid is primarily based on coal so it has somewhat of a higher CO2 footprint. I wanted to compare that with solar a solar plant but solar plant would be working only during the day in the absence of any batteries. So we would have the operation hours reduced in here but will be operating the plant only for 7 hours a day. Then there could be a third option where I am running the plant for 7 hours using solar and for the remaining 17 hours using grid. And then there could be a fourth option where I am having a solar plant and along with it comes in a good battery backup that can charge the batteries for the remaining 17 hours of operation and that was my fourth option.

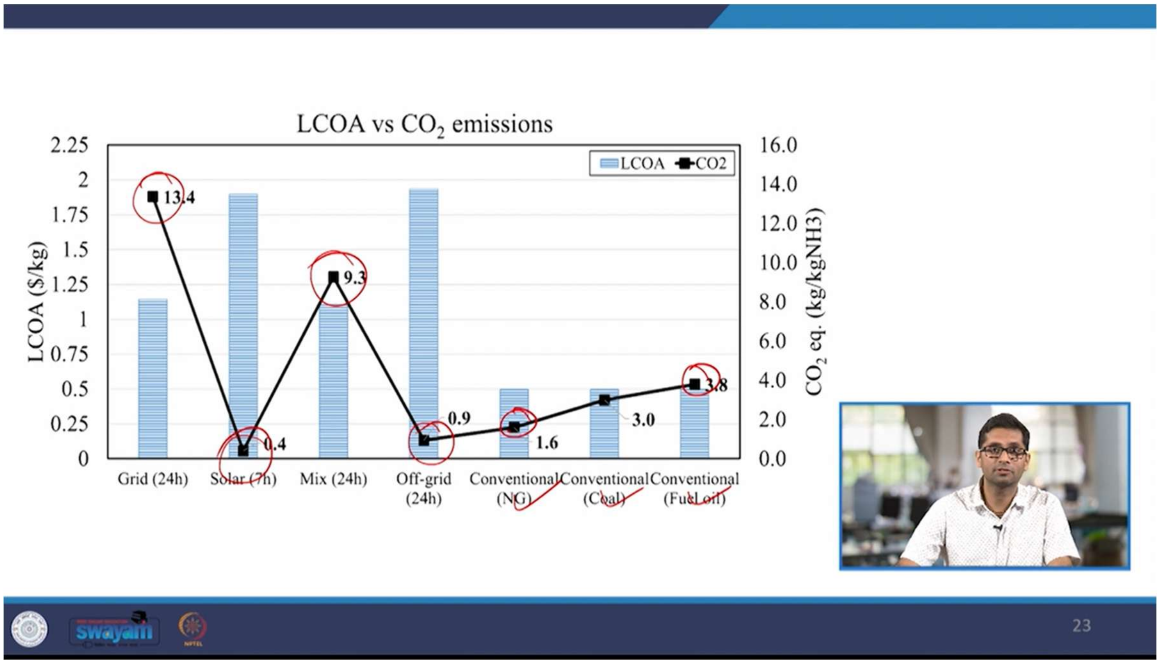



So if I compare the yearly cost which is an addition of the CAPEX as well as the OPEX we would see that the yearly cost comes out to be the least for the solar. One reason is because we are operating for the least amount of time we are just operating for 7 hours a day as compared to other ones. For the 24 hour operations it is almost similar whereas in the off grid and the cost is increasing a bit a lot because of the batteries we need battery infrastructure and these batteries are quite costly. The installation and the operation are quite costly and the typical efficiency would vary from 80 to 90% wherein we are also having the electricity losses.



