Energy Resources, Economics and Environment
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Lecture - 22 P2
Net Energy Analysis – Part 4

When we talked about batteries, most of these, many of these now where you have prototypes, they are commercial. We want to look at an early stage calculation and how the energy analysis can be used to actually compare between different options.

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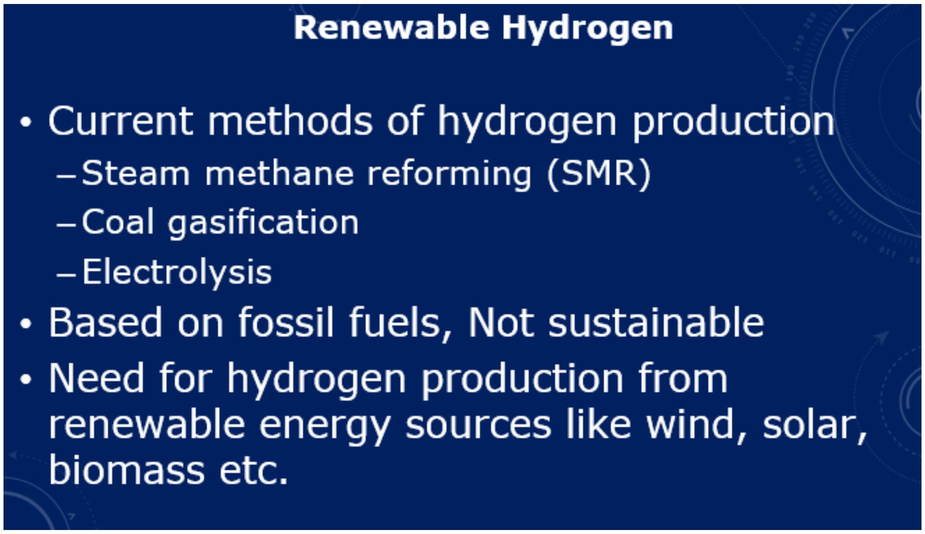

So, we talked about hydrogen and the only we can think in terms of making hydrogen viable is if we can make it from renewable sources. So, current methods of hydrogen production typically most of it 90 % of hydrogen comes from natural gas from steam methane reforming. One can also coal gasification and electrolysis mostly it is based on fossil fuels which is not sustainable from the overall viewpoint. So, we need to look at hydrogen production from renewable energy sources like wind, solar, biomass.

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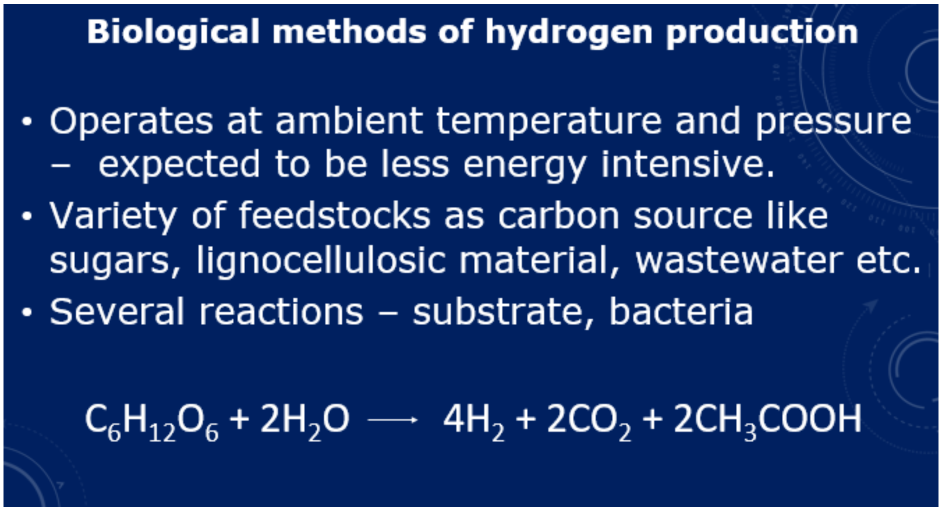

And this study the we are going to talk you about is to look at biological methods of hydrogen production. These are still at the laboratory scale, where it can operate at ambient temperatures and pressures. They are expected to be less energy intensive and they have a variety of feed stocks as carbon source like sugars, lignocellulosic material, waste water and there are several reactions, there are substrates and bacteria, so you have basically the biological feeds stock something like C6H12O6 with water giving you hydrogen, CO_2 and then another compound. So, this is the hydrogen we would separate and use.

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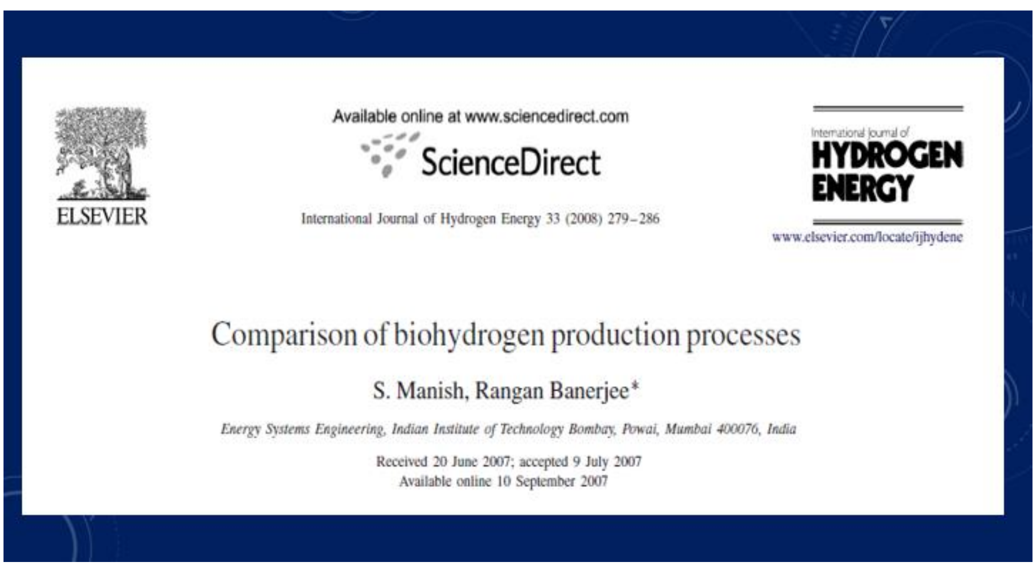

And we would like to this you can see this is a slightly old paper, it is in 2008. There is comparison of bio hydrogen production processes. So, what we said is all these processes today are still at the laboratory scale based on what has been done in the laboratories scale and the performance can we asses and see whether these are likely to be viable and how do they compare from an energy or a net energy point of view. So, we would like to calculate the NER and see if those NER's are greater than 1.

