Energy Resources, Economics, and Sustainability

Prof. Pratham Arora

Hydro and Renewable Energy Department

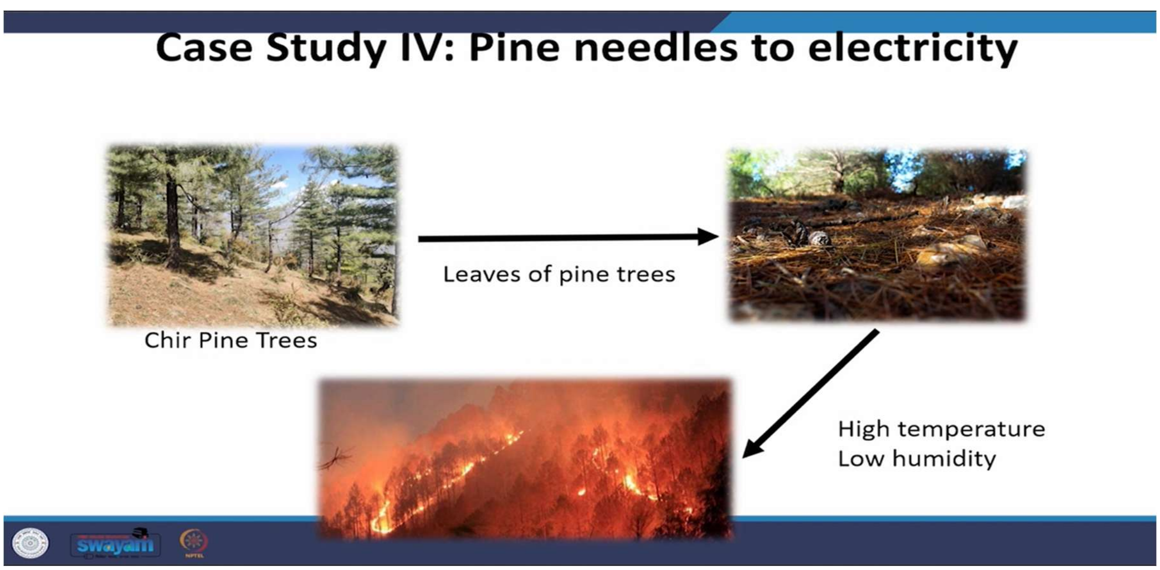
Indian Institute of Technology Roorkee, Roorkee, India

Week – 08

Lecture – 06

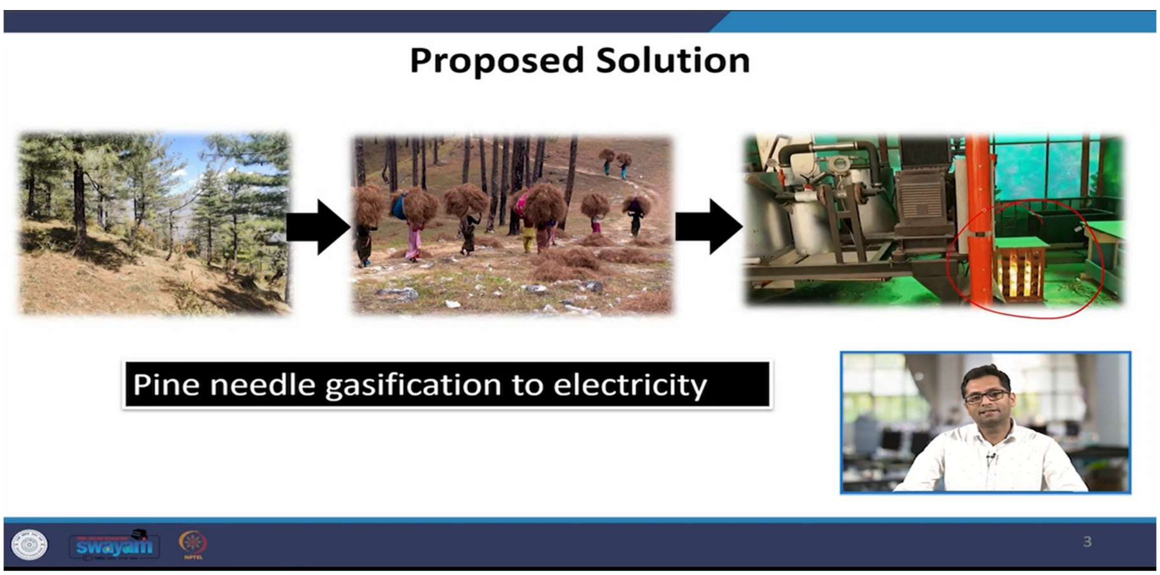
Lecture 42 - Case Studies-II

Hello everyone, welcome back to the course Energy Resources, Economics and Sustainability. So in continuation of the last class we will be discussing some more applications or case studies where we will see the application of both life cycle assessment and techno-economic analysis leading to making good decisions which can help the policy makers, decision makers take meaningful decisions for the future well-being of the society. In the past classes or in the course we have learned many tools which pertain to techno-economic analysis and life cycle assessment and this is what we will be utilizing. So one case study that we will be considering is that pertains to the northern part of the country specifically the Himalayas.

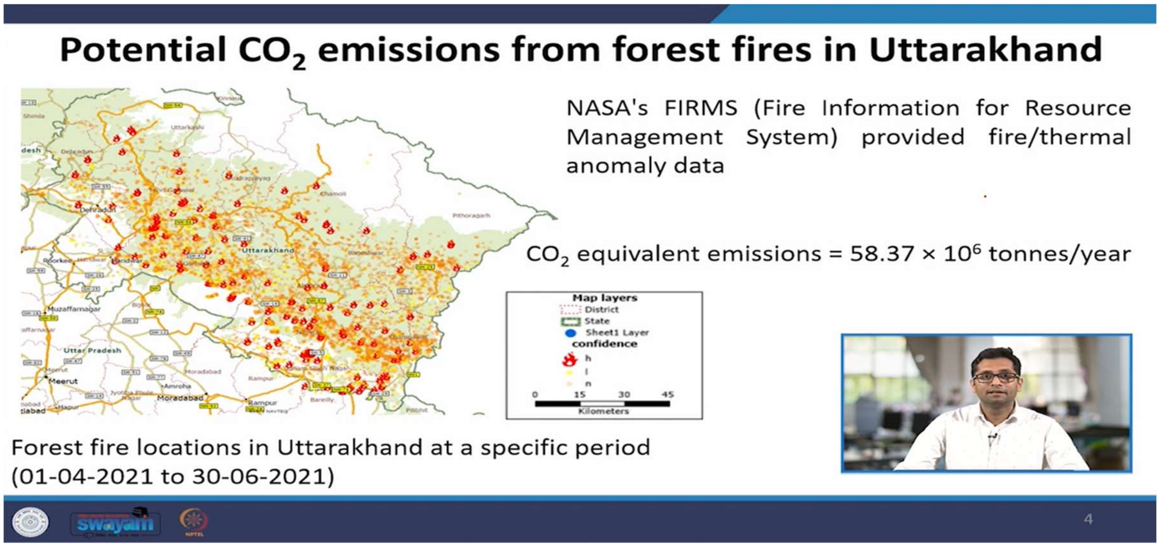


So in the Himalayas we have a lot of pine trees and the leaves of these trees which are also called pine leaders often fall during the spring season in the months of April and May and because of the dry climate it is a very good atmosphere for them to catch fire and they are one of the major reasons for forest fires that we experience in the states of Uttarakhand, Himachal and nearby areas. So not only does it have a huge effect on biodiversity it also affects the people living nearby. So this case study was undertaken by a group where we wanted to see the sustainability if these pine needles could be used for electricity production and on the land there are many NGOs also working for these kinds of proposition but we wanted to estimate the sustainability of such a process.

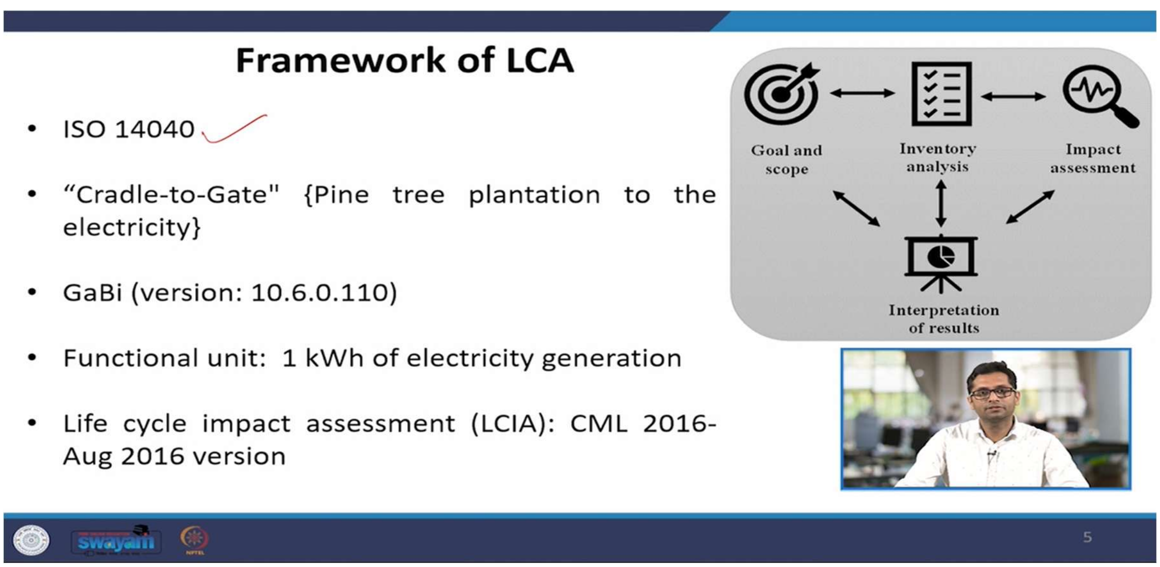
So we can see here like the local administrator have been putting in news articles where they have been putting in different orders looking for measures to use this waste which is in terms of the pine needles available in plenty and if they could be collected in a sustainable manner so as to prevent forest fires.



