Energy Resources, Economics and Environment
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Lecture 22 P1
Net Energy Analysis – Part 3

We have been looking at net energy analysis and life cycle analysis we continue with that some examples. Before we do that let me just again tell you about the criteria that we talked of.

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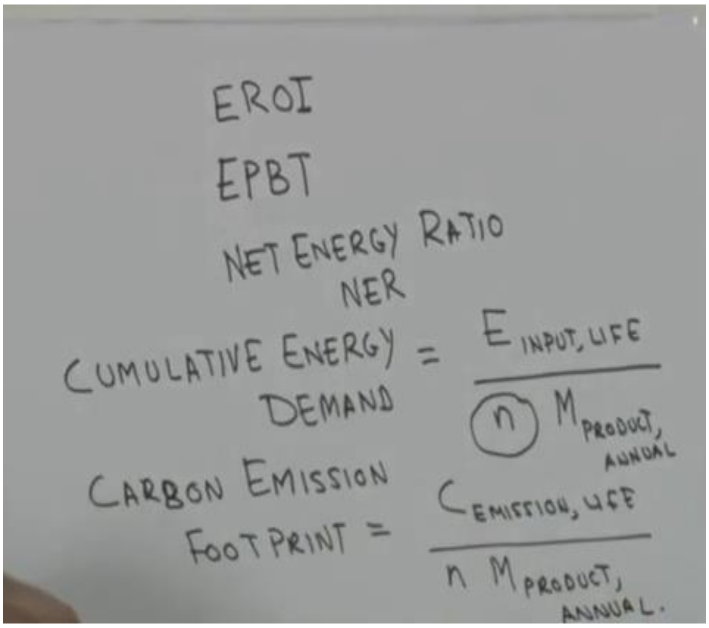

EROI

EPBT

NET ENERGY RATIO
NER

$$\text{CUMULATIVE ENERGY DEMAND} = \frac{E_{\text{INPUT, LIFE}}}{\textcircled{n}\, M_{\text{PRODUCT, ANNUAL}}}$$

$$\text{CARBON EMISSION FOOT PRINT} = \frac{C_{\text{EMISSION, LIFE}}}{n\, M_{\text{PRODUCT, ANNUAL.}}}$$

We talked about the energy return on investment EROI. We also looked at the energy payback period which is E energy payback time EPBT. And then the net energy ratio, similar to the energy return on investment, net energy ratio NER. Remember in the NER we were not using the renewable energy resources in this. In addition to this there are two other similar indicators which will be use, which is also used in literature, one is called the cumulative energy demand.

And this is often done even for products that means we take, let us say we are making steel or we are making cement, we take the total amount of energy which is required in the over the lifetime, energy input over the life and divide that by n which is the number of years of life and the output that we are producing. So, if you looking at the production, M product annual.

So, we will, so you take the cumulative energy over the life side, that is the energy input divide that by the number of years into the annual production. So, this is called the cumulative energy demand and we can compare the CED for different process route and see overall whether or not our option is better than the baseline. Similarly, we have what is known as a Carbon Emission footprint and this will be the total carbon dioxide or carbon emission whichever way you would like to do that over the lifetime, emission over the life divided by n into M product annual.

And so, what I will now show you is our examples of net energy analysis that we have done in the Indian context, these are all based on different student projects, some of them are at the master’s level, some of them are at the PhD level and so will take, this will give you an idea of how this analysis can be used for different kinds of context. And at the end we will talk about what are the advantages and disadvantages of using net energy and life cycle analysis and how do they compare with the conventional economic analysis.

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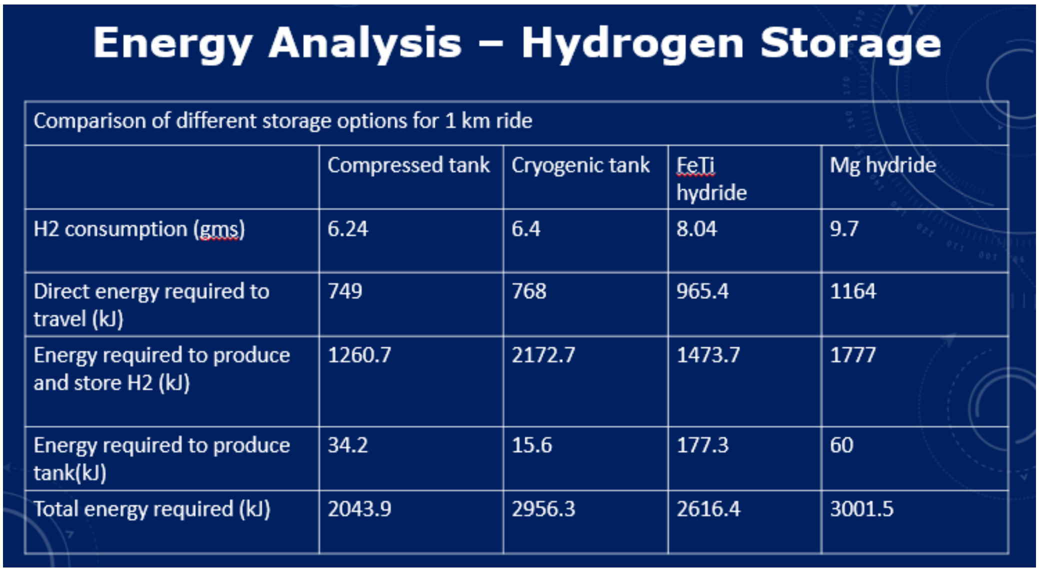

Energy Analysis – Hydrogen Storage

Comparison of different storage options for 1 km ride

	Compressed tank	Cryogenic tank	FeTi hydride	Mg hydride
H2 consumption (gms)	6.24	6.4	8.04	9.7
Direct energy required to travel (kJ)	749	768	965.4	1164
Energy required to produce and store H2 (kJ)	1260.7	2172.7	1473.7	1777
Energy required to produce tank(kJ)	34.2	15.6	177.3	60
Total energy required (kJ)	2043.9	2956.3	2616.4	3001.5

So, let us start with an example. This is an example of different, you know many of, many researchers believe that the future will be with hydrogen and hydrogen is a secondary fuel, secondary energy source. The key thing is terms of using hydrogen in a transport sector would be how do we store the hydrogen. So, there are, what we looked at here is the different kinds of, we can have like you have the CNG compressed natural gas, we can also have compressed hydrogen storage.

And this will be at high pressures and then we can also look at liquefying the hydrogens, so that there is volume gets reduced and then you have a cryogenic tank and we could also have solid state storage, metal hydride and there are number of people who are working on different kinds of metal hydride, so we can look at magnesium hydride and FeTi hydride and in this we can for a certain amount of distance which we are riding, what is the amount of energy which is being consumed.

And then direct energy required for travel, energy required to produce and stored the hydrogen, energy required to produce and store the produce the tank and so we get the total energy required for the tank. And you can see some methods of storage have relatively less energy that is required. So, for instance magnesium hydride seems to be better than FeTi hydride and if one looks at it in the case of the production and storage, in this case you will find that for cryogenics there is a significant amount of energy required for this storage.

