Basics of Mechanical Engineering-2

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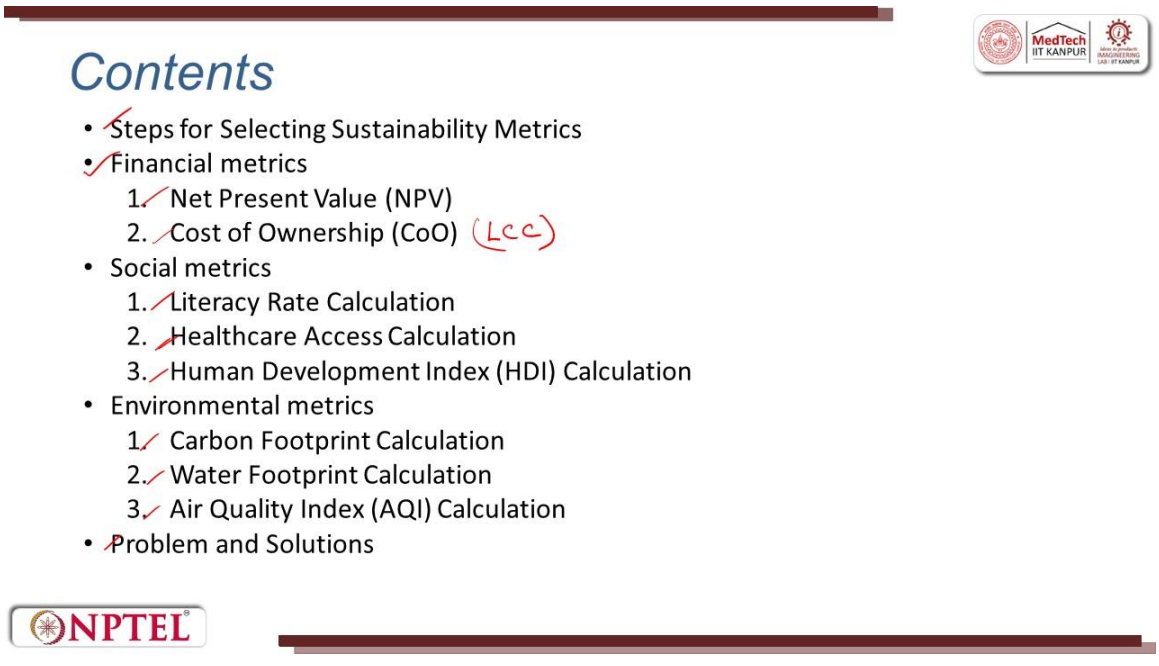
Week 12

Lecture 51

Metrics For Sustainable Manufacturing

This is the last lecture in the course Basics of Mechanical Engineering 2. I am Dr. Amandeep Singh Oberoi from IIT Kanpur. We are going to talk about metrics for sustainable manufacturing in this lecture.

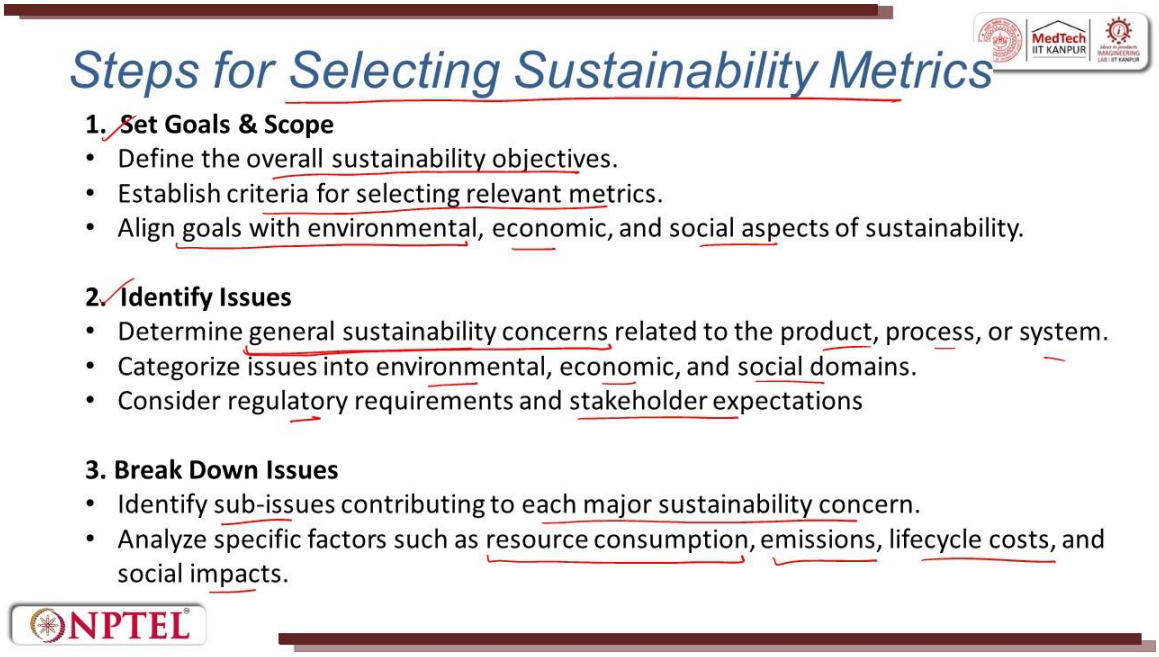


I will walk you through the following contents: steps for selecting sustainability metrics. Then we'll talk about three kinds of metrics that we discussed in the triple bottom line.

