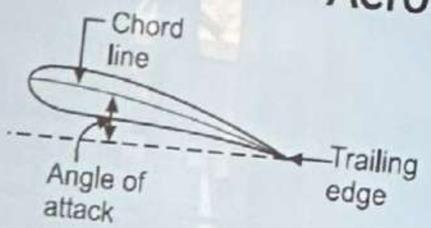
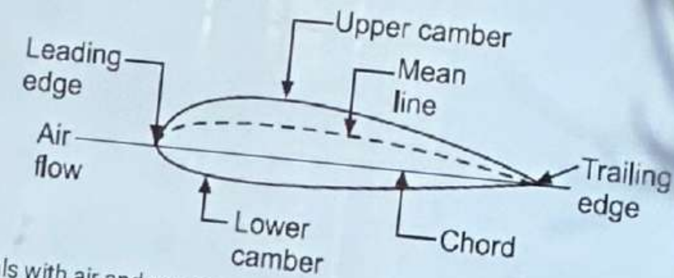
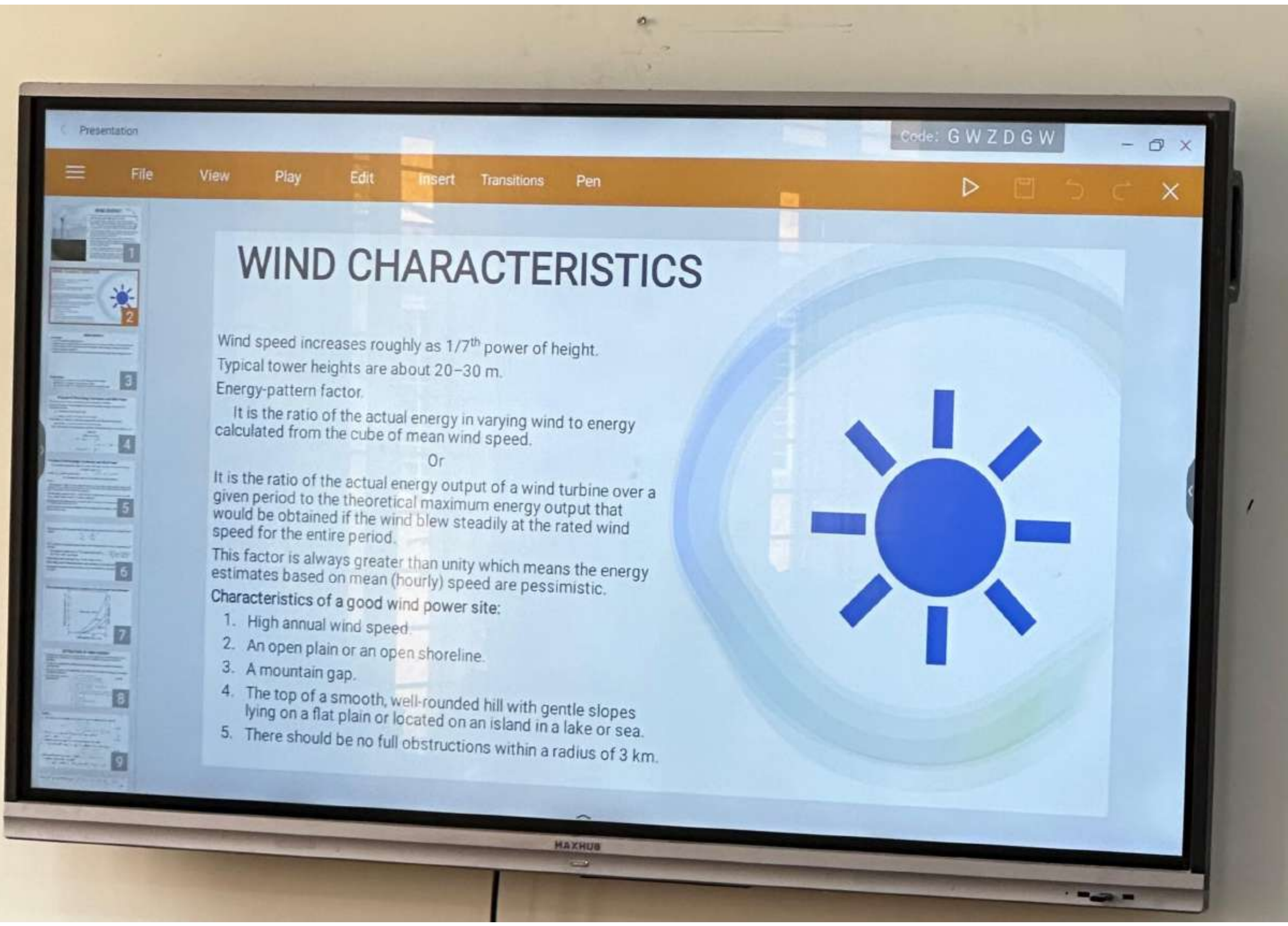
Aero foil Nomenclature