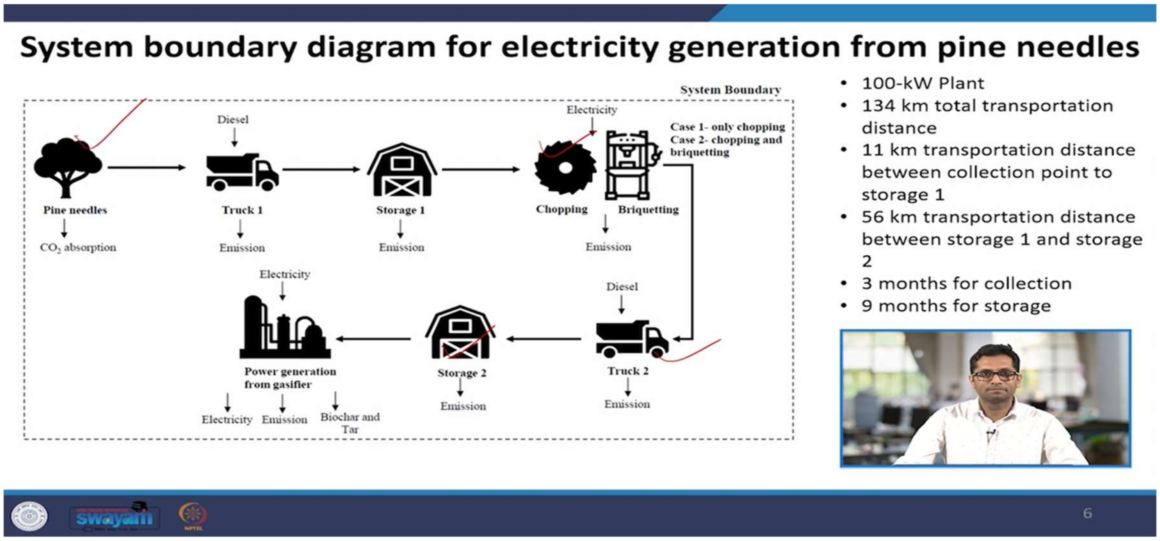
The solution that has been proposed by the civic society, by the technical or the knowledge of people has been like can we use the local people or utilize the local people who are available there for collection of these pine needles so it is mode of generation of employment for them and finally after the collection these pine needles could be used for electricity production as you can see here there is a gasifier that is working in a lab that is showing pine needles and you can see electricity being generated so it's a standalone system, 5 kilowatt system and which is entirely running on biomass like pine needles and it is generating electricity.



So we wanted to look at the potential of these solutions and of course since we would be avoiding pine needles forest fire we would also be saving in the CO2 that would be emitted because of forest fires. So as you can see these are the forest fires that have taken place in the state of Uttarakhand and you can see they have been highlighted and the data has been taken from a NASA satellite and overall the CO2 equivalent emission that might result from these forest fires are of the tune of around 58 into 10 to power 6 tons per year so that's huge.

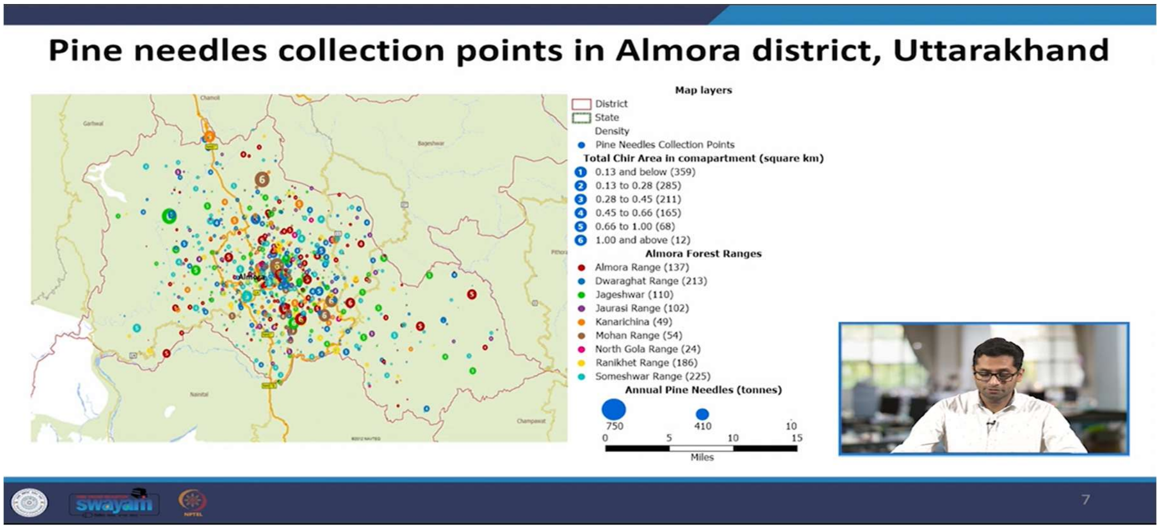


So we wanted to do a life cycle assessment of this particular pathway which again is following the ISO guidelines it's a cradle to grate approach means from the pine needle plantation to the electricity generation. We used a specialized software Gabi this is different from the software Simapro which we have discussed in the previous classes the function rate that we adopted was 1 kilowatt hour of electricity generation and CML pathways were used for estimation of the emissions.

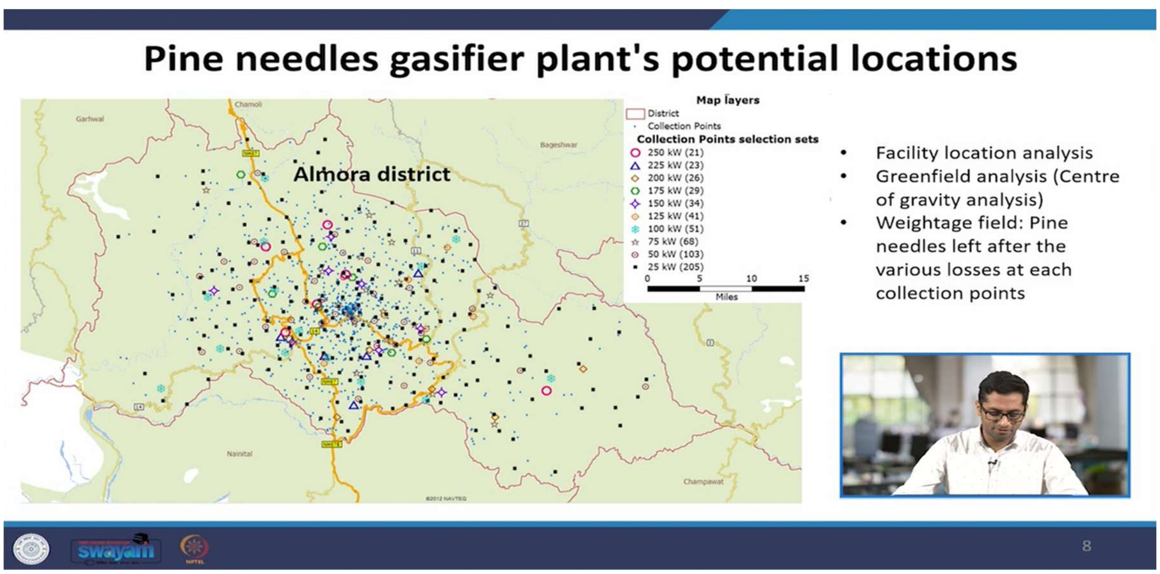


So if I take about the pathway this is the pathway was like pine needles or pine trees during its growth will be absorbing the CO2 then you would need to collect and take it to storage one and this collection would have their own emissions. After the storage the pine needles because of the low density needs to be densified or chipped in so you would have the chopping process because the typical size is almost 10 to 20 centimeters you want to chip it into smaller needles and further you can also work towards densification of these pine needles because the bulk density is quite low and the transportation that follows might be dictated by volume rather than weight.

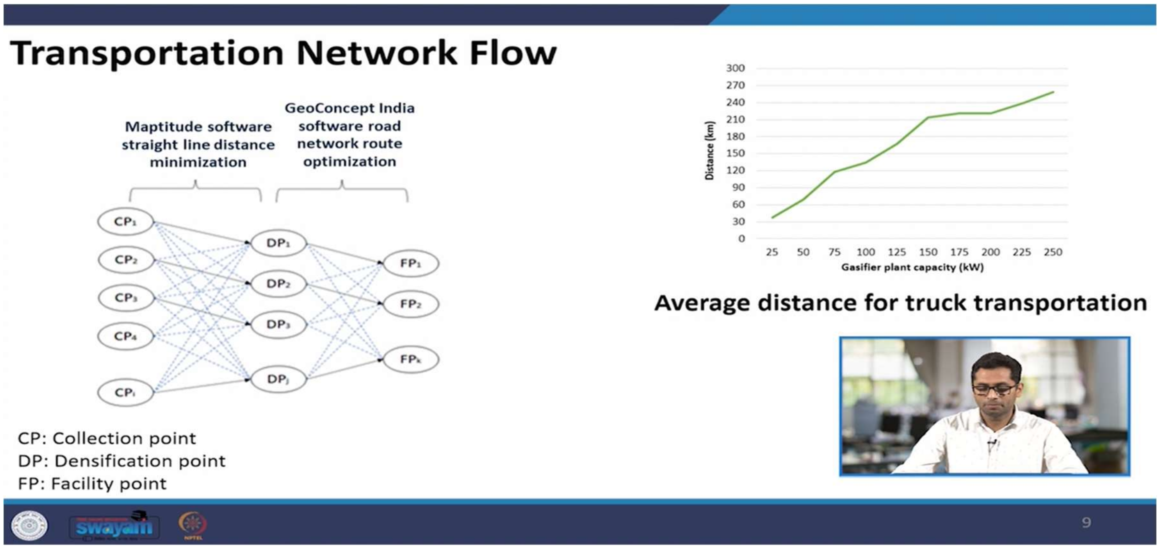
So it's always a good methodology to densify or maybe torrify the pine needles that are available then you transport it to a second storage where you would have the power generation using a process called gasification. In gasification you would normally be heating a pine needles in an insufficient supply of air the resulting would be a gas that is rich in hydrogen as well as carbon monoxide so it has somewhat of a calorific value which could be then used in a modified engine which could be producing electricity. So one of the major bottlenecks of this process would be that the collection needs to happen within a short span of three months whereas for the utilization would remain for an year or so.



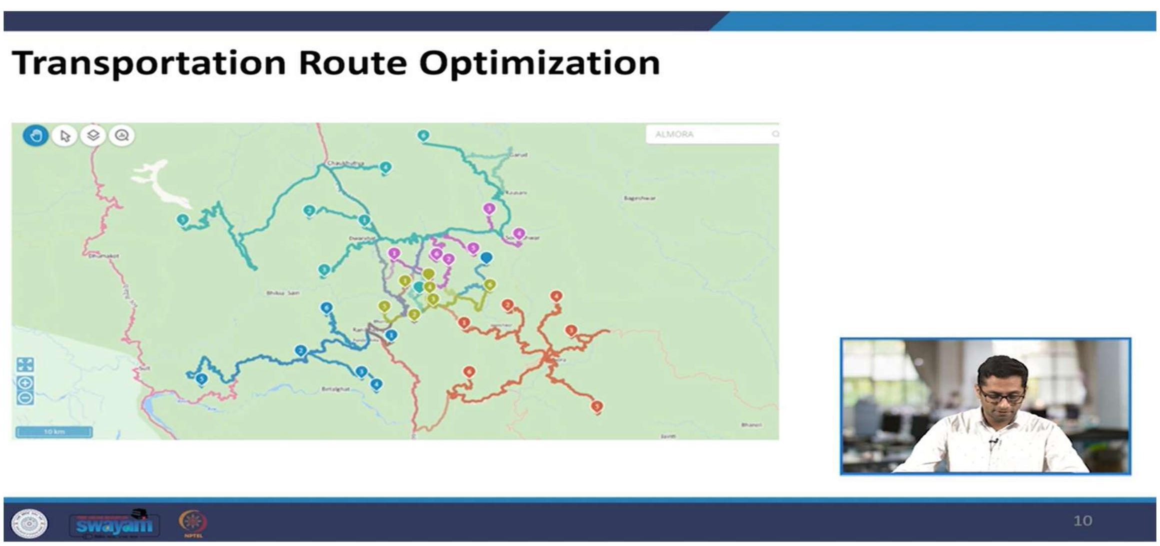
Further we wanted to see the emission that can come from the transportation itself because when we are looking at a mountainous terrains the road network is not necessarily straight there are long paths further the elevation would be very different that entails that the fuel economy for the different transportation vehicles which could be different types of trucks would be very different. So the first thing that we did was quantifying of the pine needles that are available in the different places so this quantification was done using a software called Maptitude.