We talked about the economic, social, and environmental impacts. For economic metrics, I'll discuss financial metrics. These include net present value and cost of ownership,

which is also called life cycle costing. In social metrics, we'll give a brief introduction to literacy rate calculation. Healthcare access calculation, HDI (Human Development Index) calculation.

For environmental metrics, we'll discuss carbon footprint calculation, water footprint calculation. And air quality index calculation. Then some problems and solutions. I will not cover all of the metrics, but only a few of them.

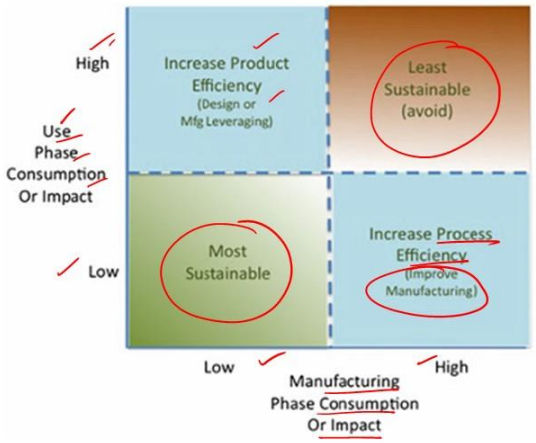


First are the steps for selecting sustainability metrics. First, select or set the goal and scope. Similarly, we have to define the overall sustainability objectives, establish criteria for selecting relevant metrics. And align goals with environmental, economic, or social aspects. What we are going to study. Identify the issues that is under study.

That is, determine the general sustainability concerns related to the product, process, or system. Categorize issues into categories. The environmental, economic and social domains. Consider regulatory requirements and stakeholder expectations.

Steps for Selecting Sustainability Metrics

Schematic of process steps for metric selection



Dornfeld, D.A. ed., 2012. *Green Manufacturing: Fundamentals and Applications*. Springer Science & Business Media.

Then we break down the issues. Break down the issues means like we saw a complete production system to the production line to the unit manufacturing process. We have to identify sub issues contributing to each major sustainability concern. Analyze the factors such as resource consumption, emissions, life cycle costs, social impacts, etc. When we break it down. We can even use this kind of the matrix here.

You can see the four quadrants here. And we have manufacturing phase consumption or impact, which could be low or high here on the x-axis. On the y-axis, we have use phase consumption or impact, low or high, in manufacturing. And if both use case and manufacturing are low, then it is most sustainable. If both are high, that is least sustainable, and in between,

we have to pick between the use phase consumption or manufacturing phase consumption. If use phase consumption is high and manufacturing phase is low, then we have to increase product efficiency in design or manufacturing leveraging. And in case manufacturing phase consumption is high and use phase consumption is low, we have to increase process efficiency, meaning we have to focus on manufacturing.

Steps for Selecting Sustainability Metrics

4. Define Criteria

- Establish criteria to evaluate and prioritize sustainability metrics.
- Consider factors like relevance, measurability, comparability, and impact significance.

5. Choose Metrics

- Select quantitative and qualitative indicators based on the defined criteria.
- Ensure the chosen metrics effectively measure sustainability performance.
- Validate metrics through stakeholder input and industry benchmarks.

That is, we break down the issue, then define the criteria to establish and evaluate. And prioritize the sustainability matrix, meaning how we collect the data. Are we going to take unit manufacturing data or unit process data? Or are we going to take aggregate data from the factory? Consider factors like relevance, measurability, comparability, impact significance, etc.

Then we have to choose the matrix. Select quantitative and qualitative indicators based on the defined criteria. Quantitative means we have selected or quantified specific data. For example, carbon footprint is quantified data. For example, energy consumption is quantified data.

Now, qualitative data example: pollution yes or no, treatment yes or no. Then, beyond specific limits, pollution occurring or not, yes or no—this yes or no is a kind of qualitative data. We choose the matrix accordingly and share the chosen matrix to effectively measure sustainability performance. Validate the matrix through stakeholder input and industry benchmarks. Let me now try to see certain matrices: financial matrices for manufacturers.