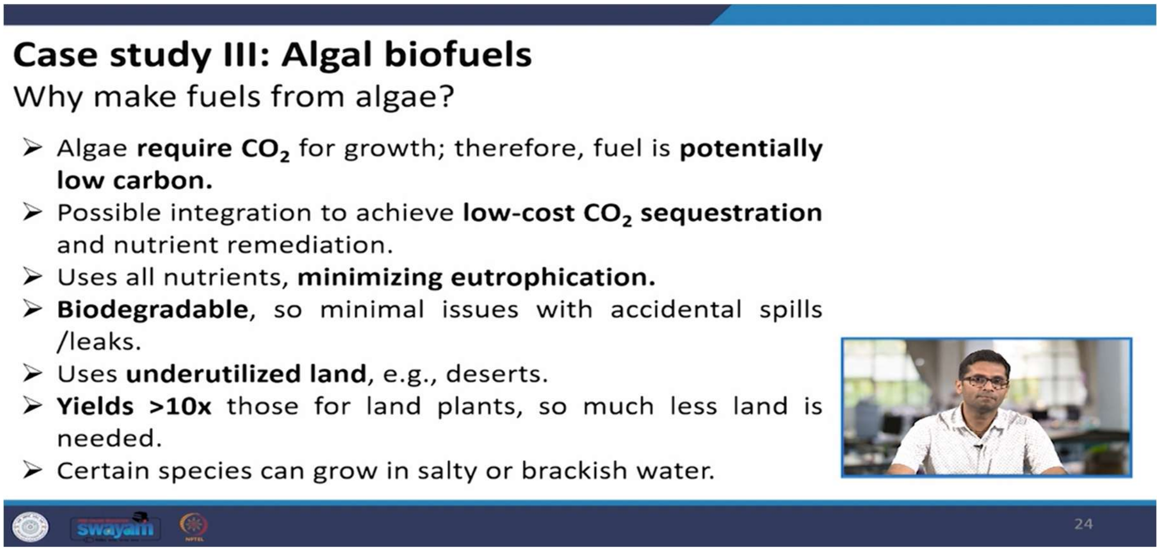

We can also compare the levelized cost of ammonia production. So if I talk about the cost of ammonia production the conventional ammonia is normally available at around 0.5 dollars per kg or 500 dollars per ton that is the normal price and if I go with the grid or the mix one I can have a price of around 1.1 or almost 1.1 dollars per kg of ammonia and if I go just with the greener route which is the solar route it can be quite higher in terms of 1.9 and if I go with batteries plus solar it would be the highest in terms of 2 dollars per kg of ammonia.


Now this needs to be also coupled with like there could be significant revenue in here from oxygen generation. So when I am going with a route where I am using electrolyzer so one of the products from electrolysis will also be oxygen. So I also wanted to see if there is a revenue stream from oxygen if that was to be accounted in as well we can see the price comes out to be somewhat lower as compared to the original processes.

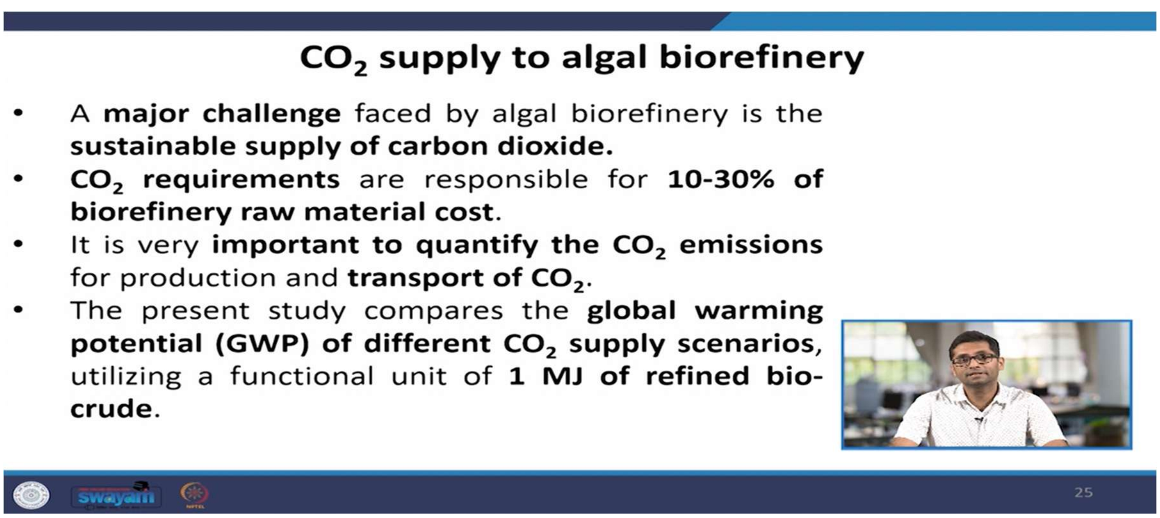



And this kind of study would also need to be coupled with an LCA so we did LCA of the whole process as well where we are showing the CO2 emissions as well. So we can see the CO2 emissions for the conventional process varies somewhere from 1.6 to 3.8 based upon what feedstock is used for the conventional process and normally it is natural gas which you see in here but we also have processes running on coal and fuel gas all the three sources being fossil based and if I would have to go with the cleaner process the electricity must come from renewable source and if I go with solar I have this CO2 impact coming to be almost one fourth of the conventional impact and almost half of what I would get from battery backed system. If I go with the grid based electricity either coupled with solar or not coupled with solar the impact is much higher in here so almost 6 to 7 times higher.