The add on materials is so when we look at the total, it turns out that the FeTi hydride has is lower than the magnesium hydride even though the energy reduced to produce the tank is lower. And so that depends on the performance and we can use for an equivalent amount of performance we can compare. And right now, as it looks like the compressed, the compresses hydrogen tank seems to be the, from an energy point of view the best option, of course there are issues in terms of safety and solid-state storage account better for the safety.

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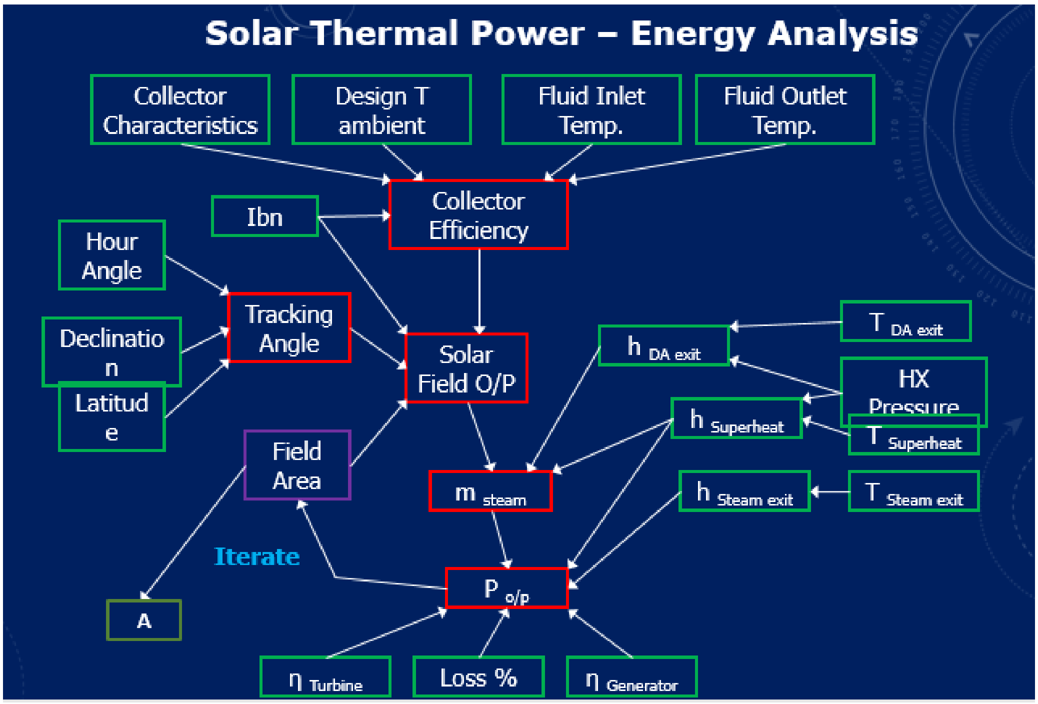

Solar Thermal Power – Energy Analysis

Collector Characteristics

Design T ambient

Fluid Inlet Temp.

Fluid Outlet Temp.

Ibn

Collector Efficiency

Hour Angle

Declination

Latitude

Tracking Angle

Solar Field O/P

Field Area

Iterate

A

$h_{DA\ exit}$

$T_{DA\ exit}$

HX Pressure

$h_{Superheat}$

$T_{Superheat}$

$h_{Steam\ exit}$

$T_{Steam\ exit}$

m_{steam}

$P_{o/p}$

$\eta_{Turbine}$

Loss %

$\eta_{Generator}$

In the case of solar thermal power we have done in the energy analysis for the both parabolic trough collectors and Fennel reflectors in all of this first what we did is we defined for a particular amount of output which we require, 50 mega watt plant with a particular amount of output, we defined the different characteristics for a particular location and then calculated the amount of steam and then the solar field requirement and then the field area.

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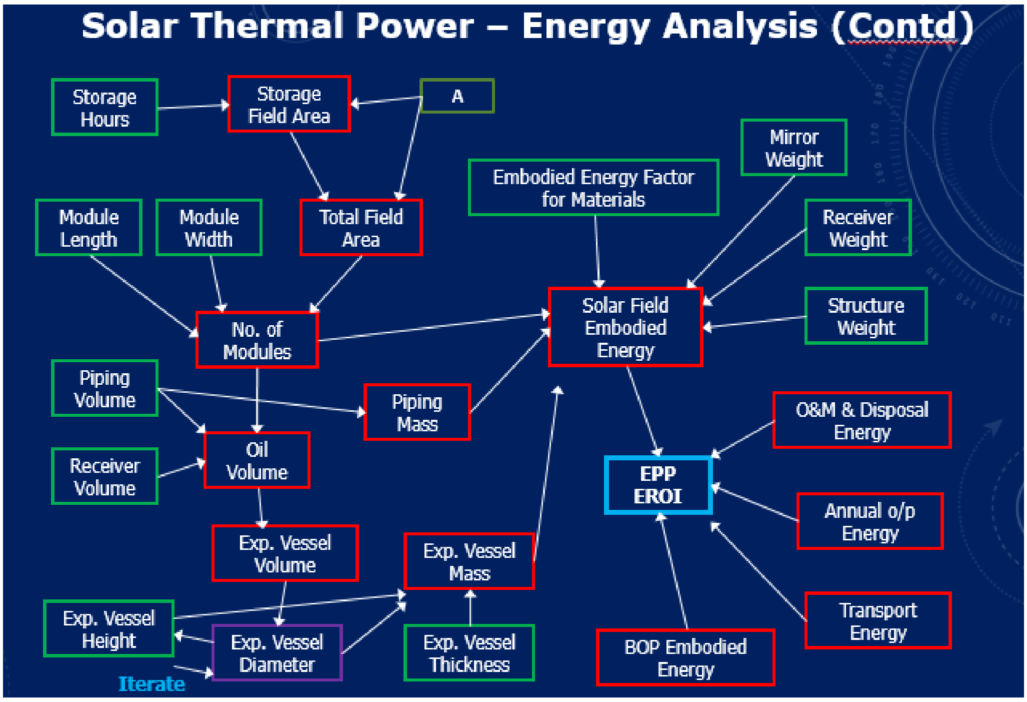

Solar Thermal Power – Energy Analysis (Contd)

Storage Hours
Storage Field Area
A
Mirror Weight
Embodied Energy Factor for Materials
Module Length
Module Width
Total Field Area
Receiver Weight
No. of Modules
Solar Field Embodied Energy
Structure Weight
Piping Volume
Piping Mass
O&M & Disposal Energy
Receiver Volume
Oil Volume
EPP EROI
Annual o/p Energy
Exp. Vessel Volume
Exp. Vessel Mass
Transport Energy
Exp. Vessel Height
Exp. Vessel Diameter
Exp. Vessel Thickness
BOP Embodied Energy
Iterate

And having got that we then calculate it, the dimensions of the modules, module length, module width, number of modules, the oil volume, the piping volume, receiver volume, the vessel dimensions and then we have an embodied energy factor for each of these materials. So, you have the solar field, steel and the glass and the mirrors and then you have the receiver mirror weight, structure weight, the energy used in this and then we got the energy payback period and the energy return on investment.

And it turns out that for the parabolic troughs collectors the energy payback period turns out to be higher than that for photo voltaic, but even then, it is of the order of about little less than 4 years which means that it is, it could be viable because the solar parabolic troughs collectors last for 25, 30 years.