Key Financial Metrics for Manufacturers

1. Net Present Value (NPV)

Formula:

$$\text{NPV} = -I_0 + \sum_{t=1}^{T} \frac{X_t}{(1+i)^t}$$

where:

X_t = Cash flow in period t

i = Interest rate

I_0 = Initial investment

- If NPV > 0: The investment is expected to generate more value than its cost, so it's financially viable.
- If NPV < 0: The investment would lead to a net loss.
- If NPV = 0: The investment breaks even.

The first financial matrix is net present value. Net present value is the discounted value of any asset to the present time for the coming years. So we have to subtract the investment. It is

$$\text{NPV} = -I_0 + \sum_{t=1}^{T} \frac{X_t}{(1+i)^t}$$

So, net present value, if it is more than 0, investment is expected to generate more value than its cost. So, it is financially viable. If it is equal to 0, it is just a break-even. Whatever we invest would only come back, no profit. If it is less than zero, investment would lead to a loss. So, net present value is one of the financial metrics.

Key Financial Metrics for Manufacturers

2. Cost of Ownership (CoO)

It is used for comparing economic feasibility.

Key cost components:

Equipment cost (C_1): Initial purchase price.

Setup cost (C_2): Installation, transportation, and training expenses.

Annual operational cost (C_3): Energy, maintenance, consumables, and downtime.

$$\mathrm{CoO} = \frac{\left(C_1 + C_2 + \frac{C_3}{(1+i)^t}\right) \times N}{B \times V_E}$$

where; i = Discount rate

t = Number of years

N = Number of pieces of equipment needed for the system

B = Total amount of output from the system

V_E = Economic value of unit output

Another financial metric that I talked about is cost of ownership. This is also known as the life cycle costing. Now, let me take an example. For example, you purchase any equipment. If I suppose purchase a bike. Motorbike, I'm talking about. Initial investment is suppose rupees fifty thousand.

And each month suppose you are spending rupees one thousand on the petrol. That is the operational cost this is the operational cost C3, initial cost 50,000 is C1. And setup cost is C2 for equipment for the lathe machine for any setup machine. There is a setup cost as well for example for bike you don't try to develop a shed. And to develop a shed you are investing rupees ten thousand.

And each month you are spending rupees 1,000 on petrol and in one year this turns to be rupees 12,000. And if you are operating this bike for 5 years, the total investment would be 50,000 + 10,000 + for 5 years 12 x 5, 60,000. This is the total cost of ownership of the product throughout its life cycle. It is the cost of ownership. So this turns out to be rupees one lakh twenty thousand for a five year period.

$$\mathrm{CoO} = \frac{\left(C_1 + C_2 + \frac{C_3}{(1+i)^t}\right) \times N}{B \times V_E}$$

Social Sustainability Metrics

Social sustainability ensures that societies provide equitable access to essential resources, services, and opportunities while promoting well-being and quality of life. It includes various metrics that measure literacy, healthcare access, and overall human development. Below are key calculations and explanations for fundamental social sustainability indicators.

1. Literacy Rate Calculation

Literacy rate is a key indicator of educational development, representing the percentage of people within a population who can read and write. Higher literacy rates contribute to better job opportunities, economic growth, and improved living standards.

$$\text{Literacy Rate}(\%) = \left(\frac{\text{Literate People}}{\text{Total Population}}\right) \times 100$$

Then comes the next matrix, which is the social sustainability matrix. Social sustainability ensures that societies provide equitable access to essential resources, services, and opportunities. While promoting well-being and quality of life. It includes various metrics that measure literacy, healthcare access, and overall human development. Below are key calculations and explanations for fundamental social sustainability indicators.

First is the literacy rate calculation. That is the number of people who can read and write, who are educated to some extent in the given society that is under study. The literacy rate is a key indicator of educational development, representing the percentage of people within a population who can read and write.

High literacy rates contribute to better job opportunities, economic growth, and improved standards. To calculate this, we have a simple relation here. Literacy rate is

$$\text{Literacy Rate}(\%) = \left(\frac{\text{Literate People}}{\text{Total Population}}\right) \times 100$$

Social Sustainability Metrics

2. Healthcare Access Calculation

Healthcare access measures the availability of essential medical services, including hospitals, clinics, and life-saving medicines. Ensuring widespread healthcare access reduces mortality rates, improves public health, and increases life expectancy.

$$\text{Healthcare Access(\%)} = \left(\frac{\text{People with Access}}{\text{Total Population}}\right) \times 100$$

Then comes the second indicator, which talks about healthcare access calculation. Healthcare access measures the availability of essential medical services, including hospitals, clinics, and life-saving medicines. Ensuring widespread healthcare access reduces mortality rates, improves public health, and increases life expectancy.

So healthcare access percentage

$$\text{Healthcare Access(\%)} = \left(\frac{\text{People with Access}}{\text{Total Population}}\right) \times 100$$

Social Sustainability Metrics

3. Human Development Index (HDI) Calculation

The Human Development Index (HDI) is a composite measure used by the United Nations Development Programme (UNDP) to assess a country's overall development. HDI considers three major factors:

1) **Life Expectancy Index (LEI):** Measures health and longevity based on average life expectancy.
2) **Education Index (EI):** Evaluates educational attainment, including school enrollment and literacy rates.
3) **Income Index (II):** Assesses the standard of living based on per capita income.