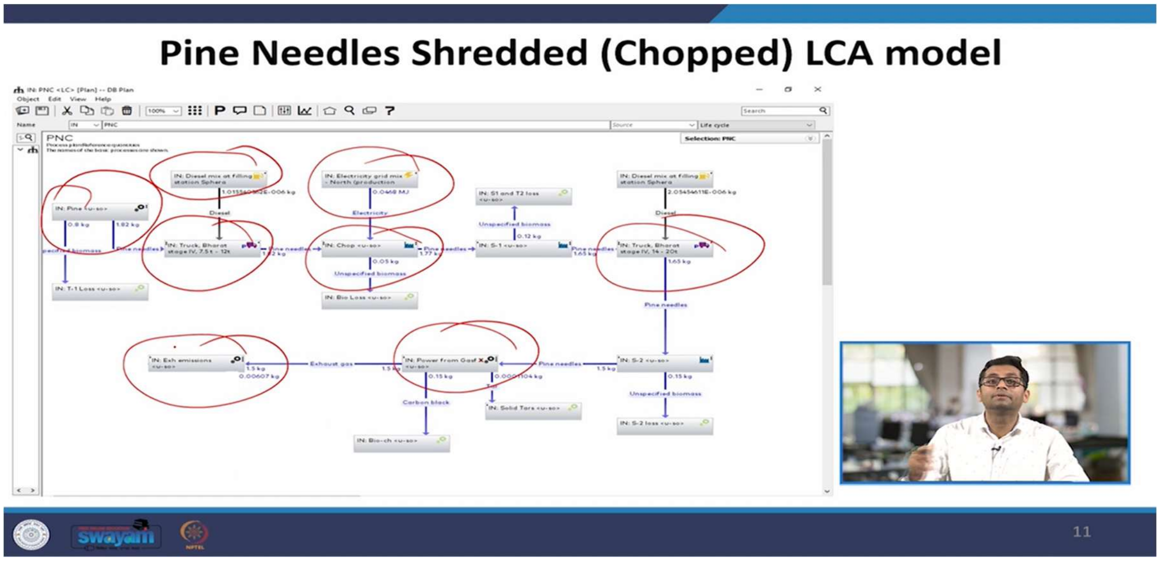
Then their correlation was made with respect to connecting the supply plants to where could be the different gasifiers that could be set up so gasifier again is an equipment that would convert these pine needles into usable electricity and they can come in different sizes. So the sizes that we looked at could vary from 25 kilowatt to 250 kilowatt of course the larger plants would be benefiting from the economies of scale but this might also entail a larger storage nearby on some maybe a slightly larger transportation as well and this is what we did with the help of the softwares.



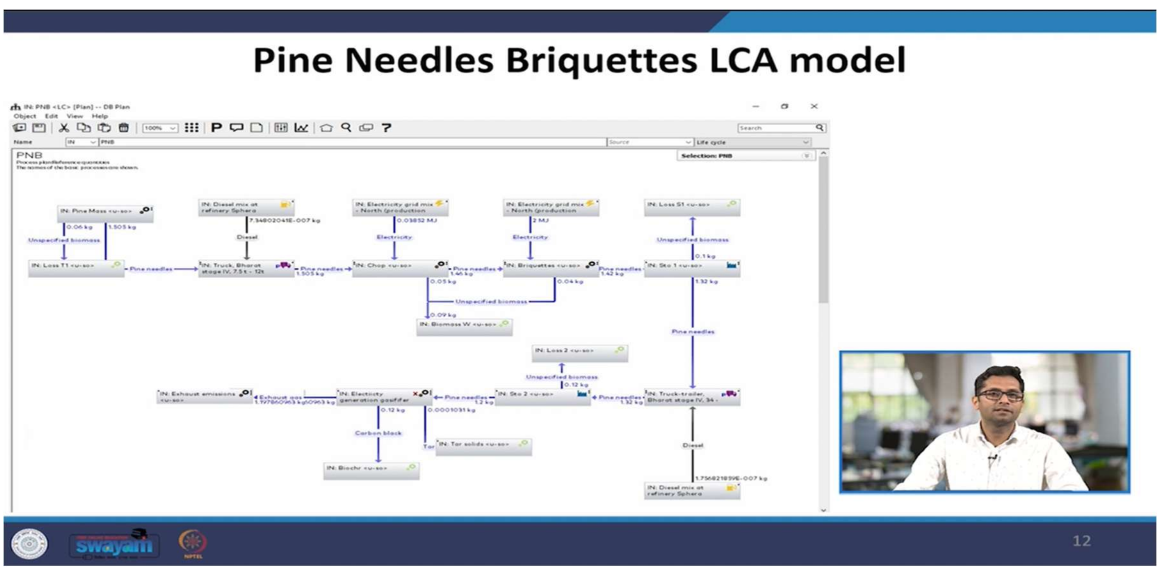
So this analysis was again done with the help of softwares and different coding where we tried to see optimize the distance that was travelled by the different transportation factors as well as the port transportation that would have to initially been taken by like the manual labor who would be collecting it and we can see as the gasifier capacity would increase that the transportation would slightly increase.



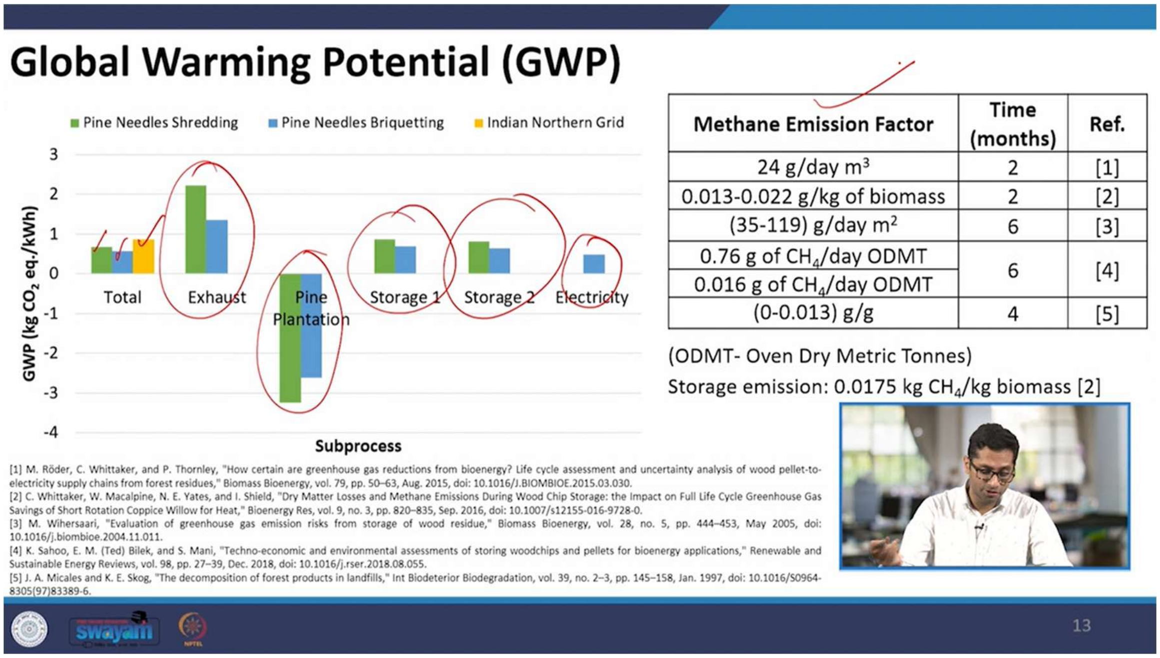
And of course this is how the road network for one particular district in Uttarakhand look like so this was for Chamoli district that this you can see that the roads are not straight there are you would have to take in considerably larger paths from reaching one point to another and this was this network was set up for six different gasifiers if they were set up in that district.



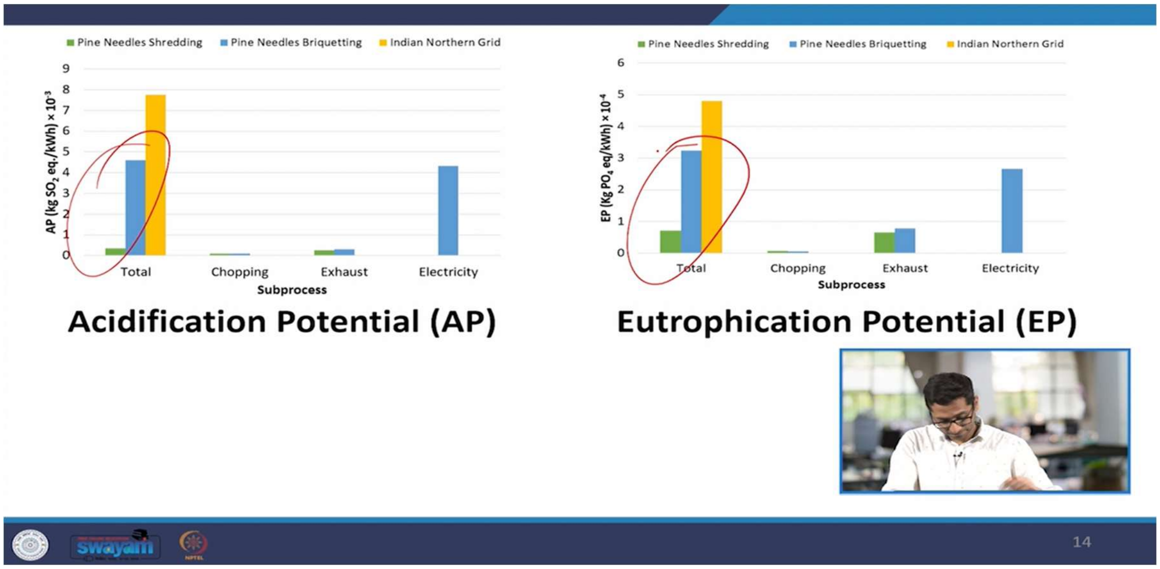
And based upon that we created a network of LCA input in the GABI software so you see the network in front of you so this was just to show you like how this particular system is different from the SimaPro one which you have learned in the earlier classes so here you can have a good graphical user interface where you can see how the systems look like so you have the pilot growing in here the transportation you can see the diesel with specific to Indian production being here the India specific electricity in here the chopping here again the secondary transportation the power generation and emissions from the gasifiers coming in here.