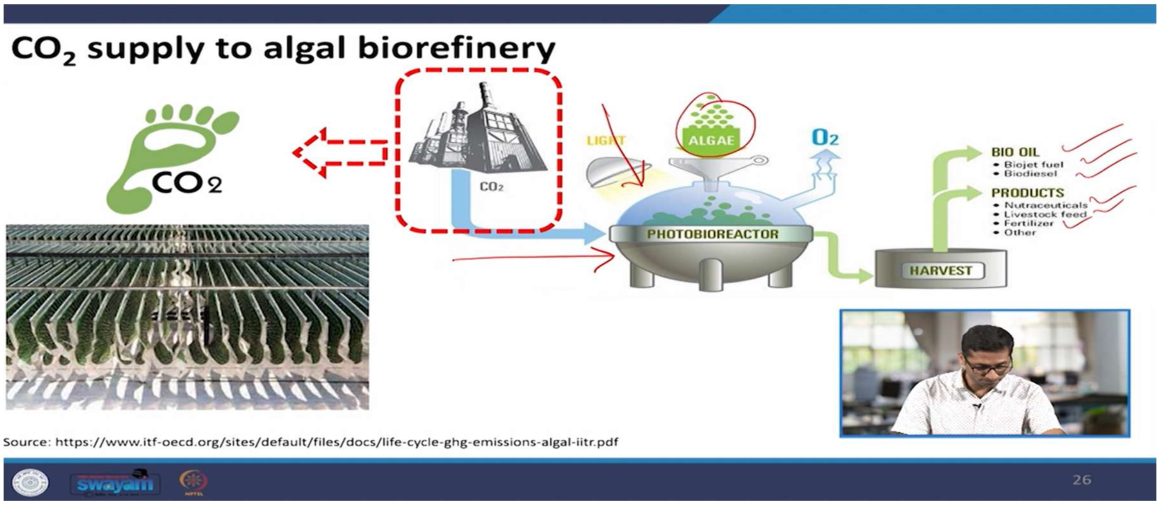
So if I am just going from hydrogen production from the grid leading to ammonia production probably it is not advisable from both the economic and emissions point of view. I can go for solar ammonia production but in that case I have significant emission reduction but the price that I am paying is also exorbitant. So these are the kinds of insights that you can get from the combination of economics as well as emission analysis through an LCA. You can compare the different kinds of processes how they compare for the different scenarios which process turns out to be better in terms of economics and are there other processes which would lead in terms of the CO2 emission reduction. We also need to understand that most of these impacts are potential of course there is no 100% surety and this is why we also need to do a sensitivity analysis what would be the impact results changing if there was a parameterization of certain parameter and try to understand the impact of those parameters on the final results.