And so, with the result that even though the economics today of solar thermal does not seem to be it is little costlier than the conventional, from an energy point of view it you recover your, the energy investment in less than 4 years. And then the remaining part is basically the advantage and you are going to get, the NER is going to be greater than 1.

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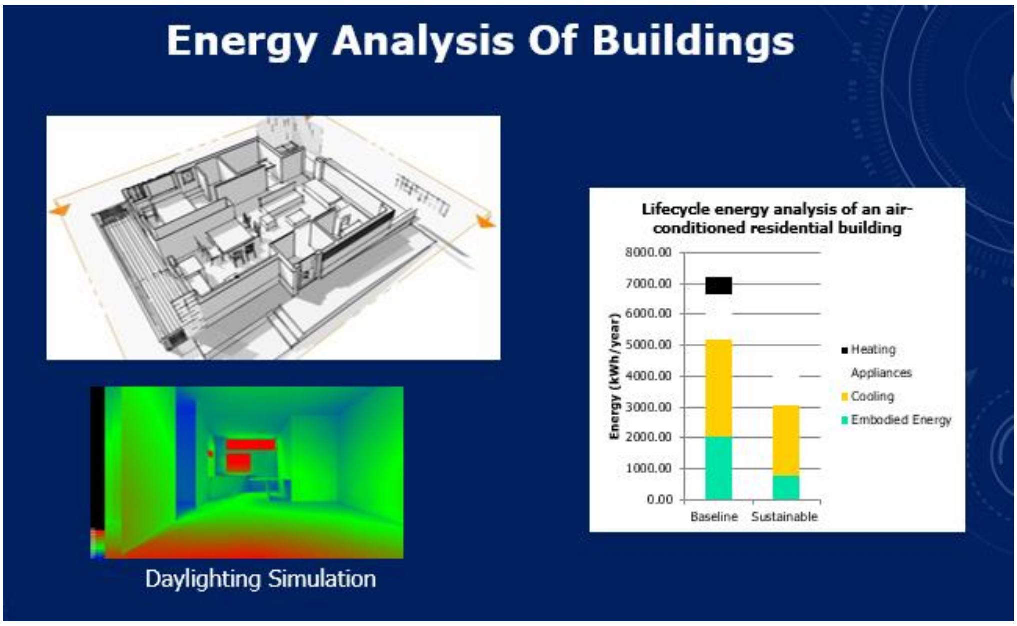

Energy Analysis Of Buildings

Daylighting Simulation

In the case of buildings one can look at different types of, in a building there is a significant amount of energy which is used in the operations. And one can look at different kinds of materials if we are using more insulation, we are using phase change materials, the initial embodied energy of the building can be slightly higher but that can reduce the operating energy.

And so, if you look at a sustainable building you will find that the embodied energy component as compared to the baseline, share of the embodied energy is slightly higher but the overall energy gets reduced. And this is another area where there is a very significant scope for improvement, we can compare different kinds of materials, we can look at what is the embodied and the operating energy and then calculate this.

Because buildings overall are extremely important, 30 to 40% of the total energy used is associated with buildings and if we can design the buildings so that the life cycle energy used is drastically lower then we can use renewables to supply that and we can have a sustainable solution which is distributed.

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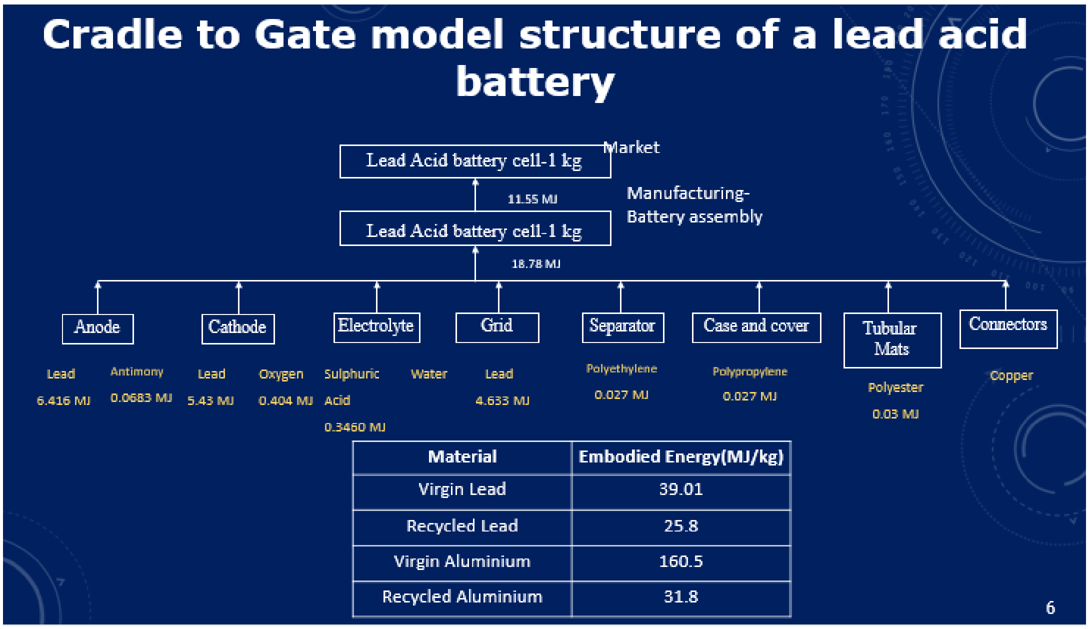

Cradle to Gate model structure of a lead acid battery

Lead Acid battery cell-1 kg

Market

11.55 MJ

Manufacturing-
Battery assembly

Lead Acid battery cell-1 kg

18.78 MJ

Anode
Lead
6.416 MJ
Antimony
0.0683 MJ

Cathode
Lead
5.43 MJ
Oxygen
0.404 MJ

Electrolyte
Sulphuric Acid
0.3460 MJ
Water

Grid
Lead
4.633 MJ

Separator
Polyethylene
0.027 MJ

Case and cover
Polypropylene
0.027 MJ

Tubular Mats
Polyester
0.03 MJ

Connectors
Copper

Material	Embodied Energy(MJ/kg)
Virgin Lead	39.01
Recycled Lead	25.8
Virgin Aluminium	160.5
Recycled Aluminium	31.8

So, now I would like to show you some results that we have done for situation where we are comparing distributed TV, battery and systems and we want to look at different kinds of batteries which are there and we have done an analysis cradle to gate kind of analysis of the different types of batteries and try to see what it means in terms of embodied energy.

So, if you look at the batteries, I just like to show you some of the steps involved and how one goes about this analysis. For more details, you can see the paper which is being written by Jani on this project. So, we can look at for a particular amount of, we were looking at a particular amount of electricity which is being generated and if we look at by weight, if you are looking at 1 kg of a lead acid battery cell, the manufacturing, the battery assembly has anode, cathode, electrolyte and you can see the amount of different materials which are there.

For each of these again in the case of lead is a question of how much is actually purchased and extracted and how much is coming from recycled and that share that fraction affects the overall calculation. Similarly, for aluminium and recycled aluminium. So, these factors can be varied and based on this the numbers will change and you can see all the different component, separator, tubular mass, connectors and the assembly of the battery all of that is put into it.