1. **Aerodynamics:** It is the branch of science which deals with air and gases in motion and their mechanical effects.
2. **Airfoil or aerofoil:** A streamlined air surface designed for air to flow around it in order to produce low drag and high lift forces.
3. **Angle of attack:** It is the angle between the relative air flow and the closed of the air foil
4. **Blade.** An important part of a wind turbine that extracts wind energy.
5. **Leading edge:** It is the front edge of the blade that faces towards the direction of flow.
6. **Trailing edge:** It is the rear edge of the blade that faces away from the direction of wind flow.
7. **Mean line.** A line that is equidistant from the upper and lower surfaces of the air foil
8. **Camber:** It is the maximum distance between the mean line and the chord line, which measures the curvature of the airfoil.
9. **Rotor:** It is the primary part of the wind turbine that extracts energy from the wind. It constitutes the blade-and-hub assembly.
10. **Hubs:** Blades are fixed to a hubs which is a central solid part of the turbine.
11. **Pitch angle:** It is the angle between the direction of wind and the direction perpendicular to the planes of blades.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WIND CHARACTERISTICS
Wind speed increases roughly as 1/7th power of height.
Typical tower heights are about 20–30 m.
Energy-pattern factor.
It is the ratio of the actual energy in varying wind to energy calculated from the cube of mean wind speed.
Or
It is the ratio of the actual energy output of a wind turbine over a given period to the theoretical maximum energy output that would be obtained if the wind blew steadily at the rated wind speed for the entire period.
This factor is always greater than unity which means the energy estimates based on mean (hourly) speed are pessimistic.
Characteristics of a good wind power site:
1. High annual wind speed.
2. An open plain or an open shoreline.
3. A mountain gap.
4. The top of a smooth, well-rounded hill with gentle slopes lying on a flat plain or located on an island in a lake or sea.
5. There should be no full obstructions within a radius of 3 km.
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Principle of Wind Energy Conversion and Wind Power

The wind power can be computed by using concept of kinetics.

A wind mill works on the principle of 'converting kinetic energy of the wind to mechanical energy'

U_w = Velocity of wind, km/h, and

ρ = Density of air (1.225 kg/m^3 at sea level);

(Air density is a function of altitude, temperature and barometric pressure)

Air density A = Area, through which the air flows.