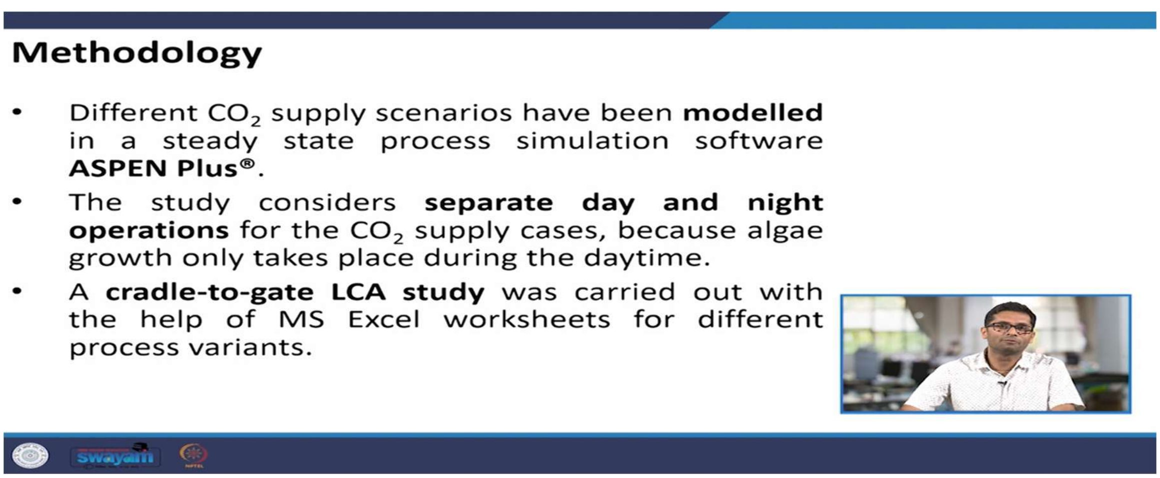

Let us also go through another case study wherein we are trying to understand algal biofuels. Now algae is a green slime that you see floating in the lakes and normally it is a problem in terms it causes eutrophication which we have tried to understand in the LCA lectures but algae is now being also proposed as a good medium for biofuel production because the photo synthetic efficiency of this algae is quite high. It is able to produce a good amount of biomass at a very fast rate but like any plant this would also require CO2 for its growth and this CO2 of course can come directly from the atmosphere but if we want to grow algae at a very fast rate normally we need a concentrated stream of CO2 that can come from in a power plant. Typical coal based power plant would have good amount of CO2 getting produced and there could be other sources as well. So we wanted to see how would the CO2 supply to this algae farm impact the final results.



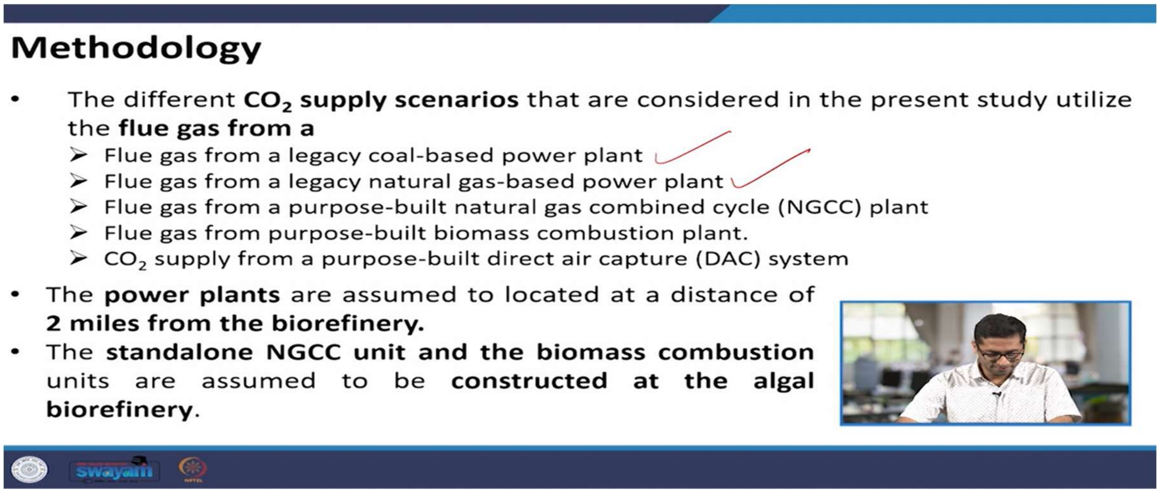

So now CO2 as I mentioned is a major problem because first thing is it has 10 to 30% of the cost plus it could also happen that like the transportation of the CO2 might have its own emission and this is what we try to quantify.