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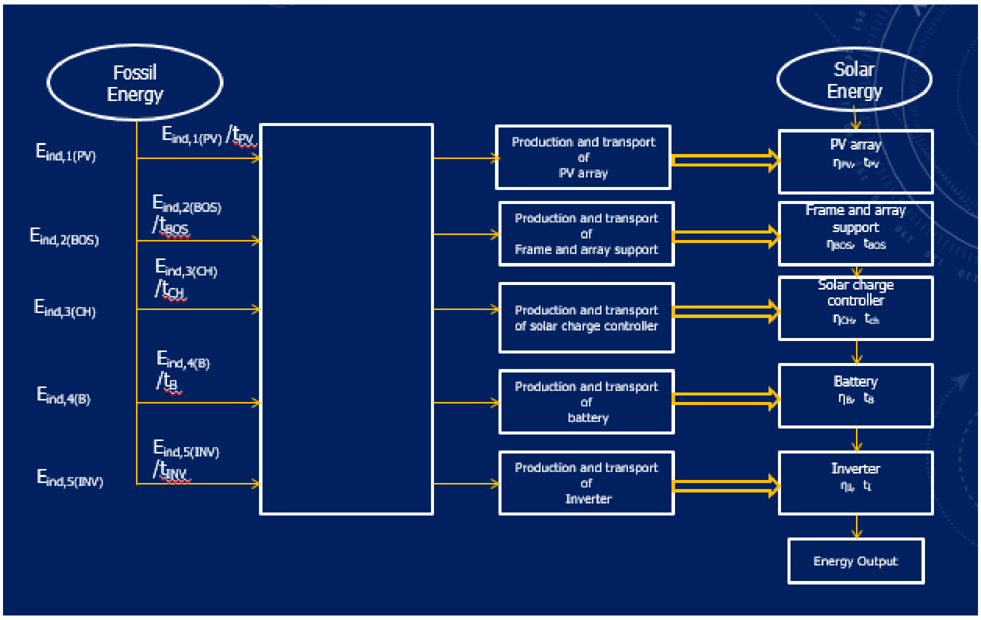

When we look at the overall cell we are PV battery system we are looking at the manufacture and transport of the PVRA, production and transport of the frame and the array support of the solar charge controller, the battery, the invertor and then based on this we get for a particular output we can make this calculation. And this gives us all the different steps in the lifecycle analysis so that we can get the total amount of energy that we are getting in this system.

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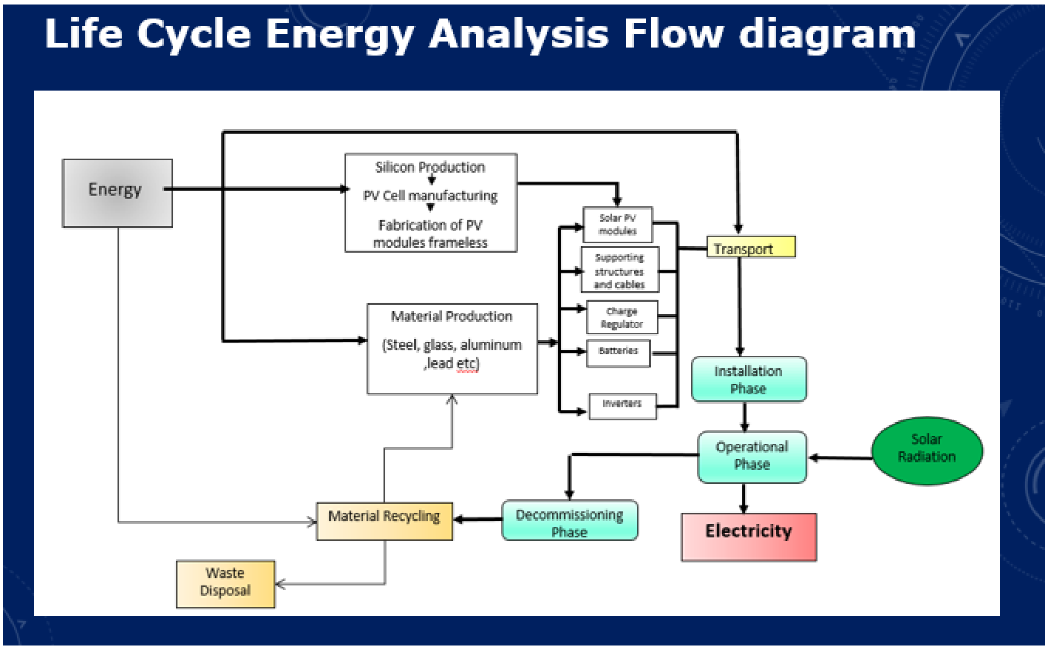

Life Cycle Energy Analysis Flow diagram

So, if you see this, this is the, this is another picture, is schematic of this which talks to, which tells us silicon production, PV cell manufacturing, fabrication of the module then frames, the materials which are there in it. And then we have the batteries and then the installation phase, operating phase and then material recycling and the waste disposal. In this case we just concentrated on this and we have not added the waste disposal phase.

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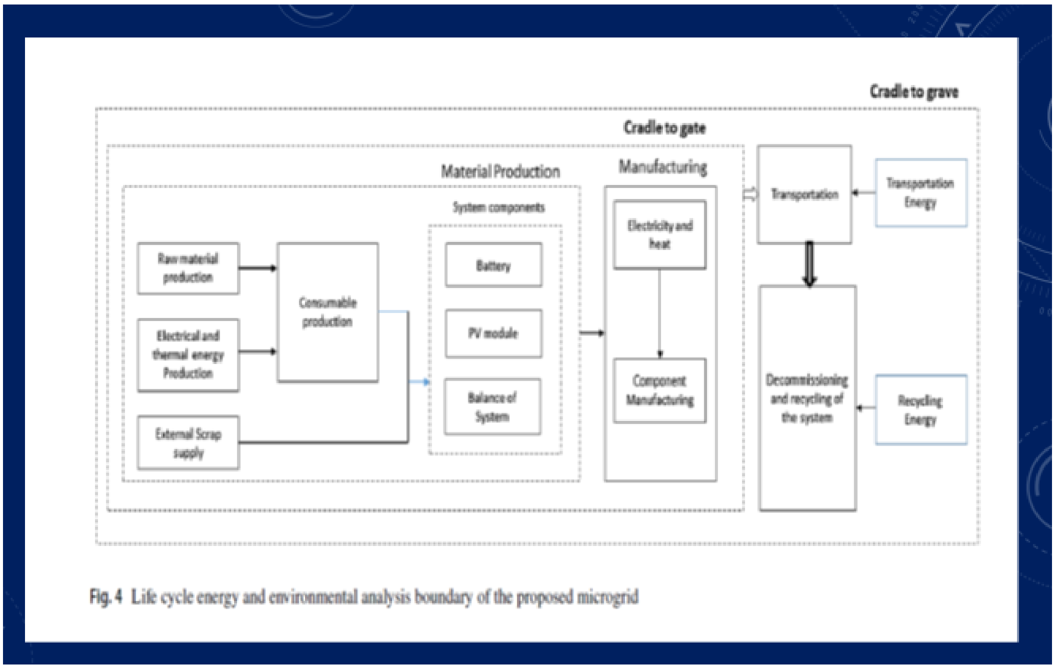

Fig. 4 Life cycle energy and environmental analysis boundary of the proposed microgrid

So, this is for the, this is the cradle to grave gate. If we wanted to do cradle to grave, we would have also needed to take the decommissioning and recycling and the transportation of this. So, in each of this there is materials, there is embodied energy in the materials, there is the electricity and the energy used which is there.