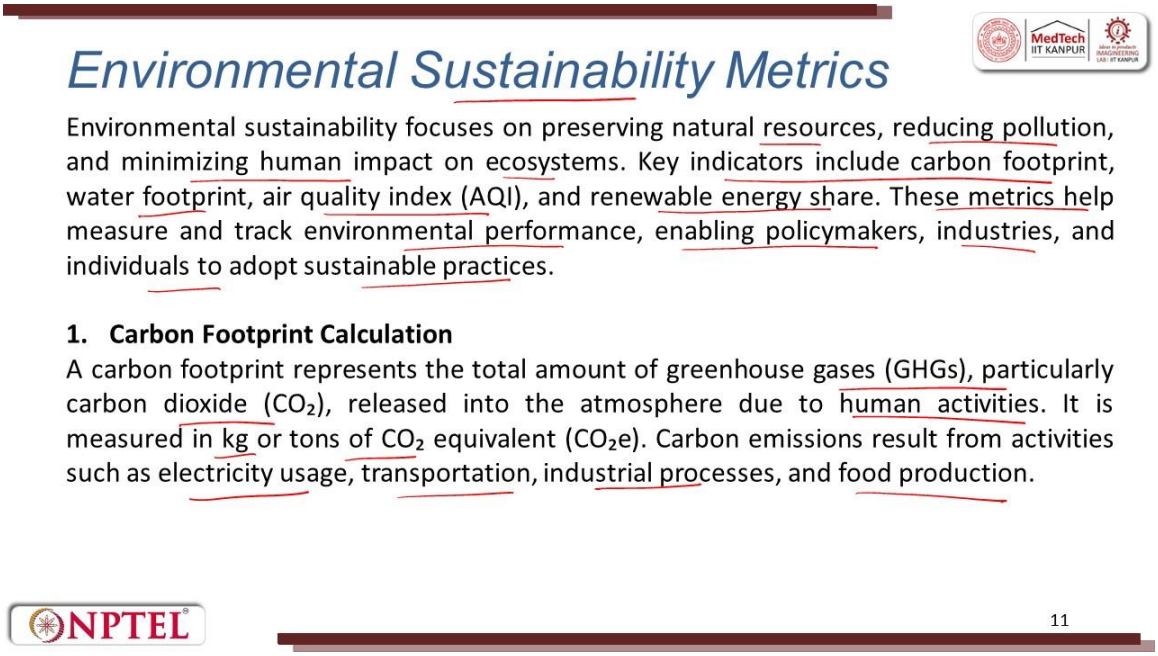
A higher HDI value (closer to 1.0) indicates a better quality of life, whereas a lower HDI suggests poor living conditions and development challenges.

$$\text{Human Development Index (HDI)} = \frac{\text{LEI}+\text{EI}+\text{II}}{3}$$

Then comes the human development index calculation. The HDI, or human development index, is a composite measure. It is used by the United Nations Development Programme to assess a country's overall development. The HDI considers three major factors.

There is a Nobel laureate from India, Amartya Sen, who has also worked in this direction to develop the HDI. So the life expectancy index is LEI. That measures health and longevity based on average life expectancy. Then we have the education index. That evaluates educational attainment, including school enrollment.

Then we have the income index, which assesses the standard of living based on per capita income. A higher HDI value, closer to 1.0, indicates a better quality of life. Whereas a lower HDI value suggests poor living conditions. And development challenges because three pointers are there: the life expectancy index, Education index, and income index, we divided by three. Take the total average. This is known as the Human Development Index.