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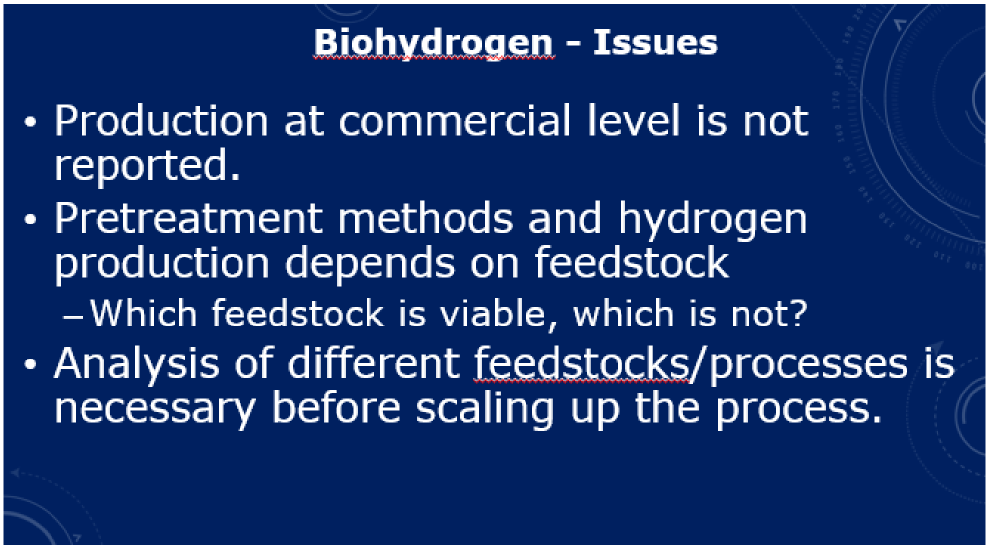

And in order to do that, so the production at commercial level not reported, pretreatment methods and hydrogen production depends on the feed stocks, which feed stock is viable which is not, which process is viable, which is not. So, the analysis of different feeds stocks and processes is necessary before we invest in scaling up the process.

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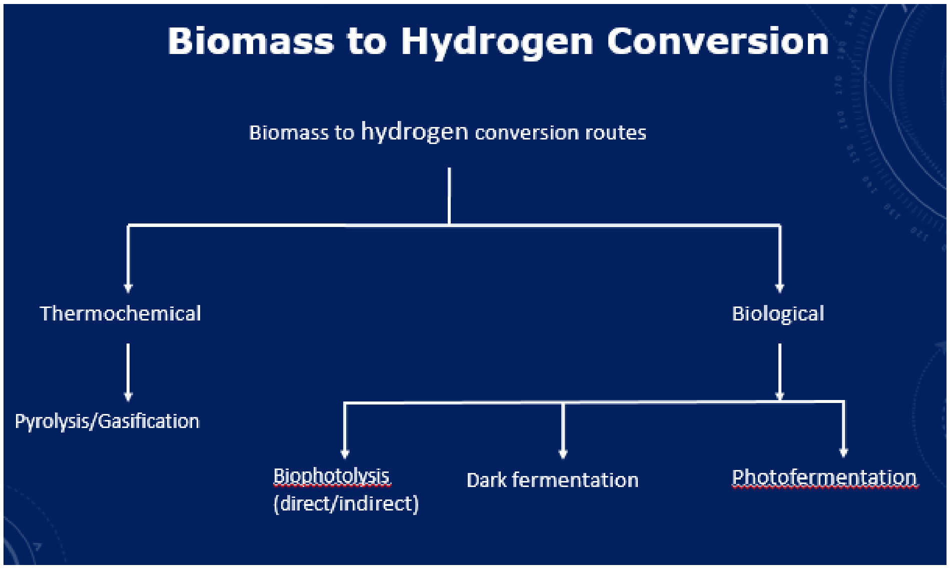

And this is the methodology that we have used. We have shown, we were looking at biomass to hydrogen there are thermochemical methods pyrolysis and gasification larger scale. We are here, we are looking at the biological processes; biophotolysis, dark fermentation, photo fermentation. I am not going to go into the details of the process I am just going to illustrate for you the methodology and some of the results and those who are interested can look at the paper and associated papers and this can be an area where there, still this is an area where there is a scope for doing active research.

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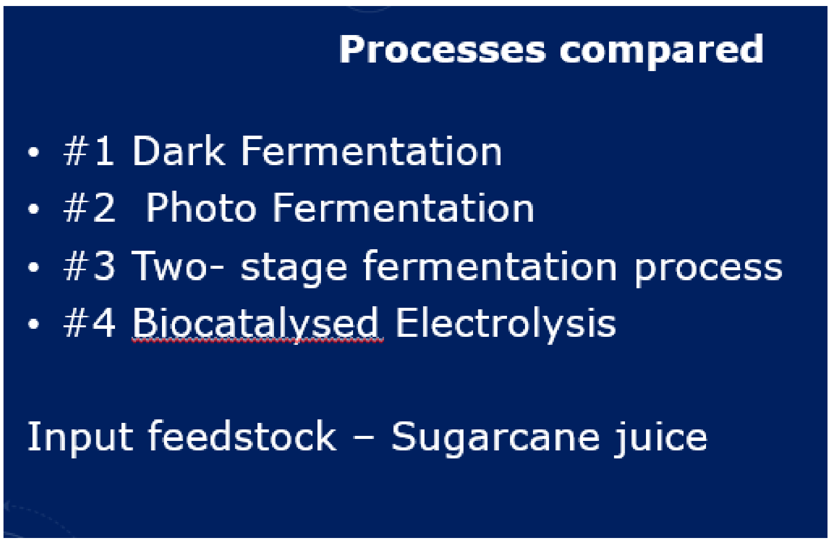

So, we would look at four different processes dark fermentation, photo fermentation, two stage fermentation, biocatalysed electrolysis. And we will take an input feeds stock sugarcane juice.