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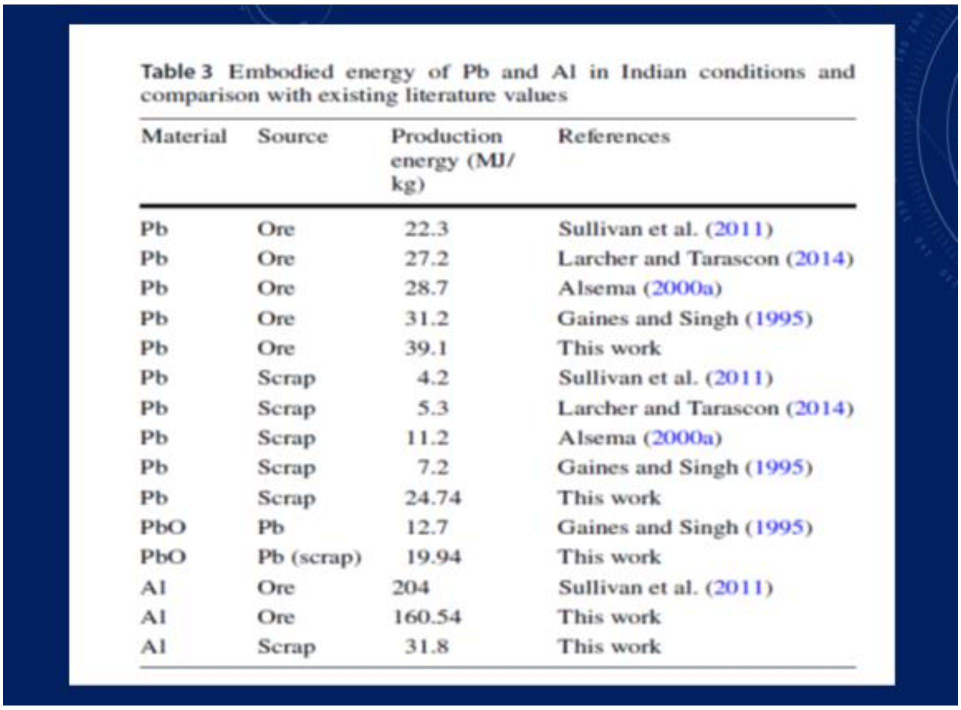

Table 3 Embodied energy of Pb and Al in Indian conditions and comparison with existing literature values

Material	Source	Production energy (MJ/kg)	References
Pb	Ore	22.3	Sullivan et al. (2011)
Pb	Ore	27.2	Larcher and Tarascon (2014)
Pb	Ore	28.7	Alsema (2000a)
Pb	Ore	31.2	Gaines and Singh (1995)
Pb	Ore	39.1	This work
Pb	Scrap	4.2	Sullivan et al. (2011)
Pb	Scrap	5.3	Larcher and Tarascon (2014)
Pb	Scrap	11.2	Alsema (2000a)
Pb	Scrap	7.2	Gaines and Singh (1995)
Pb	Scrap	24.74	This work
PbO	Pb	12.7	Gaines and Singh (1995)
PbO	Pb (scrap)	19.94	This work
Al	Ore	204	Sullivan et al. (2011)
Al	Ore	160.54	This work
Al	Scrap	31.8	This work

And just to give you an idea, when we talk about lead or aluminium there are variety of different sources which give the amount of energy per kg. So, you can see here, the from, this is the what is known as virgin lead. That means if you are just directly getting from the ore it varies from 22 to 39 different, we view this as 39.1, these are for other context Europe and others we have taken the location of the mine, the kind of ore that we have, the energy used in that and we got value of this and the details are there in the paper.

From scrap again, you can see that there is a reasonable range and of course the point to notice that the energy used from scrap is significantly lower than that in this case. And similarly, in the case of aluminium, in our case aluminium from ore, the energy, embodied energy is actually lower than the international number that is because of the current, the basis, the based on our production and our efficiency of our manufacturing and then this is from the scrap.

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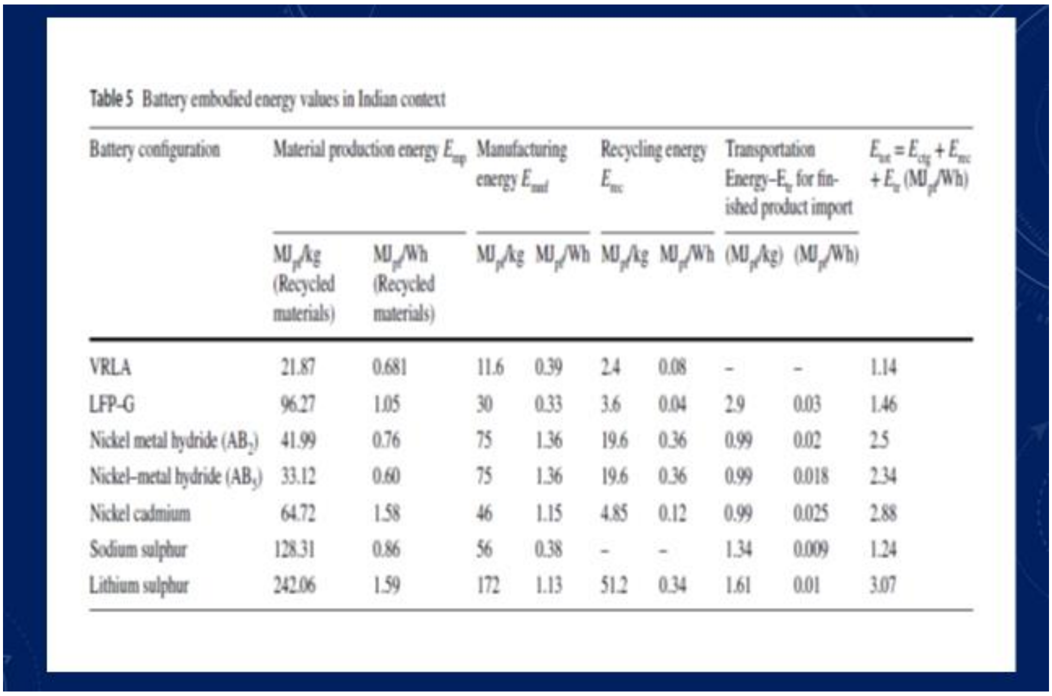