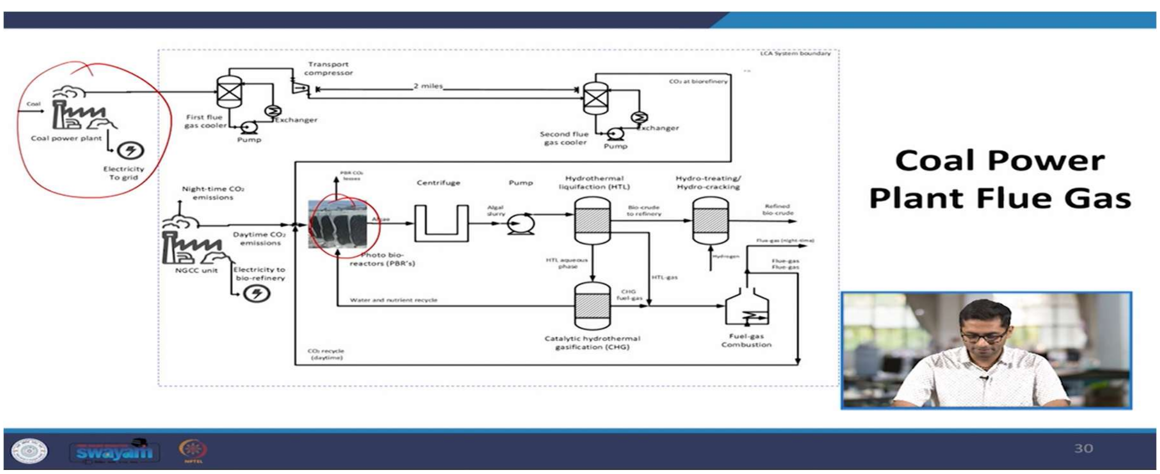

Let me try to show you with the help of figure so normally the algae would be grown in a farm like this so what you see here are photo bio reactors which would be growing concentrated algae and it uses sunlight as a source of energy then an initial algae inoculum and finally we would have the CO2 coming in and this CO2 of course can come from the atmosphere but a major source could also be from the power plants. And what do you do for the algae that is produced? You can produce different kinds of fuels maybe bio oil, bio jet fuel, biodiesel and also there could be some good products like nutraceuticals, fertilizers, livestock feed and what we wanted to analyze here is the impact of CO2 supply and the CO2 production. So the CO2 footprint of the CO2 supply itself that was an interesting study that we undertook.




So we made different CO2 supply scenarios in a software called Aspen Plus and there is a nice problem in this that the algae would only be growing during day and night sorry during the daytime whereas the CO2 production that would be happening in any power plant would be supplied day and night. So we had to reconcile the continuous supply of CO2 with somewhat of a like a diurnal growth of algae that was happening and for this we did a cradle to gate to get LCA.




And the sources of CO2 that we considered was a legacy coal based power plant that was already in place. We also wanted to compare the emissions with the natural gas based plant. Now natural gas based plant are somewhat more efficient but the CO2 that is generated is quite dilute in nature. Then we can also build a natural gas based plant which with the purpose solely to provide CO2 for the algae growth. Then the CO2 can also come from biomass combustion which is also producing electricity or as is becoming famous nowadays like we can also capture CO2 directly from the air using direct air capture systems and couple that with an algae growth field where the algae can be growing and we assume that there is a typical distance of 2 miles between the power plants and the bio refinery.



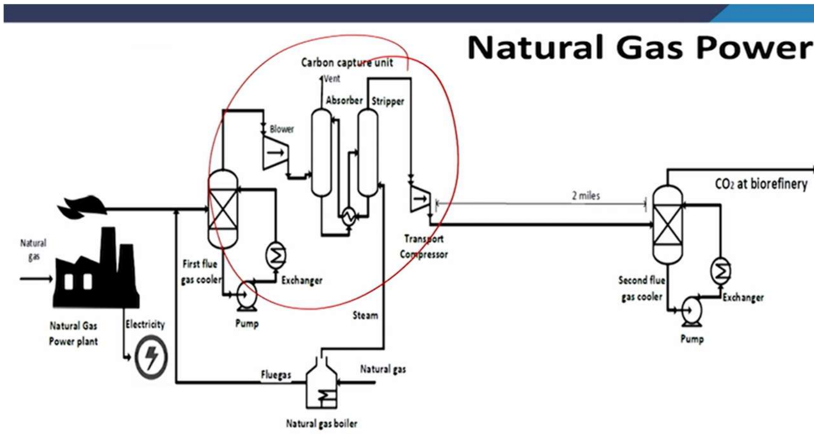

So this is what a typical plant would look like you would have the coal based power plant which would be producing electricity if supplying that to grid. The CO2 that is coming in would be scrubbed of any water or unwanted impurities, it would be compressed and then supplied to the plant where it again be compressed somewhat it goes to the algae field where it is subjected to a process called hydrothermal liquefaction which is a process that is occurring at around 200 bars of pressure and 350 degree Celsius which breaks down this algae into a sort of bio crude which could be used for production of diesel and gasoline range fuels using certain treatments. I would not again go into the details in here.