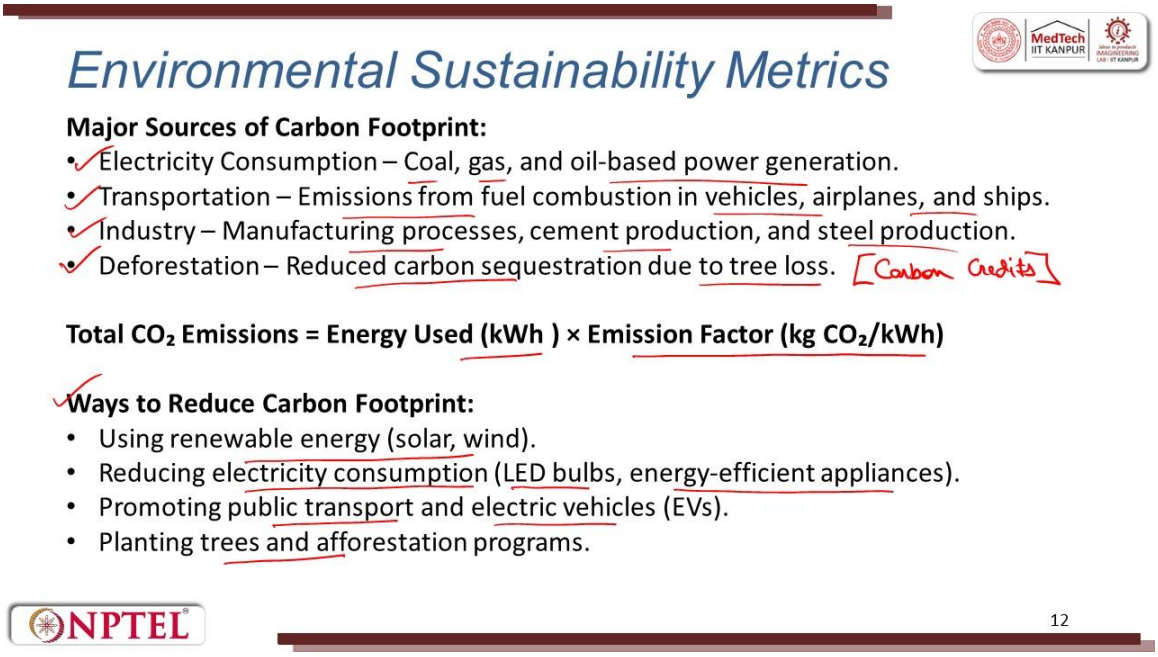


Then comes the Environmental Sustainability Matrix. Environmental sustainability focuses on preserving natural resources. Reducing pollution and minimizing human impact on ecosystems.

Key indicators include carbon footprint, water footprint, air quality index, and renewable energy share. These metrics help measure and track environmental performance. Enabling policymakers, industries, and individuals to adopt sustainable practices. So, carbon footprint calculation is very important here. This represents the total amount of greenhouse gases, particularly carbon dioxide, released into the atmosphere due to human activities.

It is measured in kg or tons of carbon dioxide equivalent. Carbon emissions result from activities such as electricity usage, transportation, industrial processes, and food production. As I said, carbon dioxide equivalent for different countries for the kinds of electricity generation sources could be different. For nuclear power, it is cleaner. Then comes hydropower.

Then come other stations. For example, from the thermal power, it is very high. Because the energy that is used and coal is burned, the carbon dioxide emission is very high.



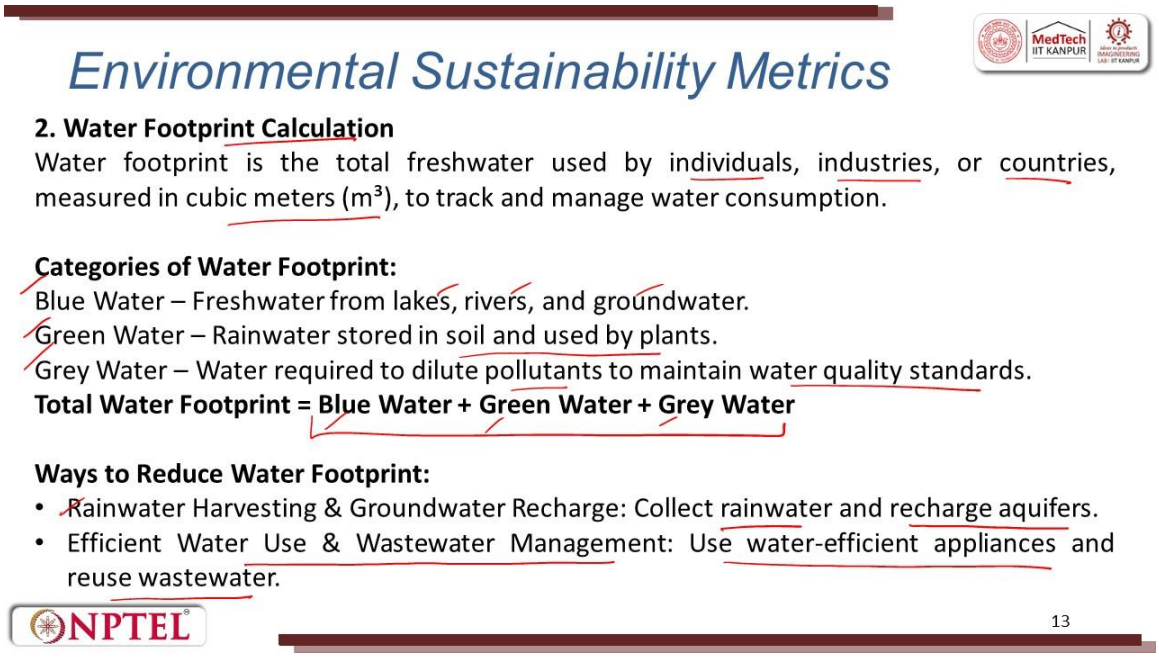
Major sources of carbon footprint are electricity consumption. That is coal, gas, oil-based power generation, transportation, emissions from fuel consumption, vehicles, airplanes.