Table 5 Battery embodied energy values in Indian context

Battery configuration	Material production energy E_{mp}		Manufacturing energy E_{mfd}		Recycling energy E_{rec}		Transportation Energy–E_{tr} for finished product import		$E_{tot} = E_{ctg} + E_{rec} + E_{tr}$ (MJ_{pf}/Wh)
	MJ_{pf}/kg (Recycled materials)	MJ_{pf}/Wh (Recycled materials)	MJ_{pf}/kg	MJ_{pf}/Wh	MJ_{pf}/kg	MJ_{pf}/Wh	(MJ_{pf}/kg)	(MJ_{pf}/Wh)	
VRLA	21.87	0.681	11.6	0.39	2.4	0.08	–	–	1.14
LFP-G	96.27	1.05	30	0.33	3.6	0.04	2.9	0.03	1.46
Nickel metal hydride (AB_2)	41.99	0.76	75	1.36	19.6	0.36	0.99	0.02	2.5
Nickel–metal hydride (AB_5)	33.12	0.60	75	1.36	19.6	0.36	0.99	0.018	2.34
Nickel cadmium	64.72	1.58	46	1.15	4.85	0.12	0.99	0.025	2.88
Sodium sulphur	128.31	0.86	56	0.38	–	–	1.34	0.009	1.24
Lithium sulphur	242.06	1.59	172	1.13	51.2	0.34	1.61	0.01	3.07

Based on this now we get for each of the different batteries, lead acid battery, lithium ion, nickel metal hydride, nickel cadmium, sodium sulphur, lithium sulphur and we get the material per kg of the material the manufacturing energy, the recycling energy, the transportation and then we get the mega Joules per Watt hour of the battery capacity. And you can see that there is quite a bit of variation in this, lead acid of course seems to be low in terms of the embodied energy and that is why lead acid is actually quite popular, its initial costs are also low, life is less and they have environmental impacts.

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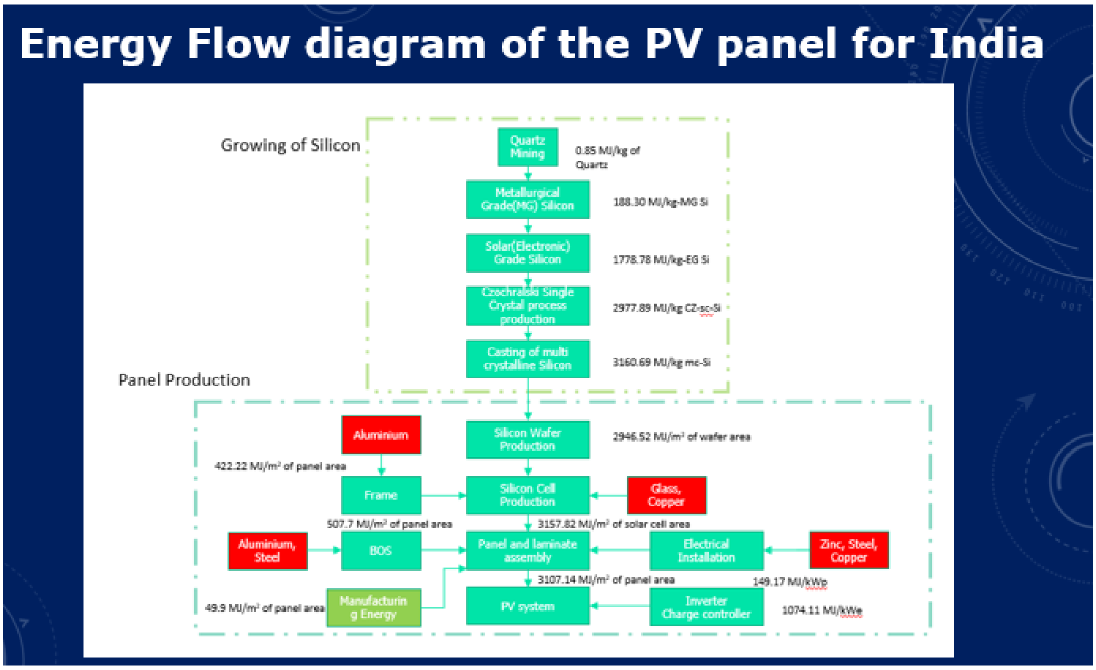

Energy Flow diagram of the PV panel for India

So, the PV panel numbers, if you see this is the breakup of the starting from quartz, the metallurgical grate silicon production, and then the solar grate silicon and then and so on. And then coming into the glass and copper, the frame, aluminium and you can see for each of these components, there are different energy inputs which have been calculated and you can find more details in this paper. This gives us finally the kind of values.

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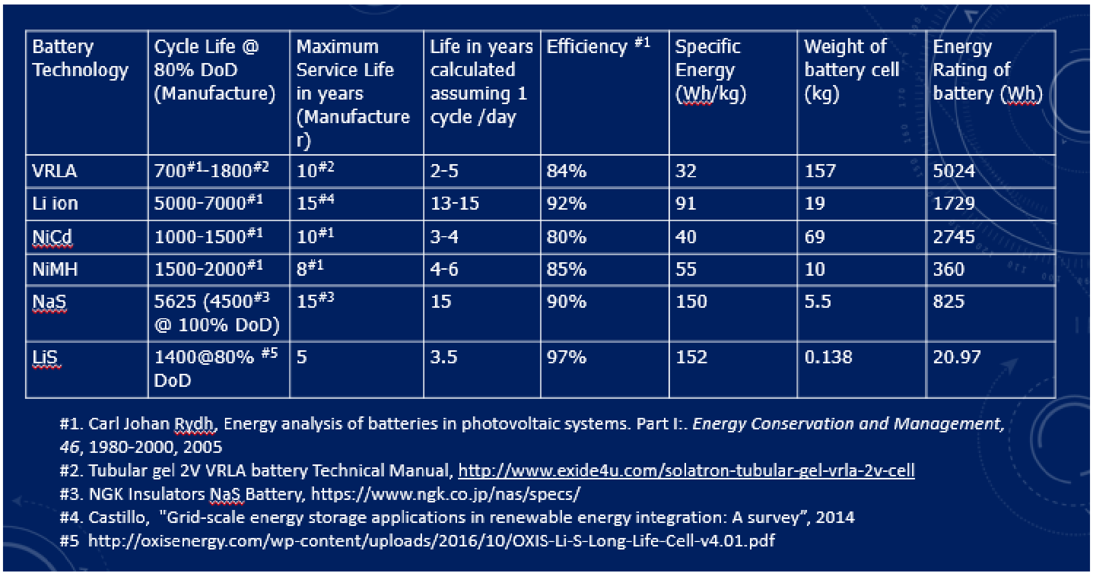

Battery Technology	Cycle Life @ 80% DoD (Manufacture)	Maximum Service Life in years (Manufacturer)	Life in years calculated assuming 1 cycle /day	Efficiency [#1]	Specific Energy (Wh/kg)	Weight of battery cell (kg)	Energy Rating of battery (Wh)
VRLA	700[#1]-1800[#2]	10[#2]	2-5	84%	32	157	5024
Li ion	5000-7000[#1]	15[#4]	13-15	92%	91	19	1729
NiCd	1000-1500[#1]	10[#1]	3-4	80%	40	69	2745
NiMH	1500-2000[#1]	8[#1]	4-6	85%	55	10	360
NaS	5625 (4500[#3] @ 100% DoD)	15[#3]	15	90%	150	5.5	825
LiS	1400@80% [#5] DoD	5	3.5	97%	152	0.138	20.97

#1. Carl Johan Rydh, Energy analysis of batteries in photovoltaic systems. Part I:. *Energy Conservation and Management*, *46*, 1980-2000, 2005
#2. Tubular gel 2V VRLA battery Technical Manual, http://www.exide4u.com/solatron-tubular-gel-vrla-2v-cell
#3. NGK Insulators NaS Battery, https://www.ngk.co.jp/nas/specs/
#4. Castillo, "Grid-scale energy storage applications in renewable energy integration: A survey", 2014
#5 http://oxisenergy.com/wp-content/uploads/2016/10/OXIS-Li-S-Long-Life-Cell-v4.01.pdf

So, if we look at the different batteries when we talk about the batteries, here you can see the difference in the cycle life, you see lithium ion has much higher cycle life than the lead acid and then the other one something in between and the life and the efficiencies, specific energy, the energy rating and of course depending on the battery efficiency for a particular requirement the ratings on the same functional unit and bases you will have different ratings and that is used for calculations.