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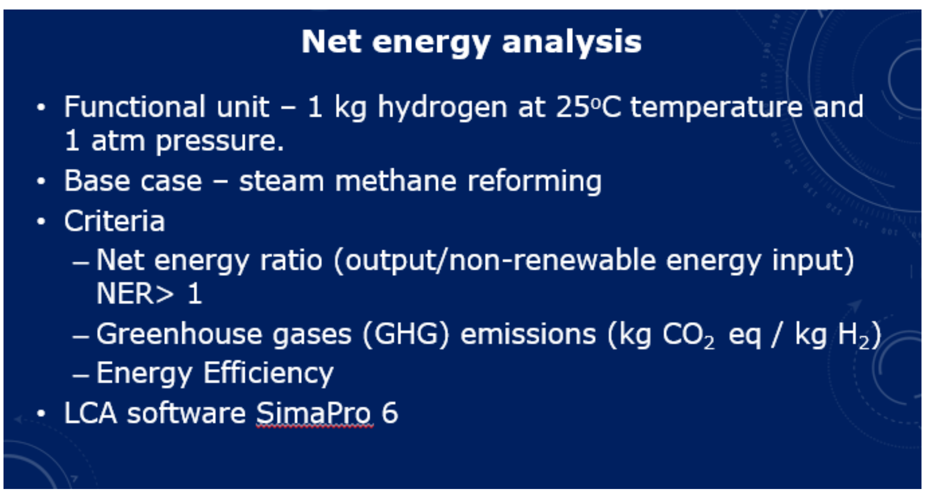

So, the functional unit that we have defined is 1 kg of hydrogen to be produced at 25^o C temperature and 1 atmosphere pressure. We compare this with a base case of steam methane reforming with natural gas and we would like to calculate one, two couples of things, one is what is the net energy ratio output by the nonrenewable energy input, the NER should be greater than 1, also what is the kg of CO_2 equivalent per kg of hydrogen and then the energy efficiency. We have used the LCA software SimaPro but we can also do this just our own calculations.

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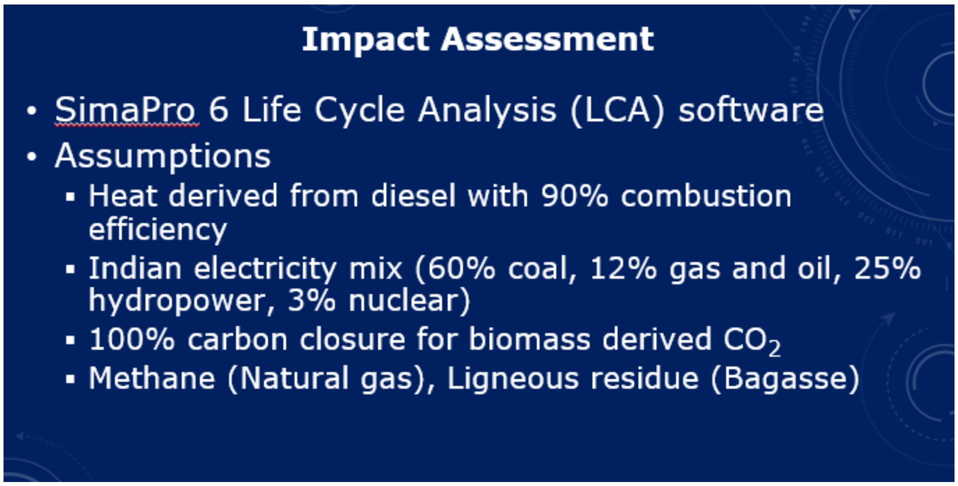

And the heat which is being used in the processing we need to produce steam, we used diesel with 90% combustion efficiency. For the electricity we use the Indian electricity mix and this is the kind of mix and we said that biomass derived CO_2 is 100% carbon closure so zero CO_2 impact and we look at natural gas and biogas as well as the residue.

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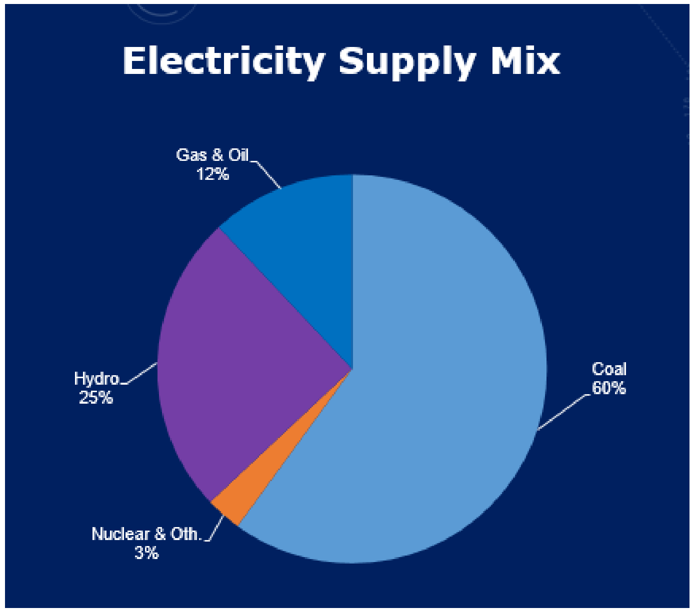

This is the electricity supply mix that has been assumed in this case.

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Steam methane reforming

Parameter	Value	Unit (/kg H_2)
Resource consumption		
Natural gas (in ground), input	3.64	kg
Coal (in ground), input	159.2	g
Iron (Fe, ore), input	10.3	g
Iron scrap, input	11.2	g
Limestone ($CaCO_3$, in ground)	16.0	g
Oil (in ground)	16.4	g
Average air emissions		
Benzene	1.4	g
Carbon dioxide	10.62	kg
Carbon monoxide	5.7	g
Methane	59.8	g
Nitrogen oxides (as NO_2)	12.3	g
Nitrous oxide (N_2O)	0.04	g
Non-methane hydrocarbons (NMHCs)	16.8	g
Particulates	2.0	g
Sulfur oxides (as SO_2)	9.5	g

There are different kinds of, for steam methane reforming as the base case we use natural gas, coal and these are all the different kinds of inputs which are used for the net energy analysis of hydrogen forms steam methane reforming which is used as a base case for comparison with these options.

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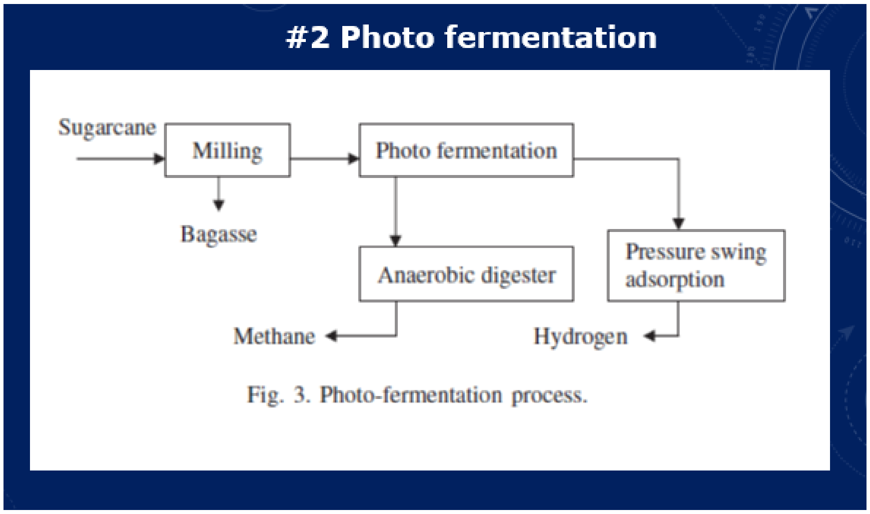

This one was the dark fermentation. In the case of Photo fermentation, we have the sugarcane mill to get bagasse then we get photo fermentation which goes to the anaerobic digester to produce methane and the photo fermentation output is separated using pressure swing absorption so we get hydrogen. In each of these processes there is some energy input which we quantified.