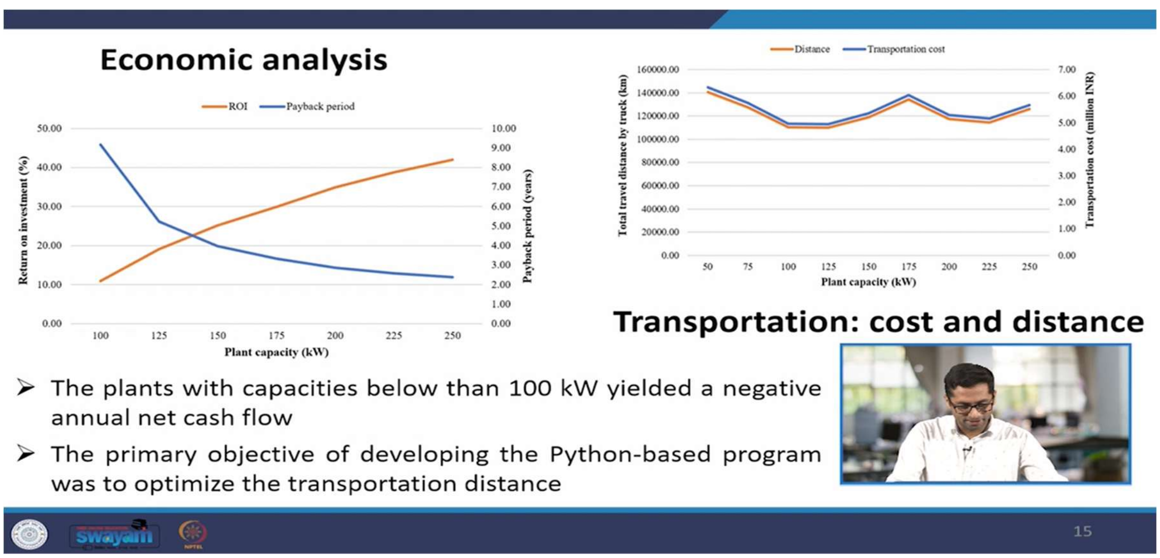
And then there was another model that was made in the same software so first one was the bio needles are just chipped in the second option we are also bricketing the pine needles which means we are densifying it so that the bulk density increases and the transportation comes down to a certain extent.



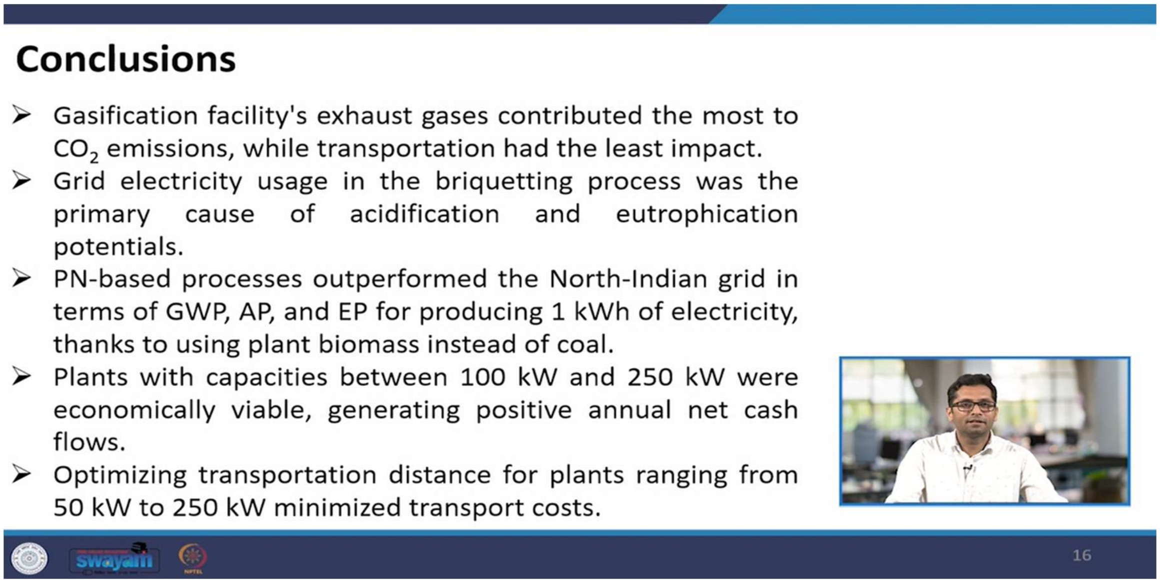
And if I talk about the solution this is what the total emissions would look like the emissions would come it from the exhaust of the gasifier because we are burning a biomass and you would have co2 and other kinds of oxides being formed in here the pine plantation during in growth will take in co2 during the storage the biomass would degrade and could have different kinds of methane emissions so that emissions could be significant or you plus if you are going for densification that would require electricity as in here so if I talk about the total emissions they vary from around 0.5 to 0.6 kgs of co2 equivalent per kilowatt hour and if I compare that with the current and grid electricity that is coming at around 0.8 or 0.9 so we are not saving much so this is the current grid electricity whereas this would be the biomass coming from two different scenarios so you can see like even from a greener route the co2 emissions could be quite near to what the grid is supplying us and further a major understanding that we developed was all the transportation looks like to be a significant one but for this particular case that we analyzed the transportation emissions were not very significant as compared to that which were coming from the exhaust or the storage so storage of biomass could be a serious concern because during the degree storage period the biomass would be emitting or degrading and this decomposition normally leads to formation of methane and like there are different studies with different methane emission factors which you can see here so there is a wide variation in that.



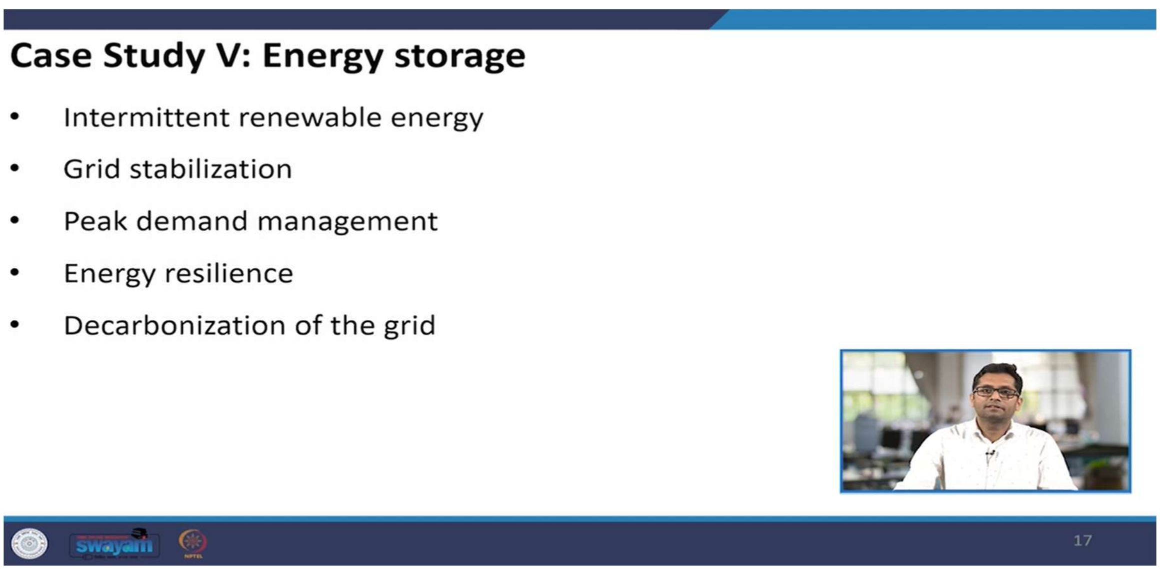
Further if I talk about the acidification and the eutrophication potential we can see for the different cases of course electricity that was used for different chopping and breakening purposes to be major contributor for this total acidification and eutrophication that was coming in and compared to the grid based system electricity we still had great saving for these two scenarios.



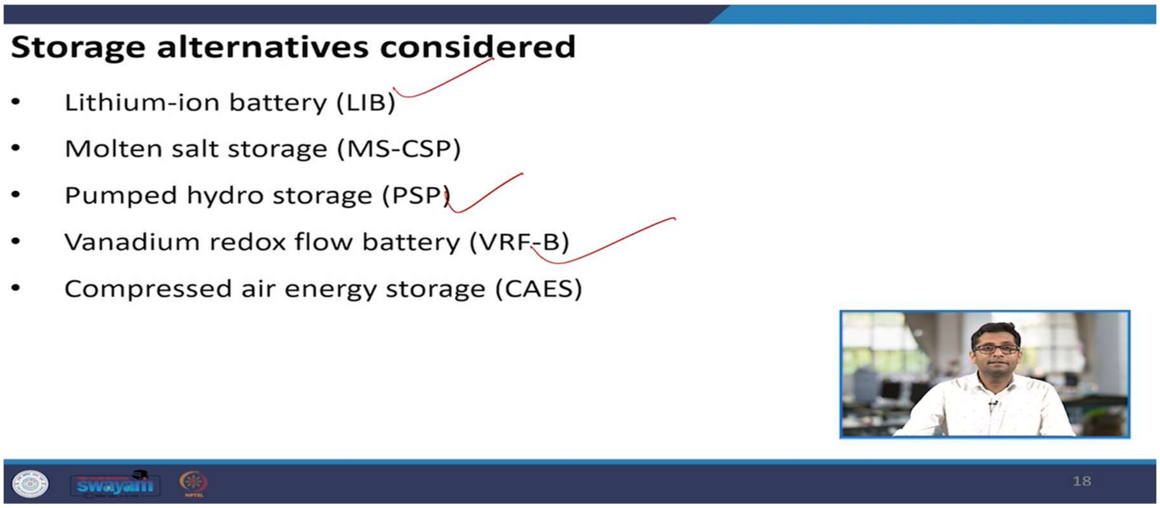
So with respect to economic analysis we can see economies of scale coming into play the larger the plant the more the return would be and lesser the payback period is going to be and we also found that in case we are having the size distribution the transportation distance might not change much it's overall the transportation distance is expected to remain in the same range.



So these were a few conclusions that we derived like there could be a wide distribution in terms of emissions the chopping could be a better scenario than the bricketing one and plus we are to gain from economies of scale the transportation distance which could look at a major bottleneck or concern didn't play a major role as well as cost as well or the emissions are concerned.