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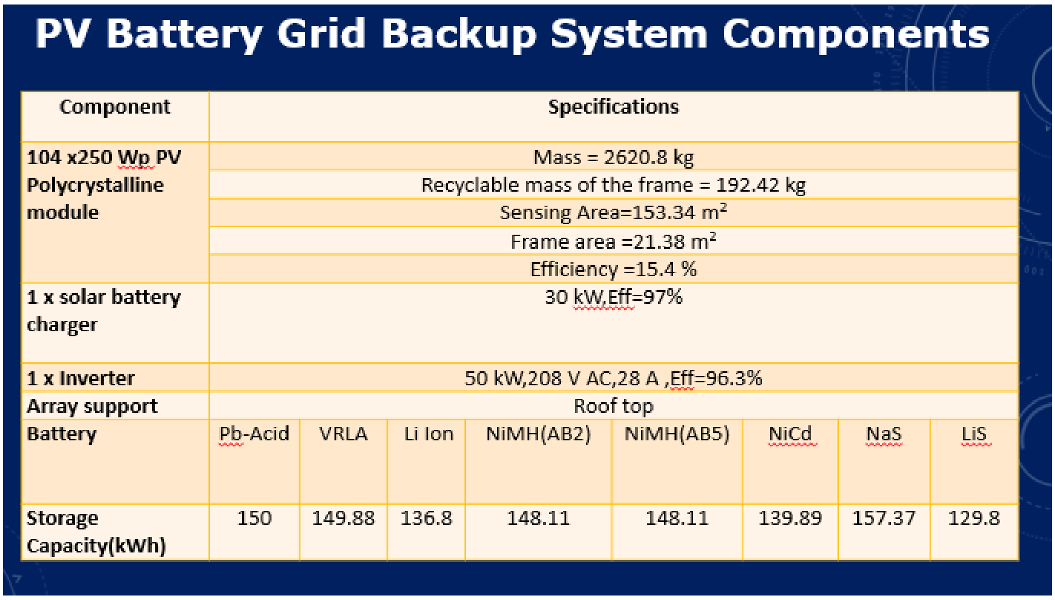

PV Battery Grid Backup System Components

Component	Specifications							
104 x250 Wp PV Polycrystalline module	Mass = 2620.8 kg							
	Recyclable mass of the frame = 192.42 kg							
	Sensing Area=153.34 m^2							
	Frame area =21.38 m^2							
	Efficiency =15.4 %							
1 x solar battery charger	30 kW,Eff=97%							
1 x Inverter	50 kW,208 V AC,28 A ,Eff=96.3%							
Array support	Roof top							
Battery	Pb-Acid	VRLA	Li Ion	NiMH(AB2)	NiMH(AB5)	NiCd	NaS	LiS
Storage Capacity(kWh)	150	149.88	136.8	148.11	148.11	139.89	157.37	129.8

And so essentially this is kind of, so you can see as we said the storage capacity lead acid is 150, lithium ion of is little lower 137 less than 140 and then these others are in that kind of range. And you can see this is the basis by which we have done these calculations.

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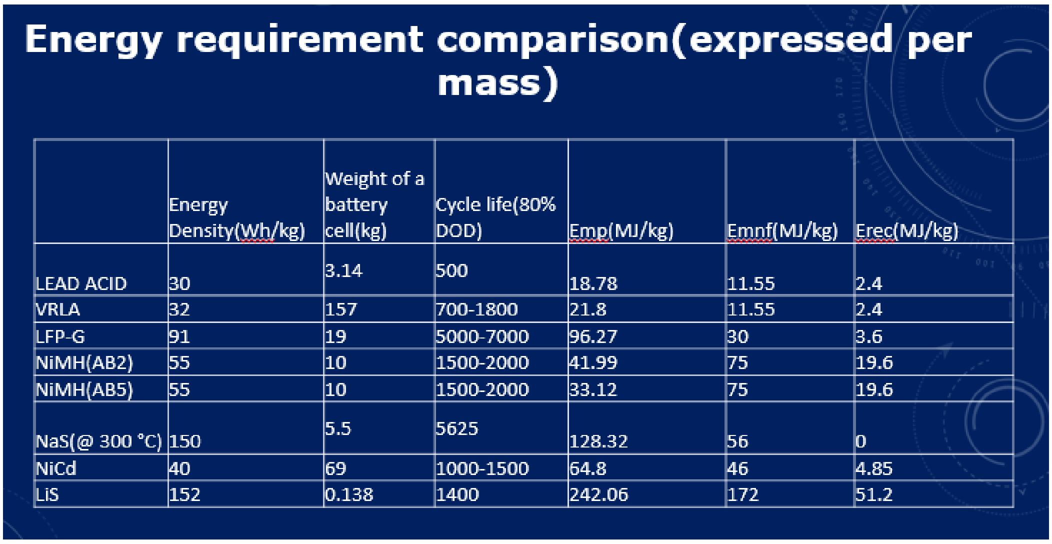

Energy requirement comparison(expressed per mass)

	Energy Density(Wh/kg)	Weight of a battery cell(kg)	Cycle life(80% DOD)	Emp(MJ/kg)	Emnf(MJ/kg)	Erec(MJ/kg)
LEAD ACID	30	3.14	500	18.78	11.55	2.4
VRLA	32	157	700-1800	21.8	11.55	2.4
LFP-G	91	19	5000-7000	96.27	30	3.6
NiMH(AB2)	55	10	1500-2000	41.99	75	19.6
NiMH(AB5)	55	10	1500-2000	33.12	75	19.6
NaS(@ 300 °C)	150	5.5	5625	128.32	56	0
NiCd	40	69	1000-1500	64.8	46	4.85
LiS	152	0.138	1400	242.06	172	51.2

Based on this then we have calculated all the different components, the recycled energy, the embodied energy, the cost of manufacture and per unit mass of battery. If you see this is how it gets calculated, you can see the energy densities and you can see lithium ion having the higher energy density, sodium sulphur even higher energy density and then this comes out in this form.