| | Natural gas-based power plant | Coal- based power plant |
|---|---|---|
| $N_2$ | 75.6 | 65.4 |
| $O_2$ | 11.6 | 4.1 |
| $H_2O$ | 8.5 | 18.6 |
| $CO_2$ | 4.3 | 11.9 |
| Temperature (°C) | 82 | 60 |

**Natural Gas Power Plant Flue Gas with Carbon Capture**

And we also have a difference in the gas or the flue gas that we get from natural gas based on a coal based power plant. So a typical coal based power plant would have CO2 emissions of the range of around 12% whereas they are quite low for natural gases power plant. So when I am talking about natural gas based plant flue gas it does not make sense to just transport 95% of the gas which is not any use. So normally you would be scrubbing the CO2, capturing the CO2 and then supplying the concentrated CO2 to the plant.

**Natural Gas Power Plant Flue Gas**

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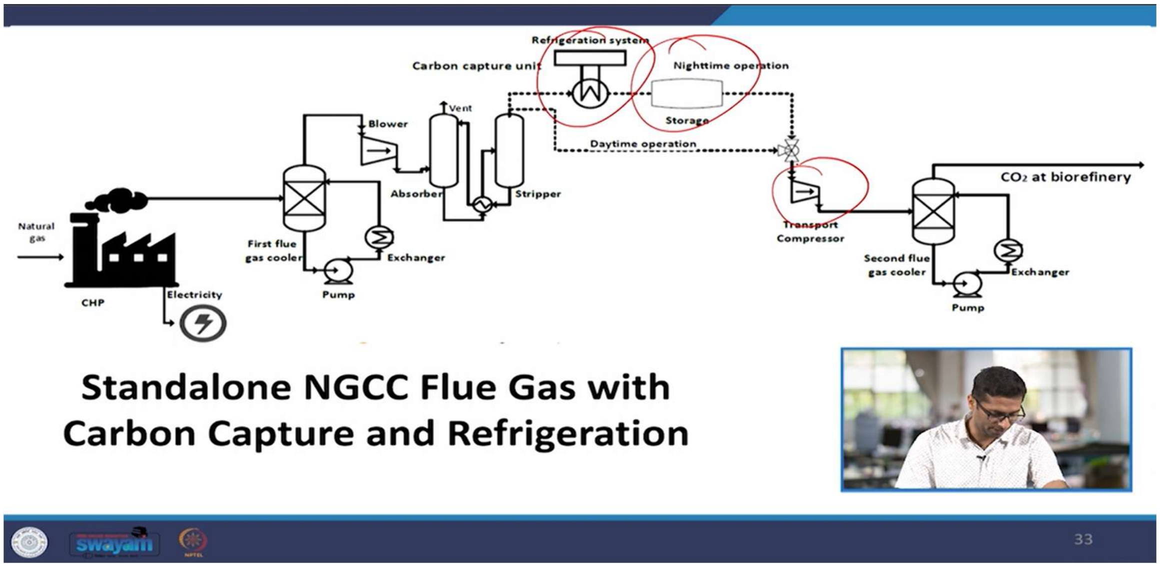
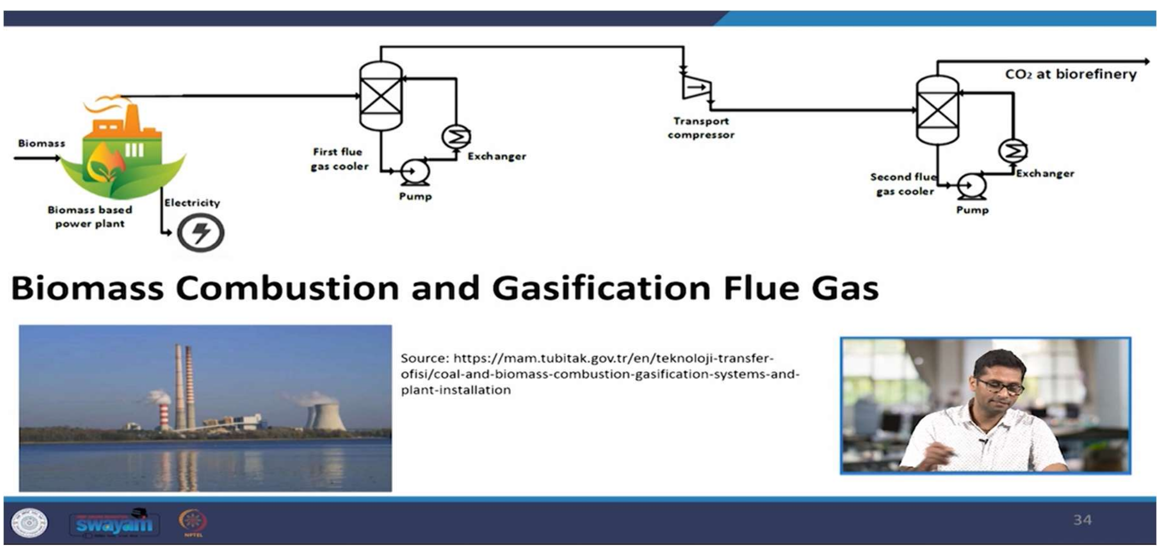
And this is what we did in the natural gas based supply scenario. You would have conventional amine based scrubbers which would be scrubbing in CO2, concentrated