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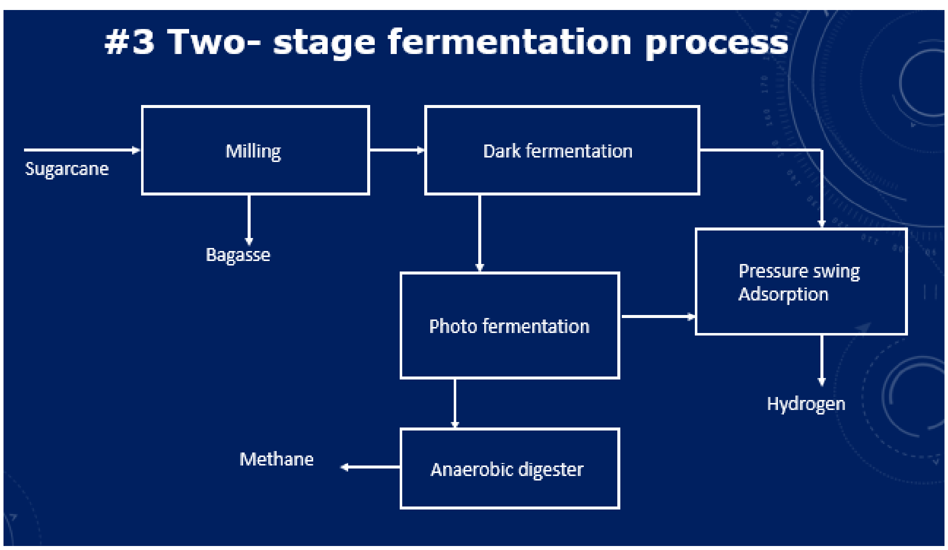

In the third process that we have is the two-stage fermentation process where again we have milling and bagasse, we have dark fermentation as well as photo fermentation and then you have anaerobic digester for methane and pressure swing adsorption for hydrogen.

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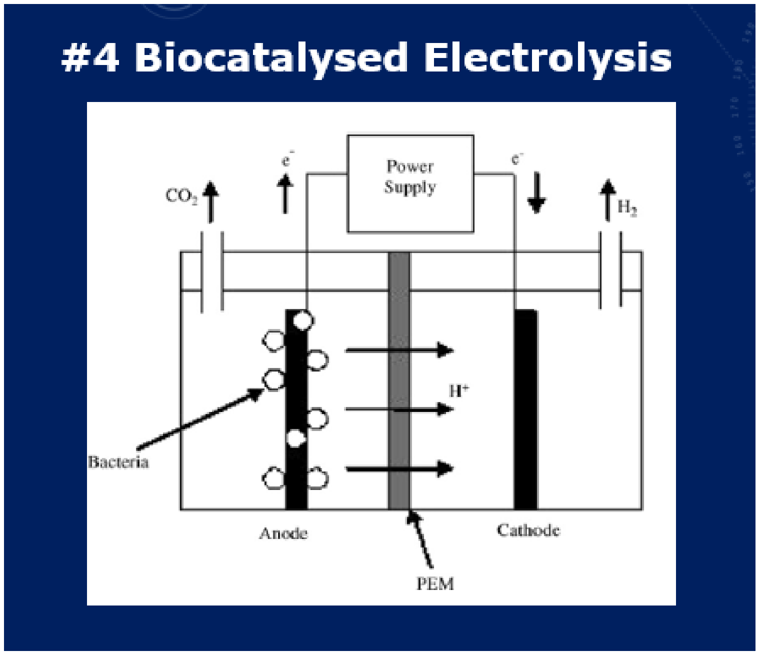

In the next process is with biocatalysed electrolysis where we have an anode and a cathode and bacteria where you have this, this is where you have the electrolysis and a hydrogen is being produced.

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Input data used in the analysis

Input variable	Value	Unit	Ref.
Electricity use in sugarcane crushing	37.8	kJ/kg of sugarcane	[20]
Sucrose output	10.45	% of sugarcane	[21]
Dry bagasse output	17.34	% of sugarcane	[21]
Optimum sugar concentration in fermentation	2	%	-
Optimum C/N ratio	47	–	[22]
H_2 production in dark-fermentation	3.4	mol/mol C_6	[23]
CO_2 production in dark-fermentation	1.7	mol/mol C_6	-
H_2 production in photo-fermentation	9.6	mol/mol C_6	[11]
CO_2 production in photo-fermentation	4.8	mol/mol C_6	-
Methane/CO_2 molar ratio in biogas	60/40	–	-
Hydrogen recovery in PSA	90	%	-
Isothermal efficiency of compressor	65	%	-
Electricity requirement in biocatalyzed electrolysis	0.6	kWh/m^3 H_2	[16]
Platinum loading in biocatalyzed electrolysis	0.5	mg/cm^2	[16]

And these are the input data in terms of the electricity used in the sugarcane crushing. And the production in the dark fermentation, photofermentation, methane to CO2 ratio, the recovery in the PSA, compressor needs electricity input so we have the isothermal efficiency and then we have the loading of the biocatalysed electrolysis, based on this we buildup for each of the process mass and energy balances.

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Results of mass and energy balance

Particular	Unit (/kg H2)	Dark-fermentation	Photo-fermentation	Two-stage process	Electrochemically assisted process
Input					
Sugarcane input	kg	281.45	99.68	93.09	90.56
Electricity input	kWh	5.8	3.89	3.82	6.42
Ammonia	kg	0.35	0.13	0.12	0.11
Platinum	mg	-	-	-	0.23
Output					
Bagasse (dry)	kg	46.06	16.31	15.23	14.82
Carbon dioxide	kg	24.59	13.44	13.04	12.39
Methane	kg	6.75	0.67	0.45	0.54

I am not going to go into details of these and look at the details in the paper and essentially what happens is that for each these the sugarcane input, electricity input, the ammonia, platinum, the outputs which are there and for each of these processes we create the inventories in terms of masses and then we also create energy content.