And ships, industry that is manufacturing processes, cement production, steel production. Deforestation is also a contributor to the carbon footprint. That is reduced carbon

sequestration due to tree loss. And when carbon sequestration is increased, you get carbon credits. So, I am only talking about a very simple matrix here.

Because we are talking about the very basics of mechanical engineering and the basics of sustainability engineering here. So, total carbon dioxide emissions are equal to energy used in kilowatt-hour multiplied by the emission factor. That is kilograms of carbon dioxide per unit kilowatt-hour. So, ways to reduce carbon footprint are using renewable sources of energy, solar, wind, geothermal, etc. Reducing electricity consumption, that is, we might use LED bulbs.

Which have lesser consumption, energy efficient appliances. For example, energy efficient motors or maybe high start rating appliances. Promoting public transport and electric vehicles, for instance. Using a bus that could transport 30 people in a go. Than using 30 cars separately, planting trees and afforestation programs.



So not only carbon footprint, we also have water footprint and air quality. Water footprint calculation. Water footprint is a total fresh water used by individuals, industries or countries measuring cubic meters to track and manage water consumption. Categories of water footprint, if I try to talk about blue water, green water and grey water are three categories. Total water footprint is equal to blue water, green water and grey water.

All together, what is blue water? Fresh water from lakes, rivers, groundwater. Green water is rainwater stored in soil and used by plants. Grey water is water required to dilute pollutants to maintain water quality standards. Waste you reduce, water footprint are rainwater harvesting, groundwater recharge, collect rainwater or recharge waste.

Aquifer's efficient water usage and wastewater management. That is using water efficient appliances and reuse waste water. There are multiple water footprint systems. Nowadays, groundwater extraction and managing the wastage of groundwater is very important. There are certain AI tools nowadays being developed.

If I say AI, generally these are industry 4.0 IoT tools that measure that each pump. If it is pumping water to different stations, from that pump. To finally what is the output coming in between if leakage is there. The sensor attached here and at the end point that could detect that in between there is some leakage that has happened.

Environmental Sustainability Metrics

3. Air Quality Index (AQI) Calculation

Air Quality Index (AQI) is a standardized measure of air pollution levels, indicating how clean or polluted the air is. It is calculated based on major pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and ozone (O_3). High AQI values indicate poor air quality and potential health risks.

AQI Value	Air Quality	Health Effects
0 - 50	Good	No risk
51 - 100	Moderate	Acceptable but can affect sensitive groups
101 - 150	Unhealthy for sensitive groups	Risk for children and elderly
151 - 200	Unhealthy	Health warnings issued
201 - 300	Very Unhealthy	Serious health effects
301+	Hazardous	Emergency conditions

Then comes air quality index. AQI or Air Quality Index is a standardized measure of air pollution levels indicating how clean or polluted the air is. For example, at certain specific points in the city of Kanpur, AQI is around or more than 300. I have given the table here. At certain points, when I went to Brampton in Canada, the AQI was only 4. It depends upon the quality of air we have.

So it is calculated based on major pollutants such as particulate matter, PM. We have PM levels: PM 10, PM 2.5, nitrogen dioxide, carbon monoxide, sulfur dioxide, and ozone. High AQI values indicate poor air quality and potential health risks. So there are AQI values. Air quality is very good between 0 and 50.

There is no risk of health effects. 51 to 100 is moderate. Acceptable, but it can affect sensitive groups. Sensitive groups means people who are prone to breathing problems. Then between 101 and 150, unhealthy for sensitive groups, posing risks for children and the elderly. 151 to 200, unhealthy; health warnings are issued.

201 to 300, very unhealthy, with serious health effects. 301 plus, hazardous, indicating emergency conditions. So in industrial areas close to chimneys or factories, sometimes it is really 301 plus.

Environmental Sustainability Metrics

$$\text{Air Quality Index (AQI)} = \frac{\text{Pollutant Concentration} - \text{Minimum Concentration}}{\text{Maximum Concentration} - \text{Minimum Concentration}} \times 100$$

Ways to Improve Air Quality:

- Promoting electric vehicles (EVs) and public transport.
- Reducing industrial emissions through cleaner technologies.
- Increasing urban green spaces (parks, tree plantations).
- Banning open burning of waste and agricultural residue.

AQI is calculated using this relationship:

$$\text{Healthcare Access(\%)} = \left(\frac{\text{People with Access}}{\text{Total Population}}\right) \times 100$$

Ways to improve air quality include promoting electric vehicles and public transport. Reducing industrial emissions through cleaner technologies and increasing urban green

spaces. Such as parks, trees, plantations, and banning open burning of agricultural residue.