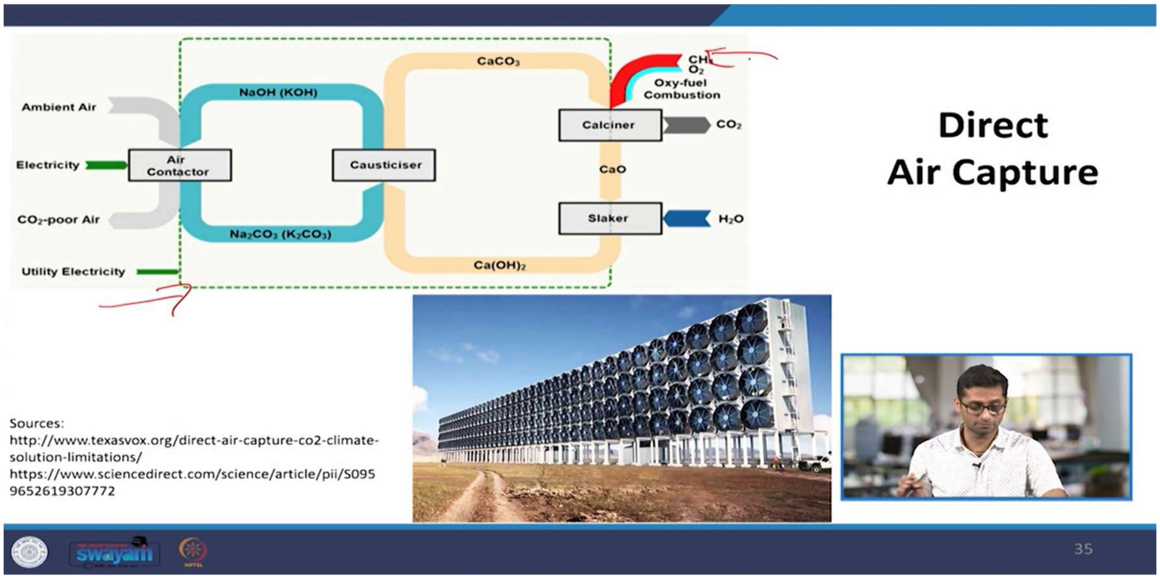
CO2 more than which having a concentration of more than 95% was supplied to the power plant.