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Results (without by product use)

Process	Case 1: Without by-products		
	GHG (kg CO_2)	Non-renewable energy use (MJ)	Energy efficiency (%)
Steam methane reforming	12.8	188	64
Dark-fermentation	5.5	61.7	9.6
Photo-fermentation	3.5	40.1	25.6
Two-stage process	3.4	39.3	27.2
Biocatalyzed electrolysis	5.3	64.8	25.7

And then in the case one, the final results without byproduct, with byproduct of course it much looks better. You can see that in all these cases the CO_2 emissions, kg CO_2 per kg of hydrogen that we have is significantly lower in all the biocatalysed, in the biohydrogen processes and it turns out that the two-stage process seems to be the best in terms of the CO_2 emissions. Similarly, if you look at the nonrenewable energy use photo fermentation and two stage process look to be similar while biocatalyzed electrolysis uses much more in terms of energy.

So, this gives us a way a direction in terms of how to move forward, in terms of processes within the process we can again use it, if you can process model and we can again it to make the comparison between making a viable process and making a process which can then go to the next stage where you can do the economics.

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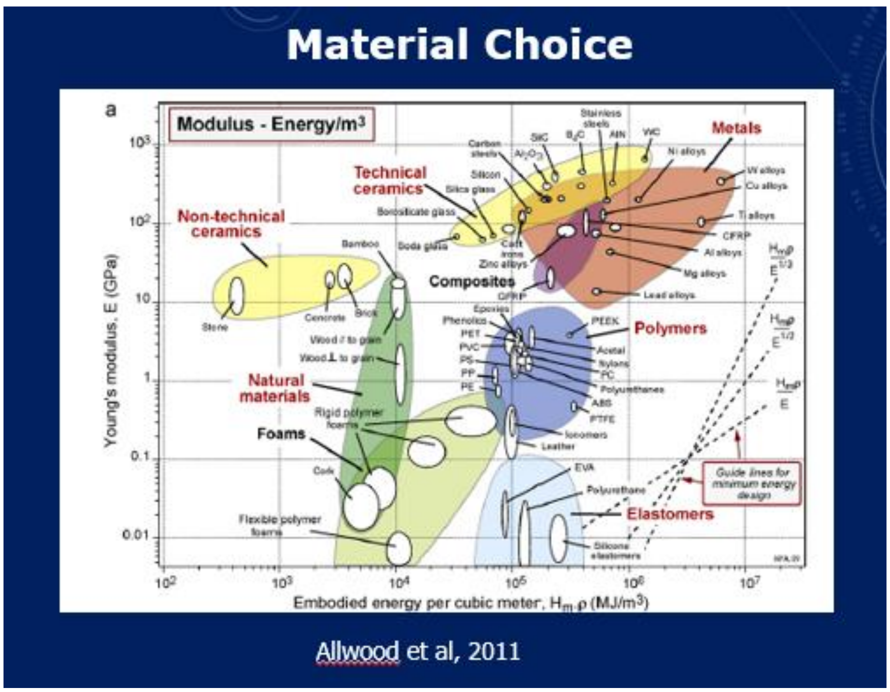

This has been, this is, these are the series of charts which have been used by Ashby which has been proposed by a UK researcher Ashby and this is reported in Allwood et al., you can see essentially the idea is that when we choose materials we often do that based on the particular application we choose from a particular set of materials. And people often historically use a particular set of materials but for some properties it is possible to have a whole host of materials.

So, for instance if you look at ceramics, metals, polymers and we look at let say the property that we are interested is a Young's Modulus. So, you can have for a given Young's Modulus a whole set of different materials between metals and ceramics and different materials have different amounts embodied energy. Similarly, we can also draw this in terms of embodied CO_2 so we can actually choose a material that uses less energy or less GHG equivalent emissions and this could be a basis for looking at the sustainable design for the future.

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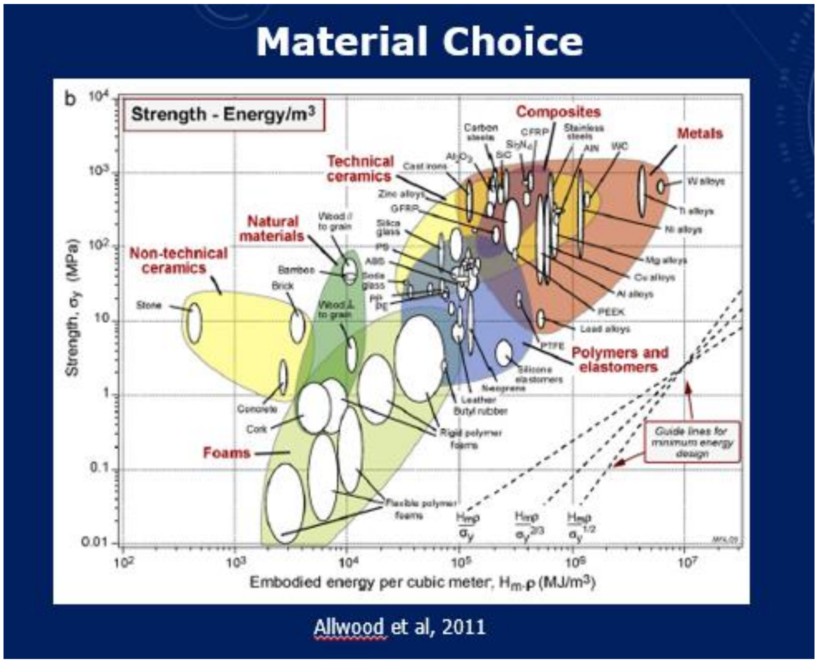

And this is just to illustrate, this is another parameter when we look at strength and so one can actually create this kind of curves and these can aid the designer in terms of choice of different kinds of materials and we are now in era where we actually have nano technology and we are creating designer materials. So, this can be even more useful because we can actually look at materials with a particular capability which has a low energy footprint, low carbon footprint.