Environmental Sustainability Metrics

4. Renewable Energy Share Calculation

Renewable energy share is the percentage of total energy consumption derived from renewable sources such as solar, wind, hydro, geothermal, and biomass. Increasing renewable energy use helps reduce dependence on fossil fuels and lower carbon emissions.

Major Renewable Energy Sources:

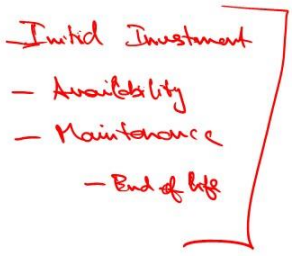
1. **Solar Energy** – Harnessing sunlight via photovoltaic (PV) panels.
2. **Wind Energy** – Using wind turbines to generate electricity.
3. **Hydropower** – Generating power from flowing water.
4. **Biomass Energy** – Using organic materials for fuel.
5. **Geothermal Energy** – Utilizing heat from beneath the Earth's surface.

Environmental Sustainability Metrics

$$\text{Renewable energy share (\%)} = \left(\frac{\text{Renewable energy use}}{\text{Total energy use}}\right) \times 100$$

Benefits of Renewable energy:

- Reduces greenhouse gas emissions and air pollution.
- Increases energy security and reduces fossil fuel dependence.
- Generates employment in the green energy sector.
- Helps mitigate climate change impacts.



Next comes the renewable energy share calculation. Renewable energy share is the percentage of total energy consumption derived from renewable sources such as solar, wind, hydro, geothermal, biomass, etc. Increasing renewable energy use helps reduce

dependence on fossil fuels and lowers carbon emissions. Major renewable sources, as I have just mentioned, include solar, wind, hydropower, biomass, and geothermal.

How do we calculate it?

$$\text{Renewable energy share (\%)} = \left(\frac{\text{Renewable energy use}}{\text{Total energy use}}\right) \times 100$$

Benefits include reduced greenhouse gas emissions, air pollution, and increased energy security. It also reduces fossil fuel dependence and generates employment in the green energy sector.

Helps mitigate climate change impacts, but it has an initial investment that is there and availability. For example, a solar power station could be set up in India, but it cannot be set up in places where the sun is not there. It cannot be set up in places like Kashmir. Then comes maintenance and end-of-life planning. For example, the PV cells used in solar power stations have a lifespan.

They have a lifespan between 8 to 20 years, depending upon the quality that you are using. So, end-of-life planning—how do we dispose of it—that is also very important. So, these are some of the concerns which are there. So, these were very basic metrics that I have introduced you to. Though this course is for the basis of mechanical engineering.

But when we talk about sustainability in manufacturing, all these metrics are taken care of. Now, I will take a few problem statements and close this lecture.

Problems and Solutions

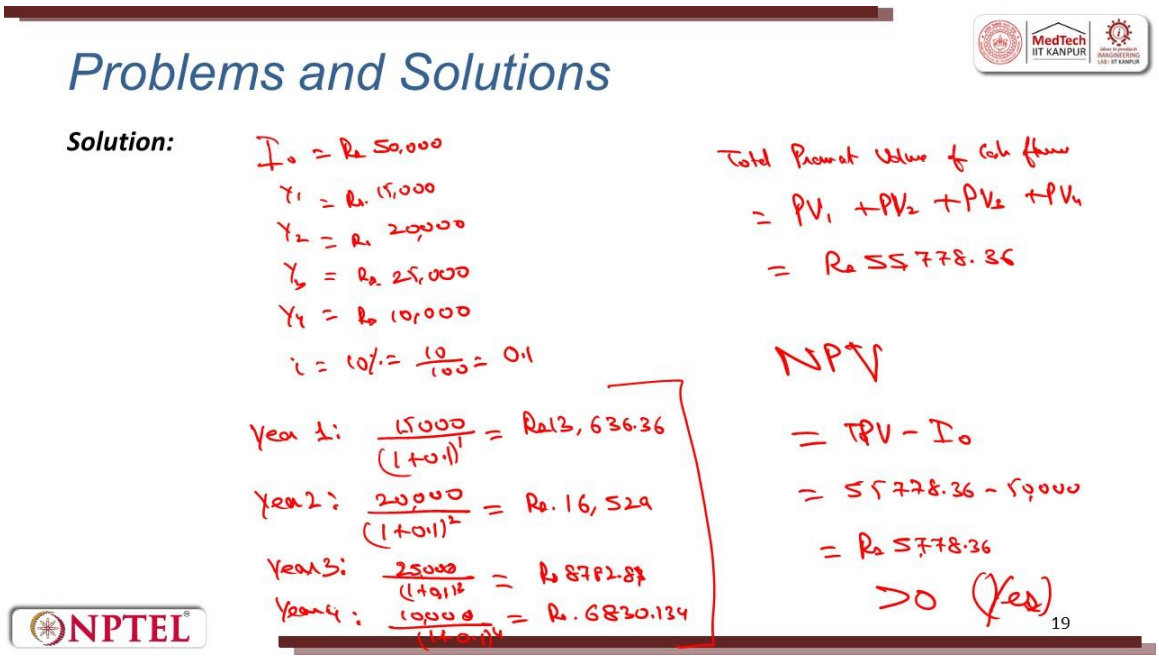
NPV

Problem Statement: A company is considering an investment that requires an initial outlay of ₹50,000. The project is expected to generate the following cash flows over the next four years:

Year 1: ₹15,000
Year 2: ₹20,000
Year 3: ₹25,000
Year 4: ₹10,000

The company's discount rate is 10% (0.10).