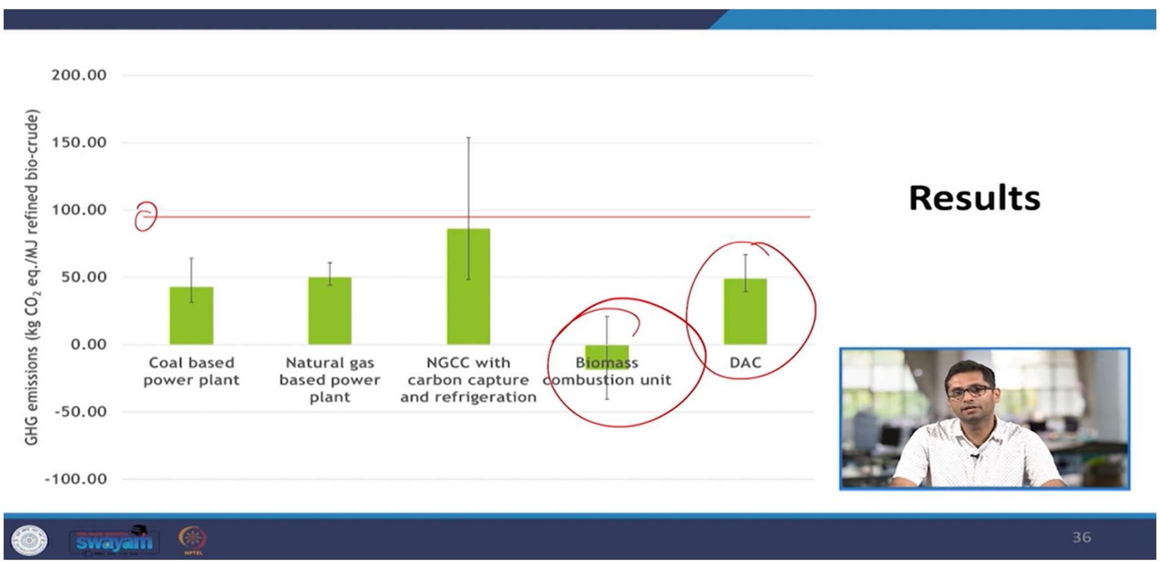

Then in the third case since I am building the power plant a natural gas based one specifically for supplying CO2 I might want to capture the CO2 that is being produced in the night time as well. So in this case I have a refrigeration system as well wherein it is capturing the CO2 that is being emitted during the night time, storing that and then supplying the whole CO2 and the daytime emission and the night time emission that was captured during the daytime for the operation of the biorefinery.




Another option could be can I produce even this CO2 from a greener source and in this case I am using biomass based system wherein I am using biomass combustion or gasification for this production of electricity and the flow gas or the CO2 emission that I am getting in here are again being scrubbed and transported to the biorefinery.




The last option that we took in was capturing of the CO2 directly from the air using the direct air capture systems. So again there are many technologies that are available for direct air capture. The technology that we focused was the one by Climeworks and it had two circuits of sodium hydroxide and calcium carbonate solutions being working together to capture CO2 directly from the air. But we also need to be careful that it also have electricity consumption that is going in further it has a calciner that would be using methane as a fuel. So all these emissions have to be accounted in for as well.




Finally, we did an LCA to see how would be the total footprint of the process in terms of like 1 mega joule of biocrude that is produced what would be the CO2 footprint of the process based upon how the CO2 is supplied and it varied quite significantly. So if I talk about the process where the CO2 is coming from coal based fire plant I can have an emission of around point sorry 45 kg of CO2 eq. per mega joule of refined biocrew that is produced and if I compare that with the conventional gasoline based fuel it is almost half. It somewhat increases for the natural gas based process because we are also using scrubbing. If I go with carbon capture and refrigeration it is becoming quite high and it almost becomes nearer or even extends somehow with the conventional fuels in some of the cases. In the biomass case I have this advantage that I am using the $CO_2$ that is generated from a biogenic source. So I am producing extra electricity as well and that is why you can see a negative emission in here. Further if I go with the DAC which is the direct air capture process and the emissions are somewhat better but still higher than a coal based power plant. So it is always better to get $CO_2$ from a coal based power plant than to build a DAC.

So even if you will be putting a good amount of money into building a plant but you won't get much of a benefit because the capturing, the electricity requirement, the methane requirement or the natural gas requirement of the DAC plant could be quite high. So these are some of the insights that you can get for a process which appears to be quite green in nature but based upon how you just supply one of the major feed stocks the results could be very different. So in this particular class we have tried to discuss some of the applications or case studies where we have seen the combined use of economics as well as LCA in making some decisions with respect to the processes that might be futuristic in nature. And we will continue this discussion in the future class as well where we are going to extend this discussion to two more processes which are India specific and try to understand the insights that we can get from the economic analysis and the LCA of such processes. With this we end today's class. Thank you.