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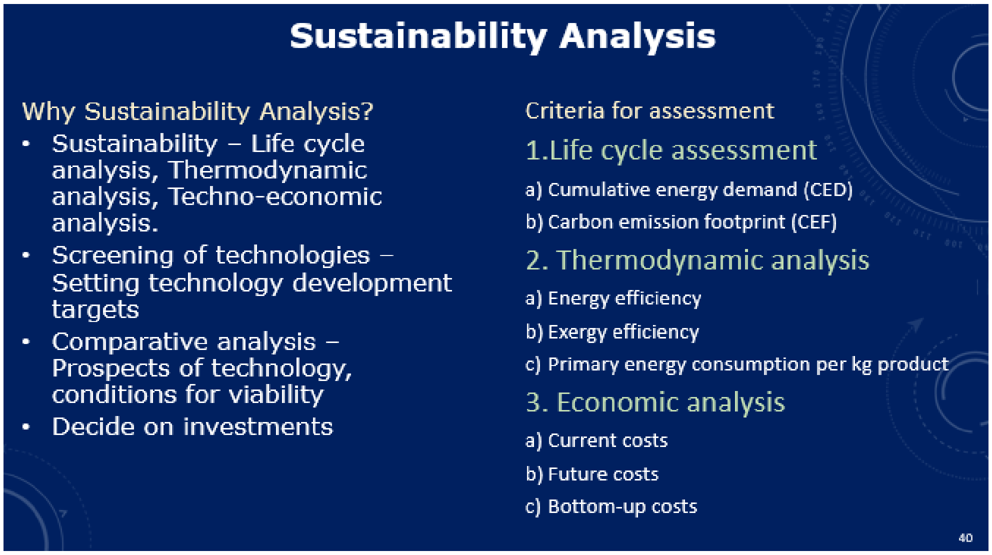

So, with this I would like to just give you the last example where we are talking of sustainability analysis where we are looking at combining all of this, the LCA, the thermodynamic analysis techno economic analysis. We would like to screen different kinds of technologies and compare them and see what are the prospects for future and this can help us in decision on investments.

So, we look at in the case of life cycle assessment these two criteria we will look at, the cumulative energy demand and the carbon emission footprint. And in thermodynamic analysis we can look at the energy efficiency, the exergy efficiency. Exergy is basically the second law of, using the second law where we convert everything into work equivalent which is exergy.

And then we can look at the primary energy consumption per kg. We can look at the current cost, future cost and bottom up cost. So, will take an example this is from a PhD thesis done recently by one of our students where we looked at the possibility of using for zinc which we manufacture currently using an industrial process using fossil fuels, how can we make the zinc manufacture process sustainable. So, we have a whole host of different options where we make it zero carbon and we would like to compare this.

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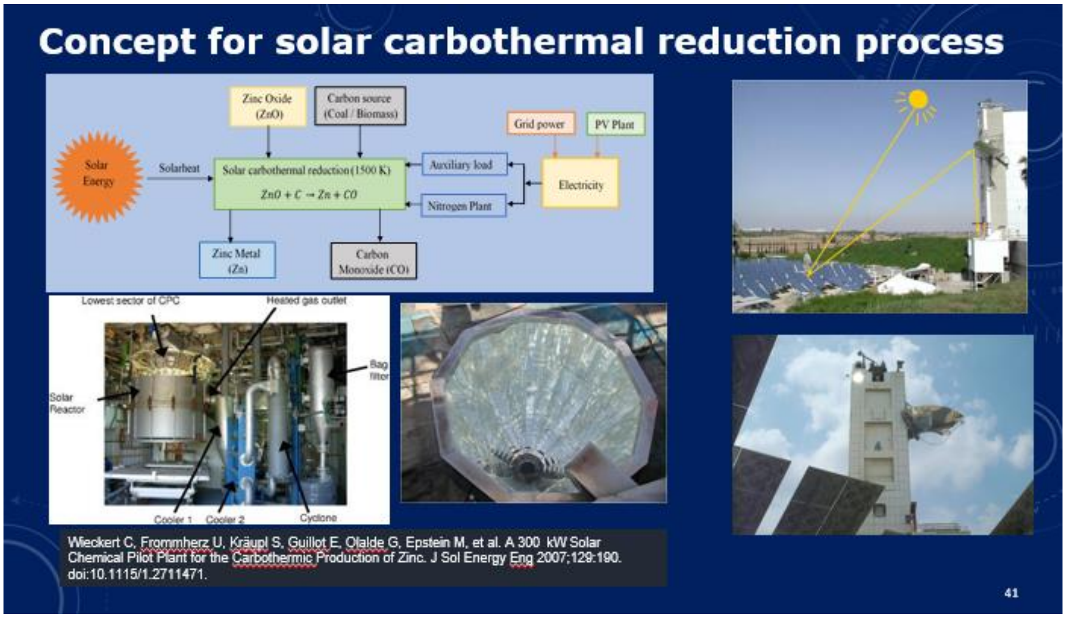

So, one of the processes that we are looking at is a solar carbothermal reduction where we start with zinc oxide and the carbon source which could be biomass or coal.

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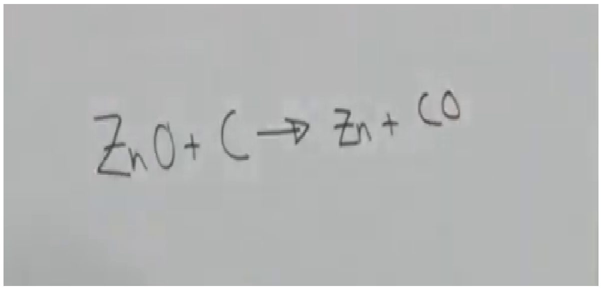

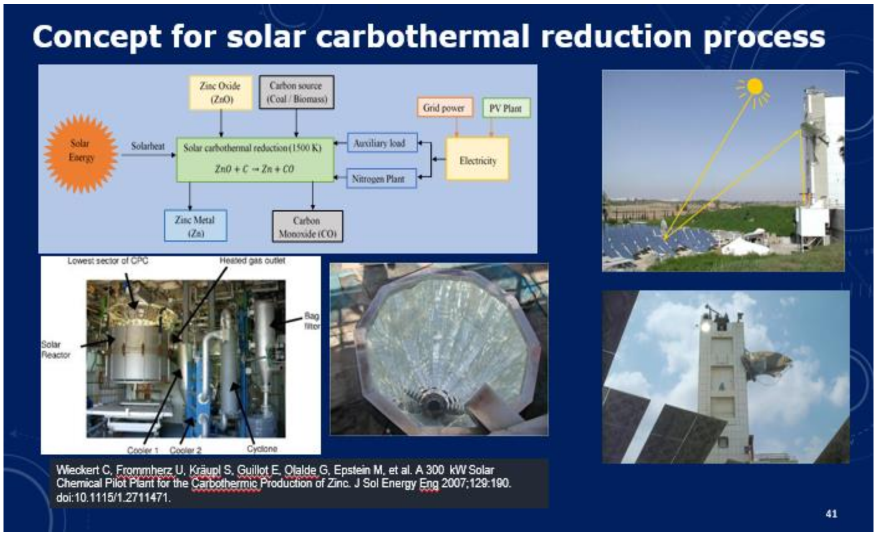

We have this reaction which is essentially zinc oxide plus carbon giving us zinc plus CO and this is a carbothermal reaction which we are carrying out at a high temperature. We generate those temperatures by getting solar thermal concentrated heat and there has been this reactor which has been there for carbothermal reaction of zinc, 300 kilo Watt reactor, compound parabolic collectors and this has been done in Israel.