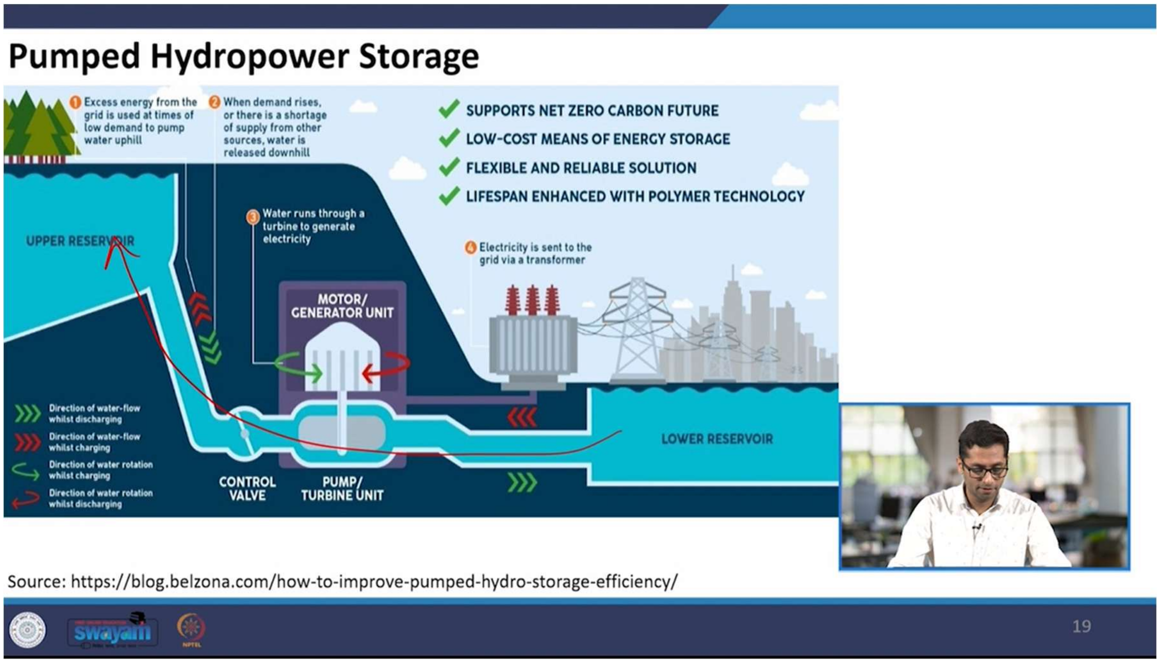
Then another study that we recently undertook was with respect to energy storage. So as we understand that India is moving towards a net zero energy goal of 2070 and we are aiming for a majority of energy production to be renewable based at that time. Now if this is going to be renewable based wind and solar are expected to play a major role in the energy supply however these two sources of energy are intermittent in nature which would meet that we need some kind of energy storage. Further storage would play a major role in terms of grid stabilization, peak demand management so the energy demand that we have is not consistent throughout the day there are certain times of the day when the demand would be much more than others so how do we manage that. Then the resilience of the grid and also the recombination of the grid are something that storage is expected to play a major role.



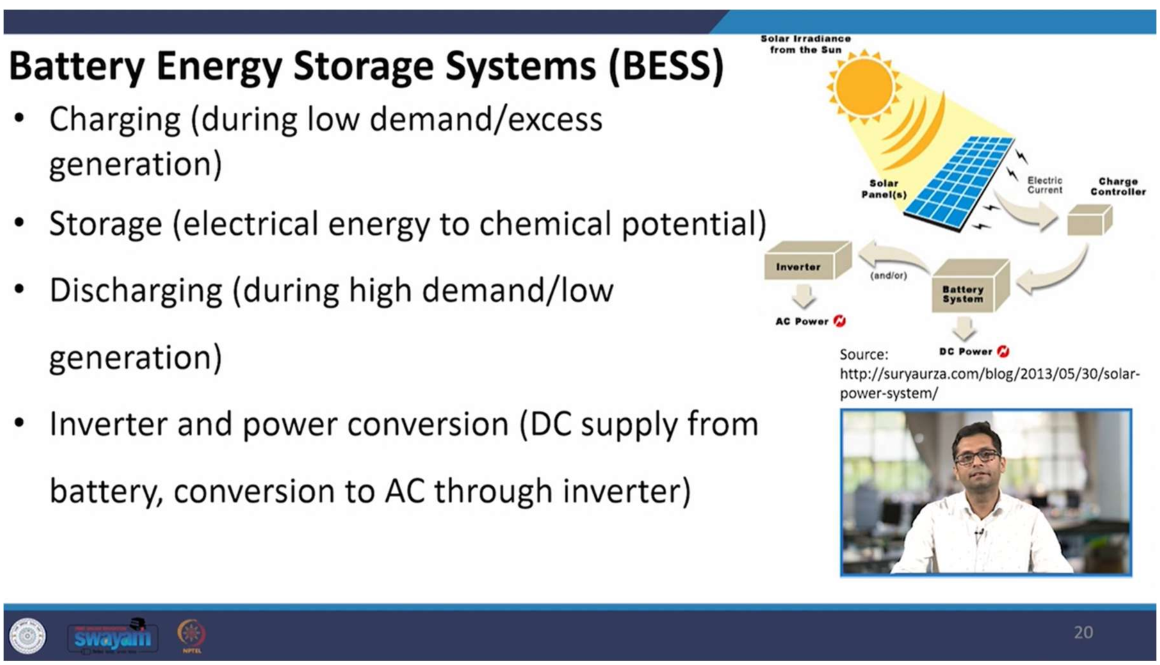
So we consider different types of energy storage options for which we have commercial plants available throughout the world and the first thing that we talk about storage would come to be amount for the batteries so lithium ion batteries are much talked about now. And then there is another sort of battery which is called the vanadium redox flow batteries which are expected to play a major role at a larger scale.

Pump storage is one type of storage that has the major application or major installation throughout the world and the case is similar for India where we have now being initiated like many pumped storage sites coming into play. Molten salt storage sites are just a scattered one like we have one or two sites in India but we have major application in the other part of the world.

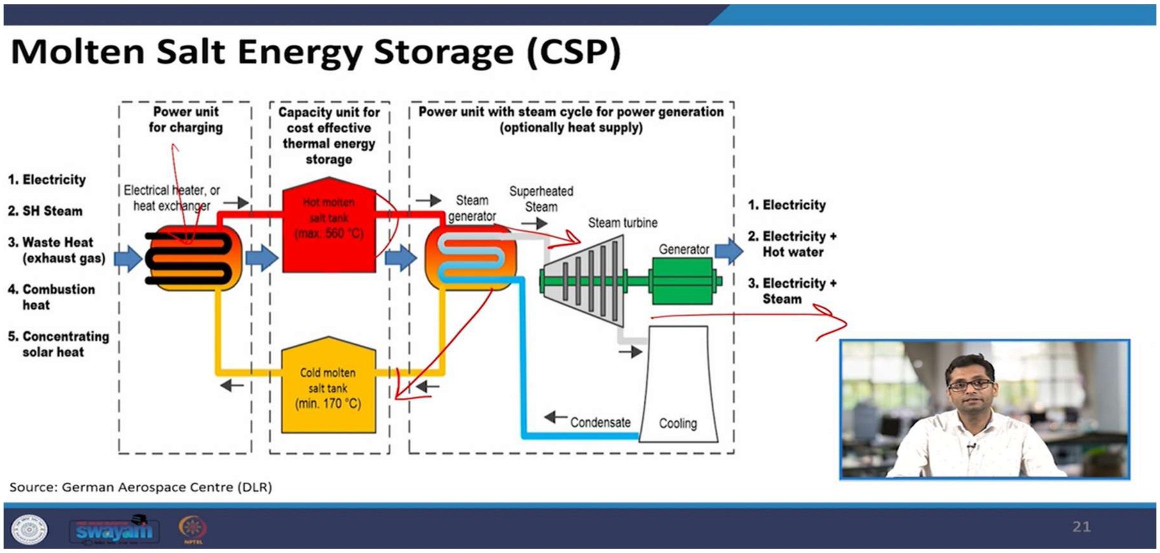
For compressed air energy storage we don't have any application in India but it is expected to play a major role in other parts of the world. So these were the five storage systems which are specifically for grid level storage. I am not talking about home electricity storage it is about like the capacity could be normally 250 megawatt or larger. So these are the types of scales that I am talking about and this is what we try to estimate the sustainability of these kind of storage for the future which is in terms of economics and both and LCA as well.



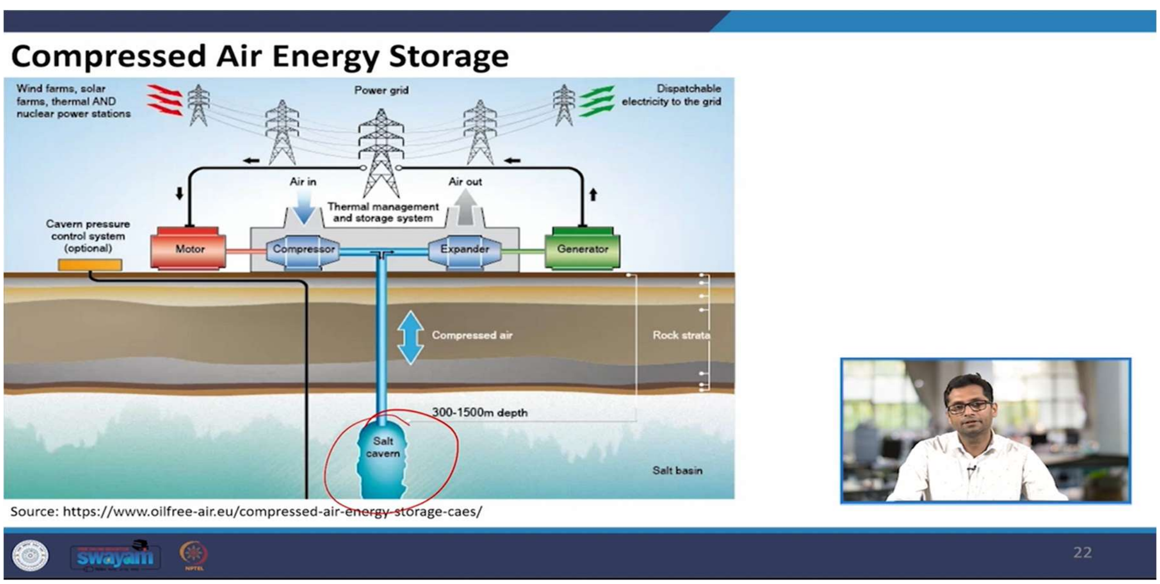
So just to give you a brief if I am talking about pumped hydro so this is basically pumping the water from a lower reservoir to a higher reservoir whenever you have extra electricity and whenever you need in power you would use the same reservoir for generating electricity through a turbine.



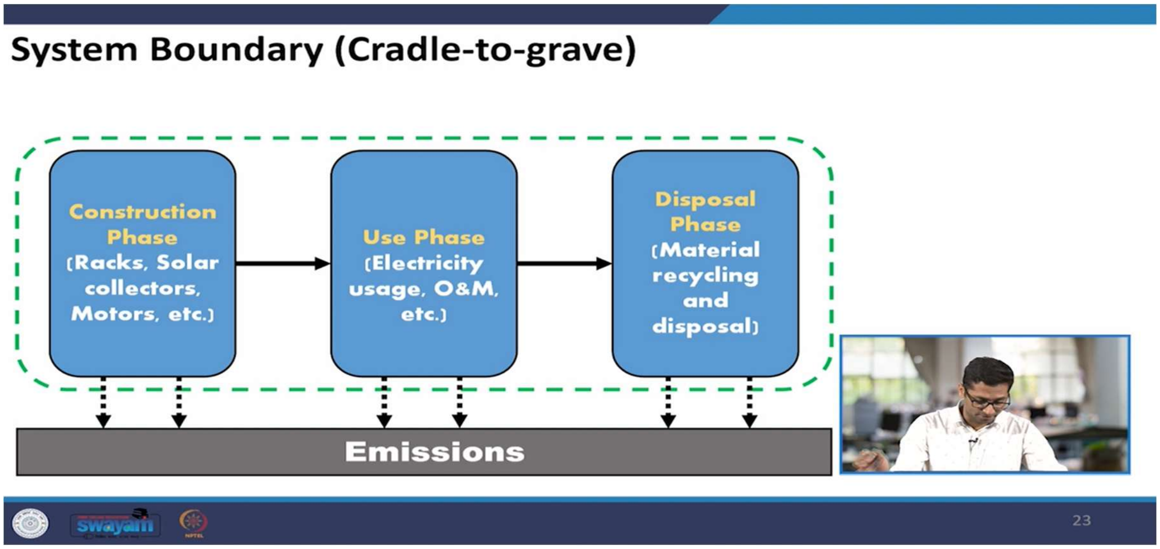
Batteries we all understand the concept is electrochemical in nature whenever you have extra electricity you charge the batteries and whenever you need electricity back you discharge it.