I. Calculate the NPV of the investment
II. Based on your calculations, determine whether the company should proceed with the investment (i.e., check if NPV is positive or negative).



The first problem here talks about net present value (NPV). A company is considering an investment that requires an initial outlay of Rs. 50,000. The project is expected to generate the following cash flows over the next four years.

Year 1, Rs. 15,000; Year 2, Rs. 20,000. Year 3, Rs. 25,000. Year 4, Rs. 10,000. The company's discount rate is 10%. Calculate the NPV of the investment based on your calculations.

Determine whether the company should proceed. We have to check whether the NPV is positive or not. If it is positive, we will accept it.

Here, the initial investment is Rs. 50,000, and per year we have these cash flows. So, the initial investment is I_0, that is Rs. 50,000. And Year 1, Year 2, Year 3, Year 4 rates or the cash flows are given which are Rs. 15,000, Rs. 20,000, Rs. 25,000, and Rs. 10,000 respectively. I have a discounted rate, i = 10%, that is 10/100 = 0.1.

Solution:

Year 1: $\frac{15,000}{(1+0.1)^1}$ = Rs. 13,636.36

Year 2: $\frac{20,000}{(1+0.1)^2}$ = Rs. 16,529

Year 3: $\frac{25,000}{(1+0.1)^3}$ = Rs. 8,782.87

Year 4: $\frac{10,000}{(1+0.1)^4}$ = Rs. 6,830.13

Total value of cash flow:

PV1 + PV2 + PV3 + PV4 = Rs. 55,778.36.

NPV:

= TPV – Io

= 55,778.36 – 50,000 = Rs. 5778.36

Problems and Solutions

Problem Statement: A fork lift truck transfers the material from one machine group to the other in a factory. Calculate the CFP for the given data:

Material handling:
Total distance travelled by the truck: 60 km daily.
Truck fuel efficiency: 15 km per litre
Carbon emission factor for diesel (fuel): 2.65 kilograms of CO_2e per litre

Equipment operation:
Daily electricity usage: 4 kWh per machine.
Number of machines: 15
Carbon emission factor for electricity: 0.8 kilograms of CO_2e per kWh.

Problems and Solutions

Solution:

$CFP_T = CFP_{MH} + CFP_{EO}$

CFP_{MH} = 4 litres × CE factor (2.65 kg CO_2e / litre)

$\frac{60 \text{ km}}{15} = 4$ litres

= 10.6 kg CO_2e

CFP_{EO} = Energy used × CE factor

= 4 × 15 × 0.8

= 48 kg CO_2e

CFP_T

= 10.6 + 48

= 58.6 kg CO_2e

Another problem statement talks about the carbon footprint, the sustainability metric. A forklift truck transfers material from one machine group to another in a factory. We have to calculate the total carbon footprint.

In real handling system, the total distance traveled by truck is 60 kilometers daily. Truck fuel efficiency is 15 kilometers per liter. Carbon emission factor for the diesel fuel is 2.65 kilograms of carbon dioxide equivalent per liter. So for different fuels, there are different emission factors.

And we have been given equipment operation daily electricity usage is 4 kWh per machine. Number of machines are 15 carbon emission factor for electricity is 0.8 kilograms of carbon dioxide equivalent per kWh.

Solution:

$CFP_T = CFP_{MH} + CFP_{EO}$

$\frac{60\ km}{15}$ = 4 liter

CFP_{MH} = 4 liter x CE factor (2.65 kg CO2e/liter)

= 10.6 kg CO2e

CFP_{EO} = Energy used x CE factor

= 4 x 15 x 0.8

= 48 kg CO2e

CFP_T = 10.6 + 48

= 58.6 kg CO2e

With this, I am closing this lecture and this course on the basics of mechanical engineering 2. We talked about the manufacturing processes. We started with the materials, different kinds of materials, and material systems. Then we talked about the basics of casting, the processes of casting. The materials in casting, the various problem statements were also discussed there. Then we talked about forming, then we went to machining. And we talked about non-conventional machining processes; welding was also discussed in between.

And I have talked about sustainable manufacturing systems in the last week here. This is the basics of mechanical engineering second delivery that we have given. The third delivery will also be called Basics of Mechanical Engineering-3. That will talk about fluid mechanics and thermal science. Let us meet in the next course.

Thank you.