You can see here that on the ground you have these heliostats which are focusing on to a reactor and this is a beam down reactor which again focuses, this translates it to a mirror and this goes to reactor which is here and this is getting very high temperatures and you can have, you concentrate it. This is one reactor which has actually been built and some performance data is available. We took that performance data and try to analyze what does this process mean if we wanted to implement this process to manufacture zinc. How would it look like in terms of the energy and the carbon?

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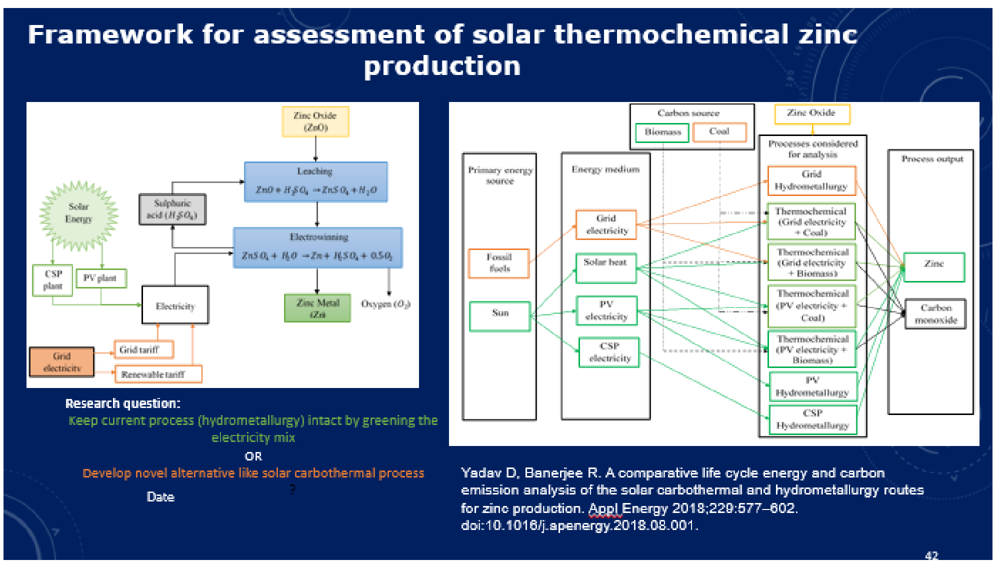

And this is how we calculate this, so essentially what happens is you can look at the multiplicity of processes, we can have either keep the process as it is zinc oxide, leaching, electrowinning, zinc metal and we can look at creating this the electricity that we are using and the heat that we are using get it from renewables that means photovoltage or CSP.

So, there is one possibility which we, the base line example is grid hydrometallurgy where you get grid electricity or we could have the solar giving you PV electricity and then running the PV hydrometallurgy or we can have solar thermal CSP, CSP hydrometallurgy and get Zinc and carbon mono oxide or we can do the carbothermal, the thermochemical and the whole host of different (techno) routes. In each of these we then identify the designed, the reactors and the systems to produce certain amount of zinc annually and then made this comparison.

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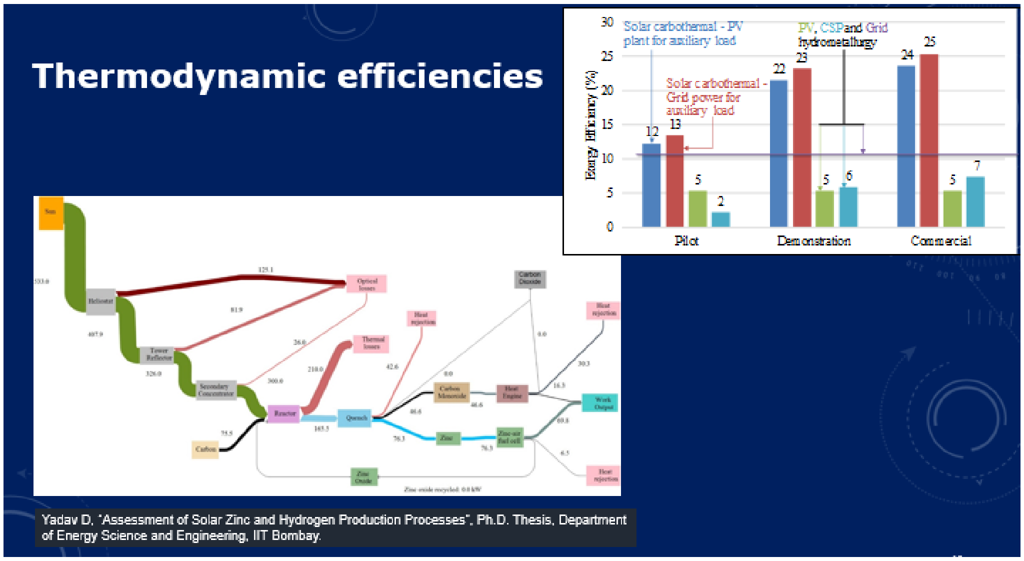

I am going to show you just the final results. When we did this, we then calculated, we developed a sort of sanky or an energy balanced diagram which shows you the different kinds of where all are the energy flows and the overall kinds of losses and the final output.

So, based on this we can see that the energy efficiency as compared this solar carbothermal and grid power when we look at solar carbothermal and the PV for the auxiliary load, we have an option of PV and CSP and grid hydrometallurgy. So, you can see that PV and hydro at the pilot scale if we one looks at it the PV and hydrometallurgy the existing process and making it PV seems to be better in terms of an energy efficiency viewpoint.