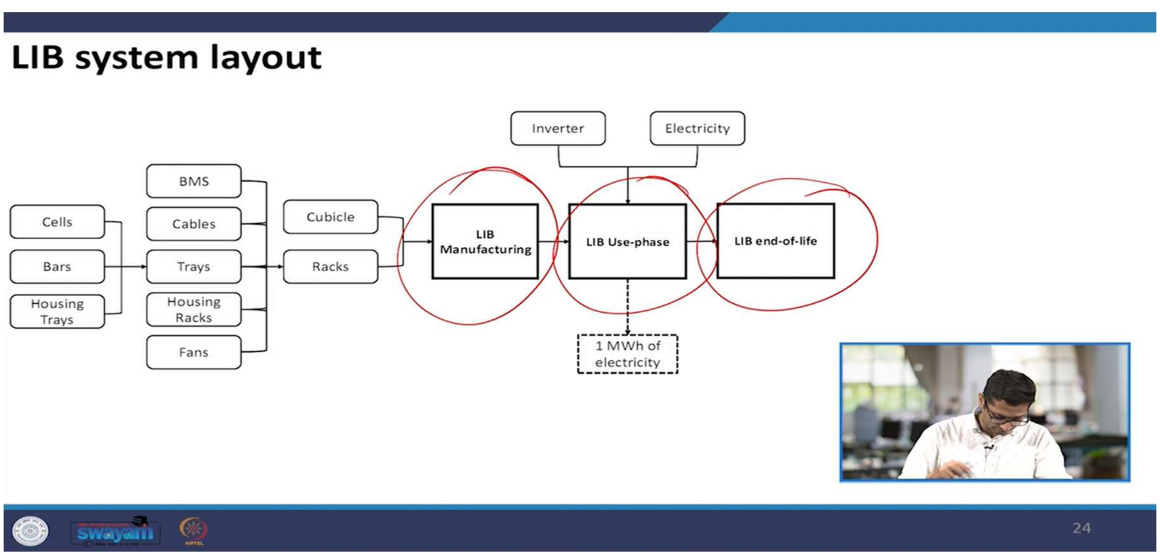
The third option could be molten salt energy storage wherein you would not need electricity for charging you would charge the system whenever you have abundant sunlight available. So the sunlight would be used for heating in a molten salt or a similar phase change material which would remain heated at a higher temperature which could be normally from 600 degrees Celsius and when you are in need of extra electricity this molten salt could be used for raising in steam which could be used for raising turbines and producing electricity. The small salt would eventually be cooled down and heated in the next day. So for such kind of system you would not need extra charging electricity so this is charged directly from the excess sunlight that would be available to you.



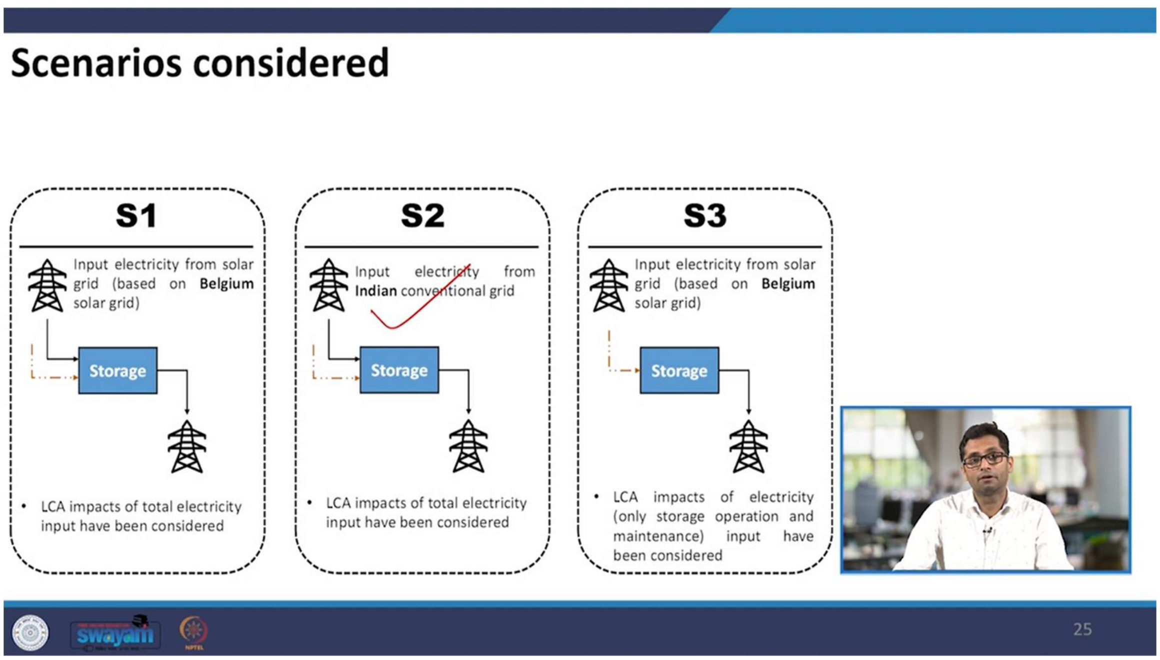
And finally an option that would be available would be compressed energy storage wherein when the extra electricity is available you would use it to compress air in some kind of underground formation one particular formation could be salt caverns there could be empty mines or similar locations where you can pump in on this compressed air and when you need in air you just pass it through an expander and run generator and produce electricity.



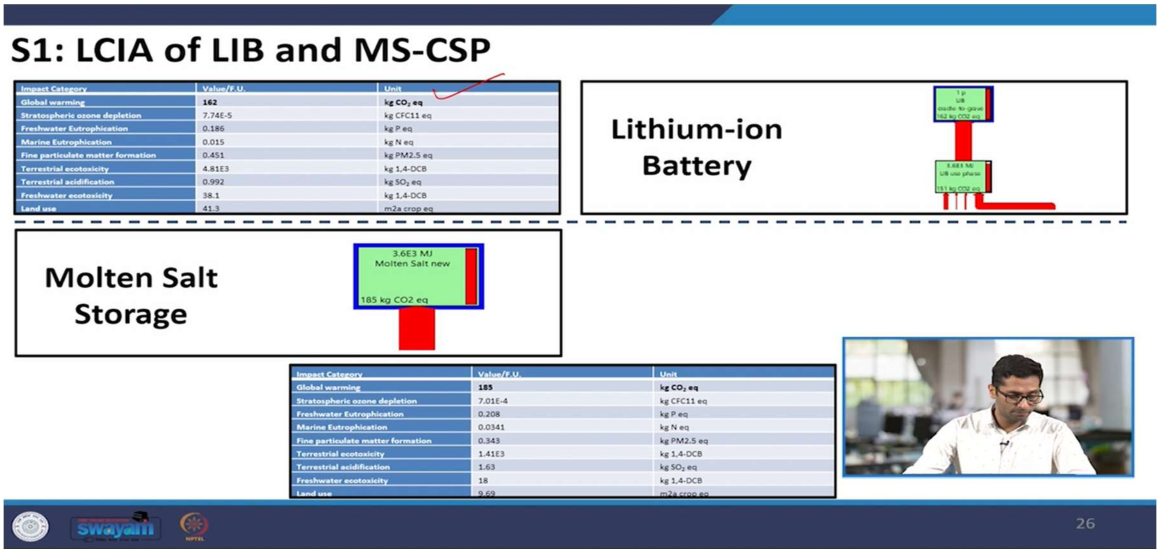
So what we try to do is we tried first we try to do an LCA which was created to grave which means it involved the construction phase the construction phase of the batteries or the different solar collectors the use phase wherein you would use electricity for auxiliary processes. So just for an example the battery packs that we use would have a huge cooling demand which would need installation of ACs and these air conditioners would be running on electricity so there would be an auxiliary demand that goes in the use phase. And finally you would have the disposal phase where you would want to dispose of the material that went into the manufacturing of the different storage option it could be lithium for the batteries it could be vanadium for the batteries it could be the solar collectors for the CSP systems and all this would have emissions during the life cycles.



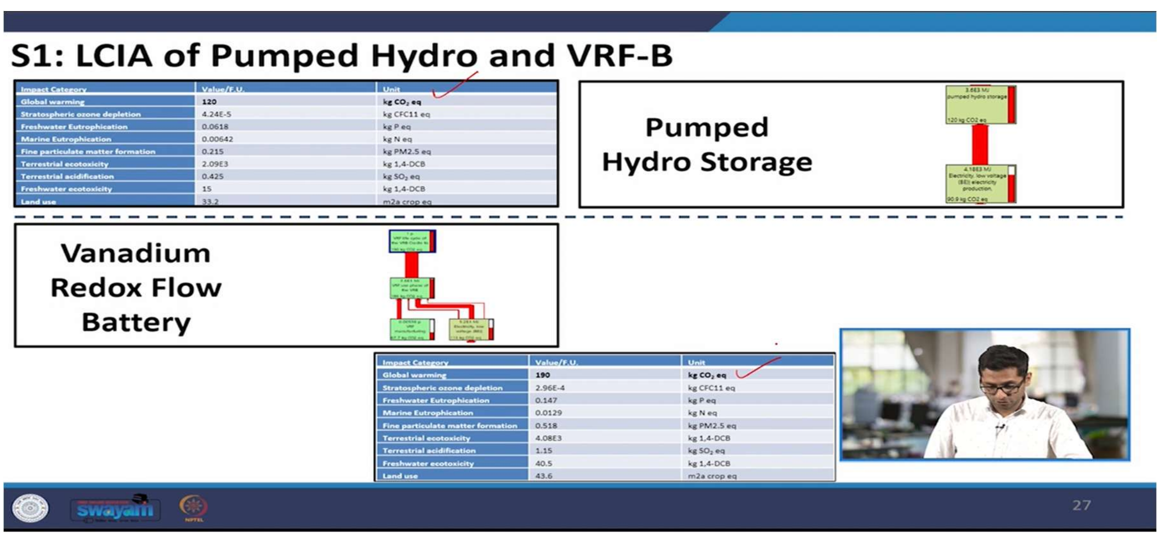
So further this is a typical system boundary that was considered for a lithium ion battery systems where you would have in the cells bars or the different racks being constructed so this all went in the manufacturing phase then you would have the use phase where the electricity input goes in so it includes both the electricity that goes for auxiliary consumption as well as the electricity efficiency that you would have. So if you are charging the batteries with 1000 kilowatt hour of electricity you won't be able to discharge at the same 1000 kilowatt hour so the discharge would always be lesser and that is true for any storage option and that is what is accounted in the use phase as well and finally when the use phase is over you would have the end of life disposal where you would dispose of the different component that went in the manufacturing of a particular storage option.