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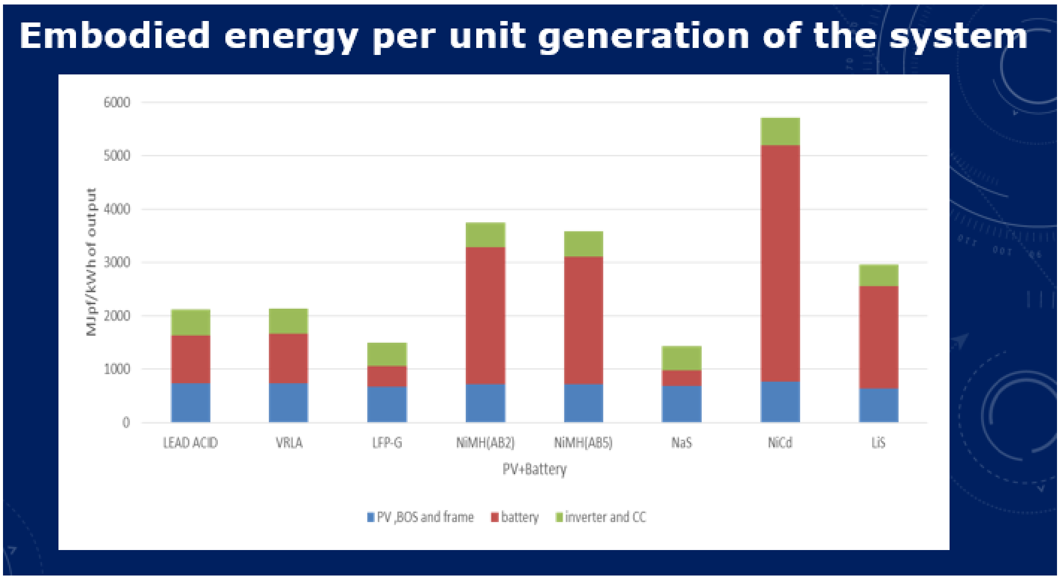

Embodied energy per unit generation of the system

So, finally when you look at the numbers this is how the numbers look, we the interesting thing to see is that per kilo Watt of output which we talked of, this is like the CED which we talked of, the cumulative energy demand, what is the energy input per kilo Watt hour of output. This is not including the solar installation which is there, this is only the amount we are using to make this and you can see that the lead, the lithium ion turns out to be the lowest energy, embodied energy.

And also, we will find that the battery adds a significant amount of embodied energy to the total and based on that what happens is that we can calculate, you can see that in some cases the battery, nickel cadmium the embodied energy is very very high and of course this also takes into consideration the difference in the lives because this is the final cumulative energy demand.

And it gives us an idea of, a comparative idea of this, it shows that you know sodium sulphur, lithium ion seems to be the options which can result in cost effective options. Today they are costly but they are from a energy view point they are actually seem to be promising. And the we can also use this as a basis for seeing, if you want to change the process of manufacture, can we change the process so that this, the energy input actually decreases and it becomes more viable.

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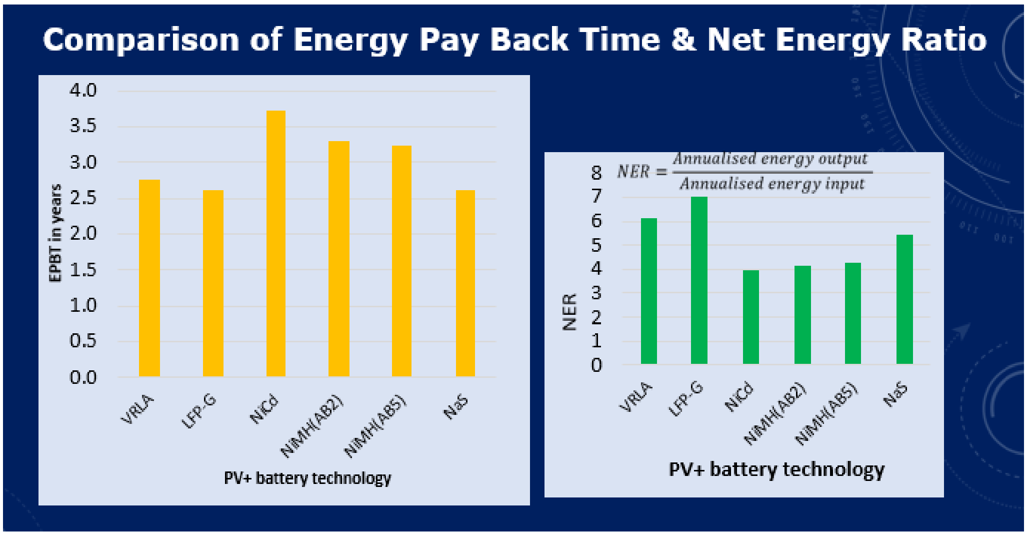

Comparison of Energy Pay Back Time & Net Energy Ratio

$NER = \frac{Annualised\ energy\ output}{Annualised\ energy\ input}$

So, you can look at this more details in the paper and when we compare this, now convert it into the NER and of course we would, higher NER is better. You can see that the lithium ion NER is of the order of about 7 which includes the PV plus battery plus the power electronics and seems to be better than the NER of the even the lead acid and but lead acid seems to better than most of the others.

And you can see the payback period is of the order of about 2, little more than 2 years for lead acid and lithium ion. This gives you an idea of, you can compare these results with the numbers that we saw earlier from NREL and from global numbers, you see there are some variance and that depends on the Indian context as well as the scale at which we make these calculations.

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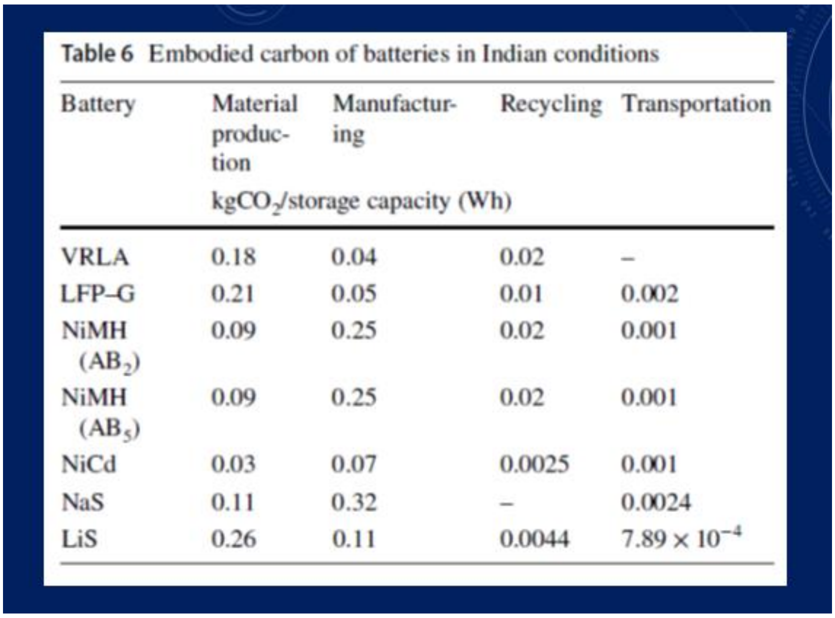

Table 6 Embodied carbon of batteries in Indian conditions

Battery	Material production	Manufacturing	Recycling	Transportation
	kgCO$_2$/storage capacity (Wh)			
VRLA	0.18	0.04	0.02	–
LFP–G	0.21	0.05	0.01	0.002
NiMH (AB$_2$)	0.09	0.25	0.02	0.001
NiMH (AB$_5$)	0.09	0.25	0.02	0.001
NiCd	0.03	0.07	0.0025	0.001
NaS	0.11	0.32	–	0.0024
LiS	0.26	0.11	0.0044	7.89×10^{-4}

We have also calculated then the embodied, carbon of the batteries and then this can be used to look at the CO_2 options.