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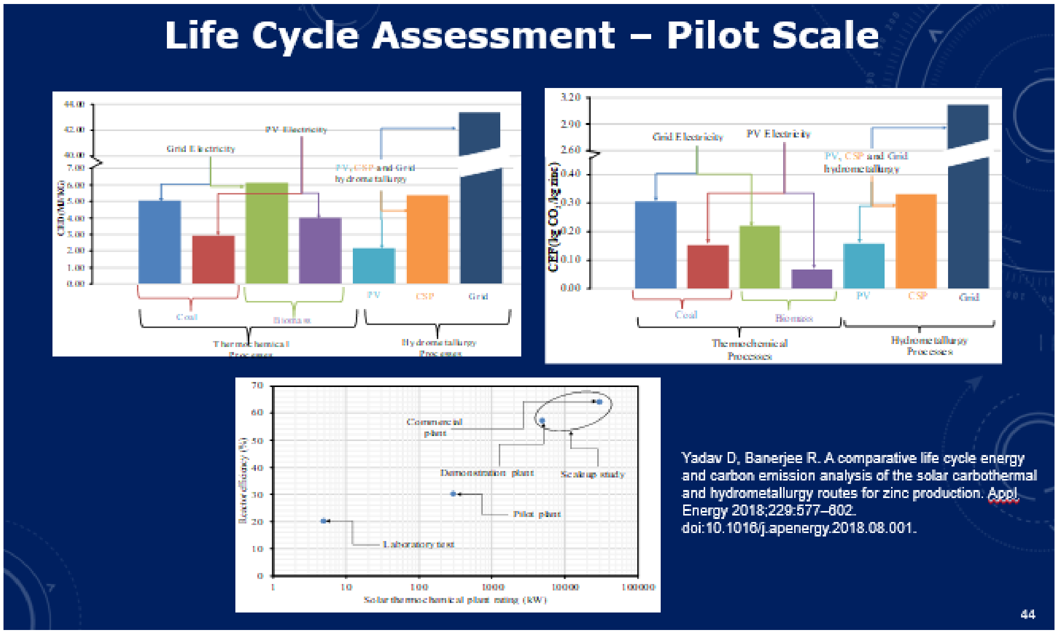

However, from a CO_2 viewpoint, when we look at the life cycle assessment from the cumulative energy demands CED and the CEF you can see very clearly that with grid electricity this is the mega Joules per kg of zinc that we are getting and with PV we can, this reduces very significantly and CSP also this reduces if we can get the thermochemical route with biomass then we can actually get somewhat nearer the PV though it is still little higher than the PV.

However, on a CO_2 basis you can see very clearly that if we compare a thermochemical process with biomass, thermochemical process with biomass then it is possible to actually go ahead and make the thermochemical process with the PV for the auxiliary and the thermochemical process turns out to be better than the PV hydrometallurgy option. So, this shows us that it is possible to actually go ahead and we can look at a new renewable base process for zinc. And it is possible actually that we can modify all the industrial processes so that they become zero carbon.

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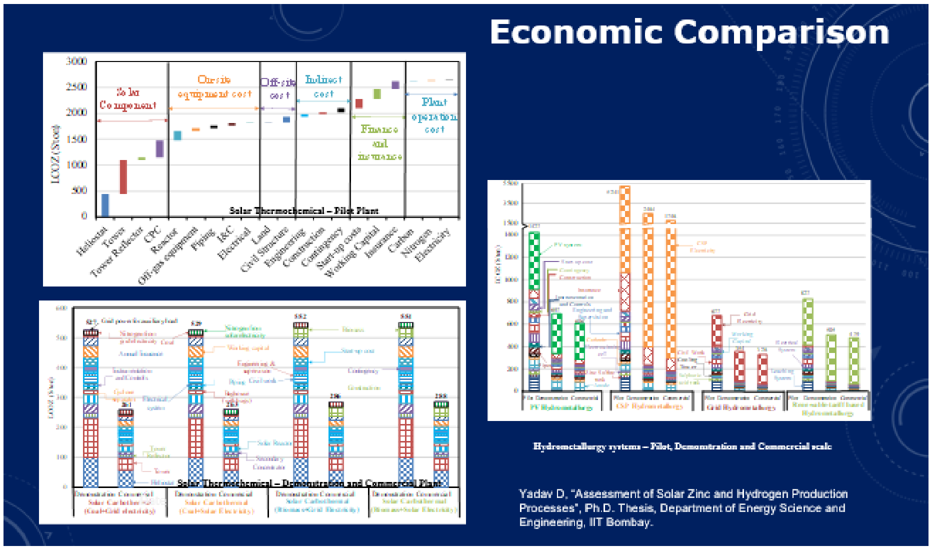

There are multiplicity of different possibilities in terms of routes and when we do the initial pilots and the experiments, one can actually use net energy and life cycle analysis and the carbon footprint as a bases for making this comparison. Now, what does it look like in terms of economics?

Now, interestingly of course, when we look at economics these, all these routes that we talk of are much costlier today. They are costlier by a factor of 10 but it is possible with technology development and volumes that this cost we can go down significantly in the future.

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Levelized cost of Zinc ($/ton)

Process / Year	Pilot			Demonstration			Commercial		
	2018	2030	Bottom-up	2018	2030	Bottom-up	2018	2030	Bottom-up
Solar carbothermal (Grid power + Coal)	2658	2145	950	527	420	285	261	217	184
Solar carbothermal (Solar power + Biomass)	2685	2172	977	553	447	312	288	243	210
Renewable tariff hydrometallurgy	827	786	-	505	464	-	479	437	-
Grid Hydrometallurgy	677	677	-	354	354	-	328	328	-

Yadav D, "Assessment of Solar Zinc and Hydrogen Production Processes", Ph.D. Thesis, Department of Energy Science and Engineering, IIT Bombay.

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So, for instance if we look at it the solar carbothermal with biomass which is the route that we are looking at is depending on the way you do the estimates about to 1000 to 2000 dollars per ton as compared to the grid hydrometallurgy commercial one which is order of 300 dollars per ton, of course this is at the pilots scale, if we make this at the commercial scale and we expect the kind of cost reductions that are possible then we can actually go ahead and get in that same range.

So, it is possible that we can do this kind of a cost reductions. So, now when you look at net energy analysis, life cycle analysis; life cycle analysis gives us a way in which we can look at over the entire life cycle, the environmental impacts and the energy impacts.

Net energy analysis at times what happens is especially in the case of new technologies and when we are looking at going from the research and the lab scale to the pilot scale or pilot scale to the before commercialization, it is very difficult to estimate what would be the cost.

In a situation where you have limited information about the cost and there are only one or two companies which are exploring this, it is important to look at how does a new technology look at from the point of view of the overall energy that is input, is the NER greater than 1, what is it look like in terms of the CO_2 impact.

So, these are additional tools and techniques available to you which you can use along with the economic calculation and the emission calculations and that can help in sort of screening and deciding where it can go. In some cases, if you find that the ratios, the energy numbers and the cost numbers are almost similar then it is likely that there is no not much scope for reduction or it needs major break throughs.

In cases like where you find that the energy inputs are much lower but the cost are at a higher factor it means that with technology development and commercialization it is possible that, that technology may actually yield better results. So, an energy, net energy analysis can help and direct some of the choices of new materials, new processes.

And this is something which is being used but not used as much as it could be and this is something which I hope you will use when you analyze different energy systems and you specially look at new things coming out to see that they are viable from an overall energy point of view. With this we will close with this module and we will go to the next module which will be on energy policies and how we can do policy analysis.