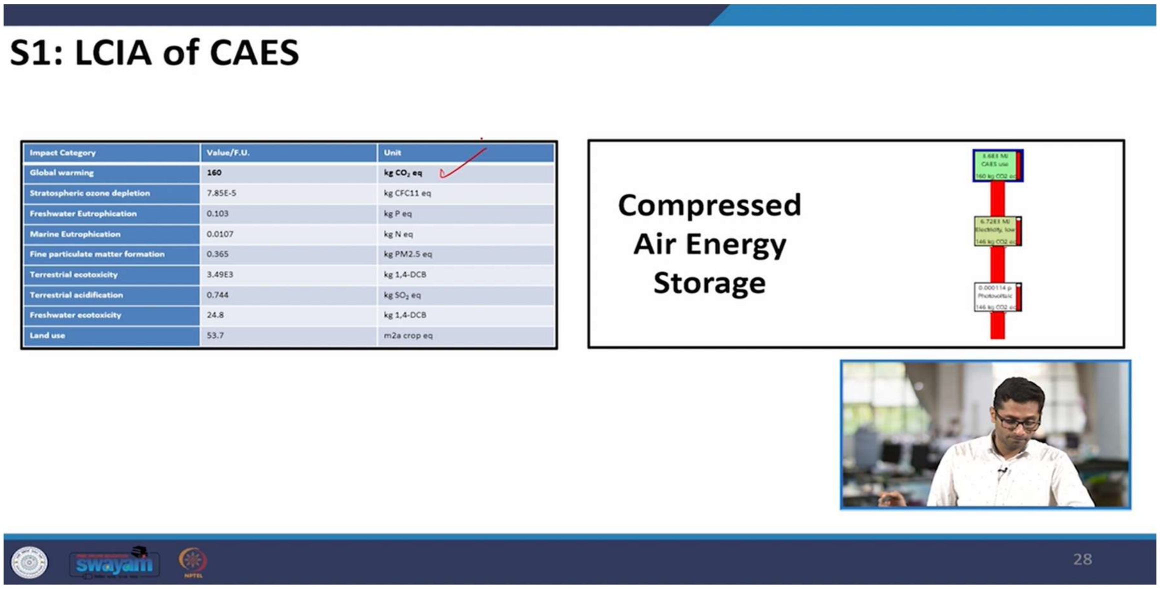
So I also we consider three different scenarios in the first scenario we considered that the charging is happening through a predominantly solar grid so for that like one such grid was available for the country of Belgium and we would operate the same thing and this is what we expect a similar condition in the coming few years so the grid would be predominantly based on renewables then in the second was the Indian conventional grid the grid that we have as of today and in the third case we are not considering the footprint of the charging electricity we are just considering the footprint of electricity that was used for auxiliary processes or the electricity that was lost so we have just the footprint of the storage. In the first two cases it also intakes like the electricity that comes in also has the footprint of that or includes the footprint of the electricity production how it the electricity was produced if it was produced through renewables or was it produced through predominantly fossil-based grid. The reason why it is important is because unlike the efficiency losses could be different for the two cases if I am having 90% efficiency of a storage option and if I am having a fossil phase based grid the efficiency losses might end up making a bigger concern for the case in which we have a grid that is based on fossil fuels rather than a grid that is based on solar.



So solutions that we or the answer that we got and here in we use the SIMAPRO software and that I believe Ankur has explained to you and this study itself was done by Ankur where he tried to estimate and the different emissions for the different storage options so we can estimate the global warming potential of say lithium ion batteries which turns out to be 162 kgs of CO2 eq. per megawatt hour of electricity stored and we can also have the ozone depletion potential, the eco toxicity, acidification and use that is available something similar for molten salt which comes out to be a bit higher.

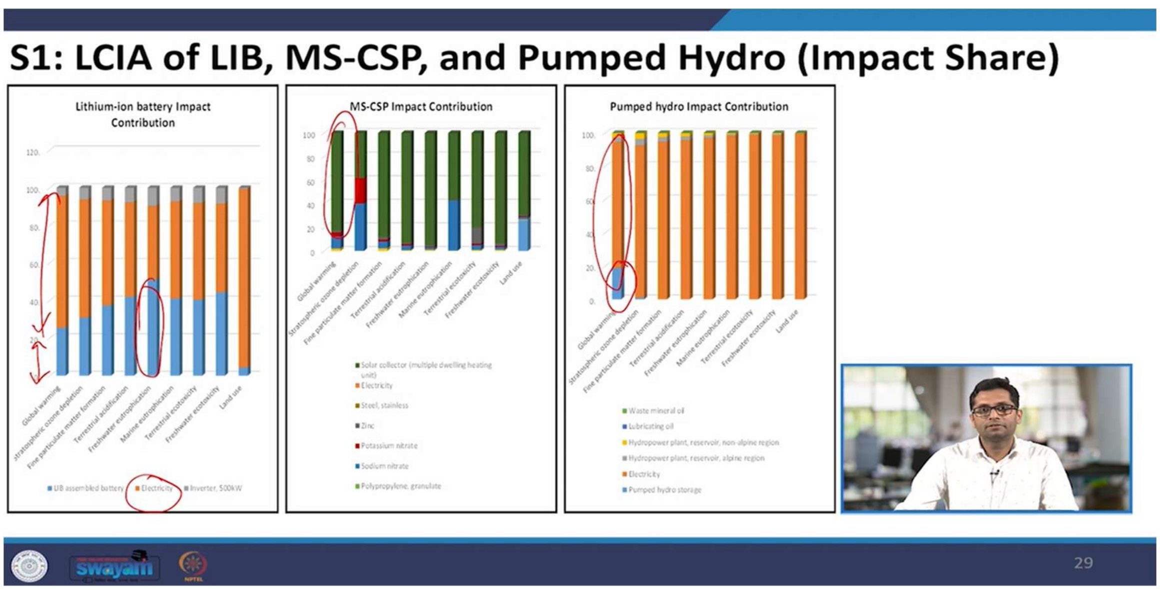


Then if I consider the pumped hydro it was found to be the lowest one at around 120 and if I talk about the vanadium redox flow batteries it had a potential of 190 which happened to be the highest one in this case.

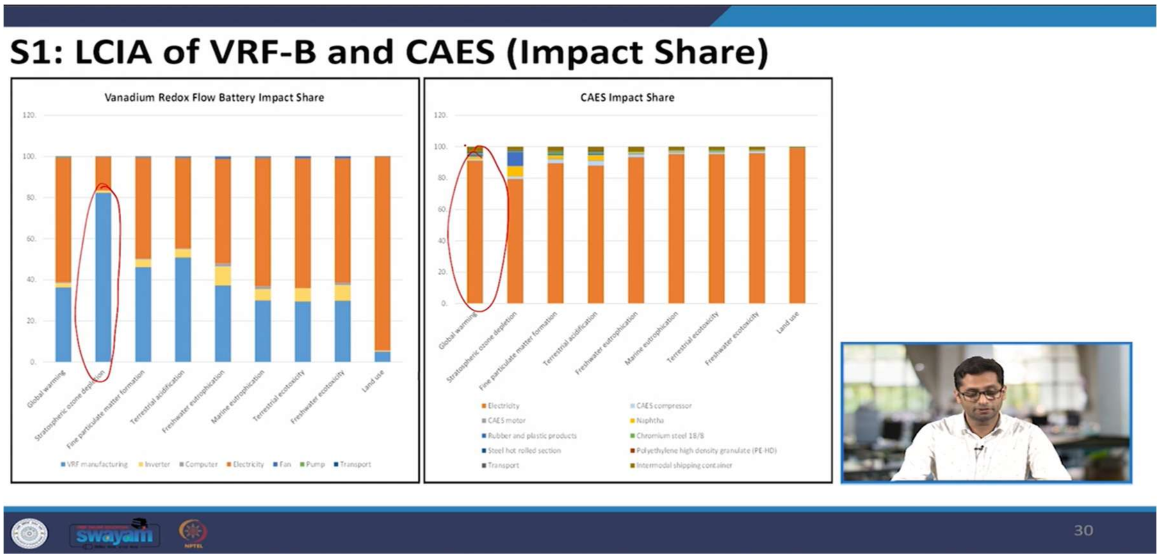


Impact Category	Value/F.U.	Unit
Global warming	160	kg CO_2 eq
Stratospheric ozone depletion	7.85E-5	kg CFC11 eq
Freshwater Eutrophication	0.103	kg P eq
Marine Eutrophication	0.0107	kg N eq
Fine particulate matter formation	0.365	kg PM2.5 eq
Terrestrial ecotoxicity	3.49E3	kg 1,4-DCB
Terrestrial acidification	0.744	kg SO_2 eq
Freshwater ecotoxicity	24.8	kg 1,4-DCB
Land use	53.7	m2a crop eq

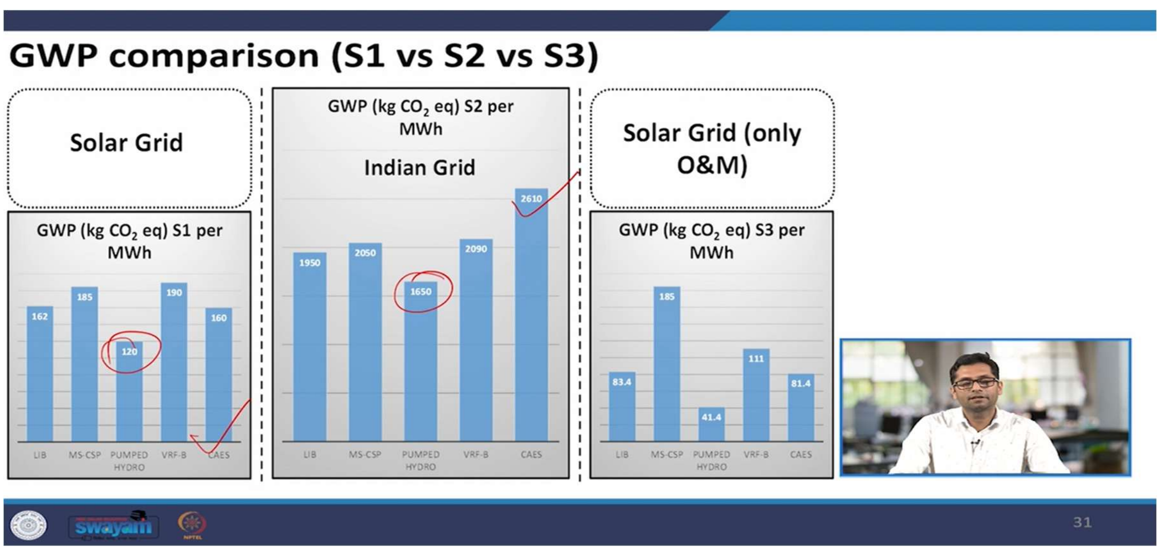
Compressed air was somewhere in between at around 160 and we can also do a comparison of the different emission categories and where these emissions are basically coming from.



So if I look at the lithium ion batteries a majority of the emissions would be coming from the charging electricity which you see in here and the construction phase also has a bit of an emissions the least one comes from the inverter or the disposal one. Further here in we can see if I talk about eutrophication, the eutrophication could be a major concern in the construction phase. If I look about the concentrated solar plants we see electricity doesn't have a role to play here majority of the emissions would be coming from the manufacturing of the solar collectors. So we don't see any electricity playing a role here. If I talk about pumped hydro again we would have electricity playing a major role and of course we would have certain emissions coming from the pumped hydro storage itself because it would need entail a land use change the vegetation that was initially occupying the space where the pumped hydro would have been created might have vegetation being buried and this vegetation might degrade over the time causing in the emissions.



We can see similar emissions from a vanadium redox flow batteries. In the redox flow batteries we can see that a manufacturing phase might have significant emission in terms of ozone depletion so that might be a bit of a concern. If I talk about the compressed air electricity again dominates majority of the emissions.



So if I look at the comparison in terms of the different scenarios that was considered we can see pumped hydro coming out to the least but the numbers could be very different based upon the type of grid that we are going if you consider the present grid the Indian grid at present the results would be somewhat different compressed air which comes out to better in here comes out to be the worst and the reason I have already explained pumped hydro again comes out to be almost the best one in both the scenarios and the results would be again be somewhat different if I am just considering and the emissions that are coming from just the auxiliary consumption and we are not taking the emissions associated with the incoming electricity.

Total Lifetime Cost = $\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}$

Total Lifetime Output = $\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}$

$$\text{LCOE} = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Output}$$

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Levelized cost of Electricity

- I_t = Investment and expenditures for the year (t)
- M_t = Operational and maintenance expenditures for the year (t)
- F_t = Fuel expenditures for the year (t)
- E_t = Electrical output for the year (t)
- **r** = The discount Rate
- **n** = The (expected) lifetime of the power system

Further we also did an LCOE we have briefly discussed this part in the economic parts as well how we would calculate the LCOE so we have done the levelized cost of electricity for the five different options as well.

Techno-economic analysis of PSP

Table: Technical assumption in the analysis of a PSP

Parameter	Unit	Value
Base year for LCOS calculation	Year	2023
Technology		PHS
Projeect construction time	Years	5
Project lifetime excluding the construction time	Years	40
Power capacity	MW	250
Charging/discharging cycle per day	Number	1
Discharging time	Hrs	6
Operation cycles per year	Cycles	365
Normative availability	%	95%
Storage round trip efficiency	%	80.5%
Annual gross energy generation capacity	GWh	547.5
Annual energy generation @95% availability	GWh	520.1 25
Transformation losses	%	0.5%
Auxillary consumption	%	0.7%
Net annual saleable energy	GWh	513.8
Annual energy required for pumping	GWh	680.1

Table: Financial assumption

Parameter	Unit	Value
Equity	%	30.0%
Return on Equity	%	16.5%
Interest on loan	%	9%
Discount rate (WACC)	%	11.25%
Loan Tenure	Years	20
Moratorium	Years	1
Annual O&M expense	%	3.5%
Annual O&M cost escalation	%	4.77%
Working Capital - O&M	Months	1
Working Capital - Receivables	Months	1.5
Working capital - Maintenance spares	%	15%
Salvage value at end of life	%	10%
Number of years for accelerated depriciation	Years	14
Annual depriciation rate for first 14 years	%	5.28%
Interest on Working Capital	%	11%
Corporate Tax	%	25%
Tax holiday	Years	10
Assumed CAPEX	Crore ₹/MW	4
I. Direct costs	Lakh ₹/MW	196
II. Indirect costs	Lakh ₹/MW	4
III. Electro Mechanical work cost	Lakh ₹/MW	200
Total Capex	Lakh ₹/MW	400
Electricity tariff for charging battery	₹/kWh	3
Cost escalation for input/saleable electricity	%	0%
Sale tariff	₹/kWh	15

Table: Parametric results

		1 cycle per day	1.5 cycle per day
IRR	%	28.54%	37.6%
NPV	Lakh ₹	1,85,525	3,34,085
LCOS	₹/kWh	7.88	6.58

Note: LCOS also includes the cost of electricity for charging.

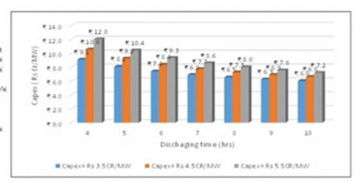


Fig: LCOS sensitivity analysis

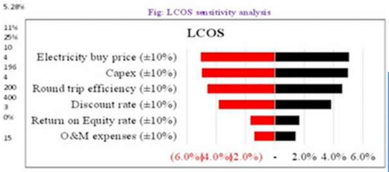
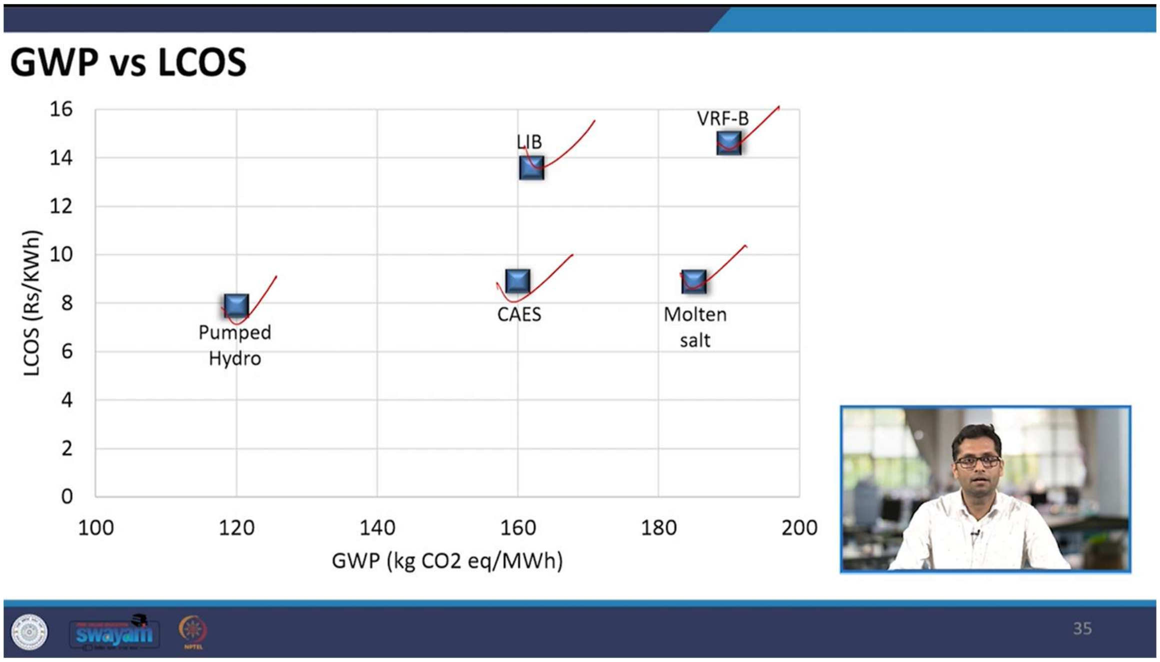
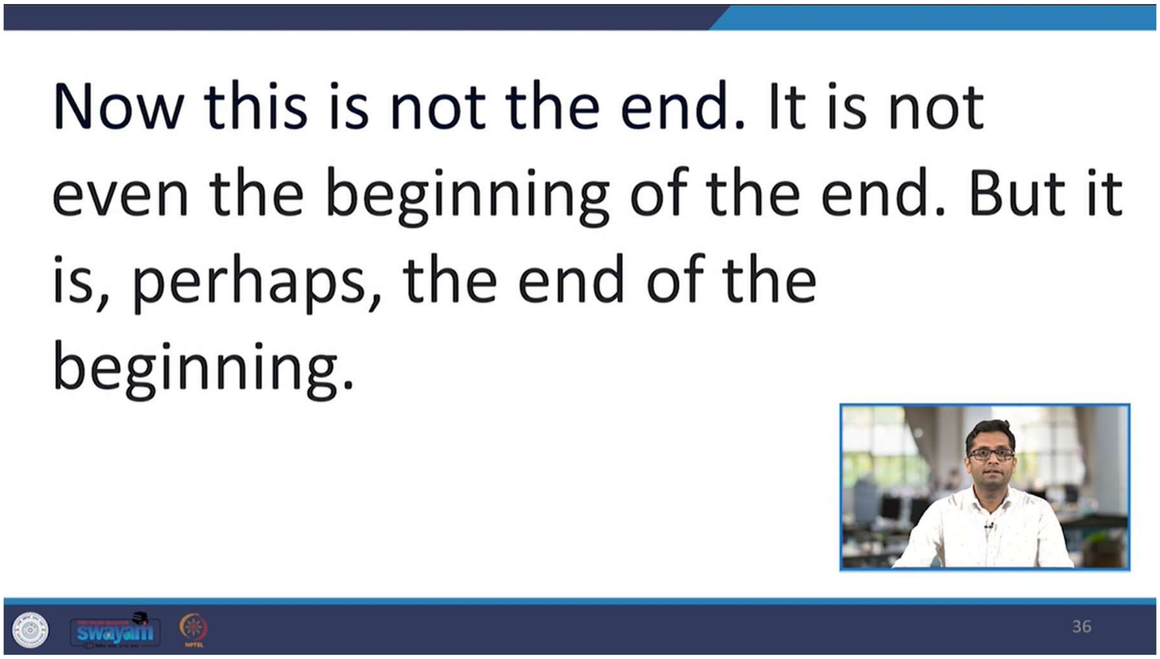


Fig: LCOS sensitivity analysis

And this was quite comprehensive this is something we have discussed in the earlier classes so I wouldn't go into the detail but it was basically the average electricity price that I would be paying over the lifespan of the project for the electricity generation.



And if I look at the results this is how the combined result would look like on the x-axis you would have the global warming potential of the different storage options we have five options which is the pumped hydro the compressed air lithium ion batteries vanadium redox flow batteries as well as molten salt. So in terms of GWP we would have the pumped hydro fearing quite good and then on the y-axis you would have the levelized cost of storage in terms of rupees per kilowatt hour or rupees per unit of electricity. Again here we see pumped hydro has that part with the lowest technologies so it is one of the lowest technology that would we would have pumped hydro, gas as well appear almost having similar price. Batteries which have been much advertised as an energy storage option have typically have higher storage cost if you're talking about grid scale and this is one of the reasons why we are not seeing many battery installation as of today but in the future things might change as the batteries are getting produced on scale. So again this is a typical application where the skills that you have learned in terms of LCA and techno economic analysis can come in very handy and could assist the decision makers make meaningful decisions for the future because if we are going towards a net zero world we would have to quantify the emission that would come from every part of the life cycle and we also need to account from the emission that would come from the storage as well.



So this was another case study just to make you understand the application of the tools that we have learned and with this I would try to end the course and I would like to end with a statement that and the skills that we have learned it's not the end it's not even the beginning of the end it is perhaps the end of the beginning there's a whole world for you guys to explore so there we have just provided you the basic understanding of few things and it is up to you to explore it and it for personally for me it was a learning experience in case anyone has any doubts comments or any suggestions for the future please feel free to connect to me on the email I'll be happy to reply to your queries as in when time allows and with this we would like to end the course hope it was a learning experience for all of you. Thank you.