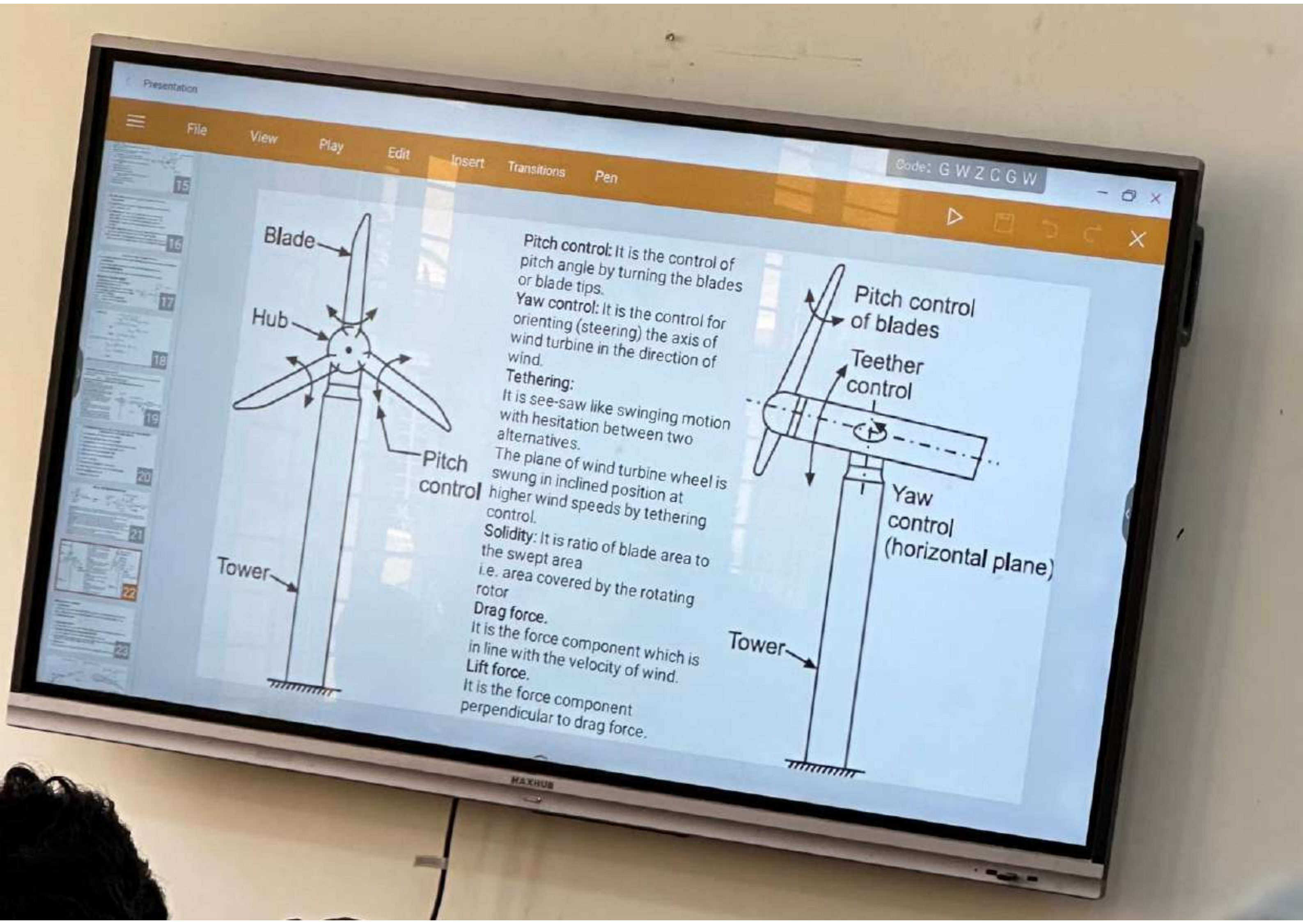
Then, the amount of air passing in unit time (m) through area A, with velocity U_w is given by:

Mass, $m = \rho A U_W$

$$\therefore \quad \text{Kinetic energy (K.E.)} = \frac{1}{2} m U_w^2$$

$$= \frac{1}{2} \times \rho A U_w \times U_w^2 = \frac{1}{2} \rho A U_w^3 \text{ watts}$$

$$i.e. \quad \text{Total power } (P_{total}) = \frac{1}{2} \rho A U_w^3$$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Blade
Hub
Pitch control
Tower
Pitch control: It is the control of pitch angle by turning the blades or blade tips.
Yaw control: It is the control for orienting (steering) the axis of wind turbine in the direction of wind.
Tethering:
It is see-saw like swinging motion with hesitation between two alternatives.
The plane of wind turbine wheel is swung in inclined position at higher wind speeds by tethering control.
Solidity: It is ratio of blade area to the swept area i.e. area covered by the rotating rotor
Drag force.
It is the force component which is in line with the velocity of wind.
Lift force.
It is the force component perpendicular to drag force.
Pitch control of blades
Teether control
Yaw control (horizontal plane)
Tower
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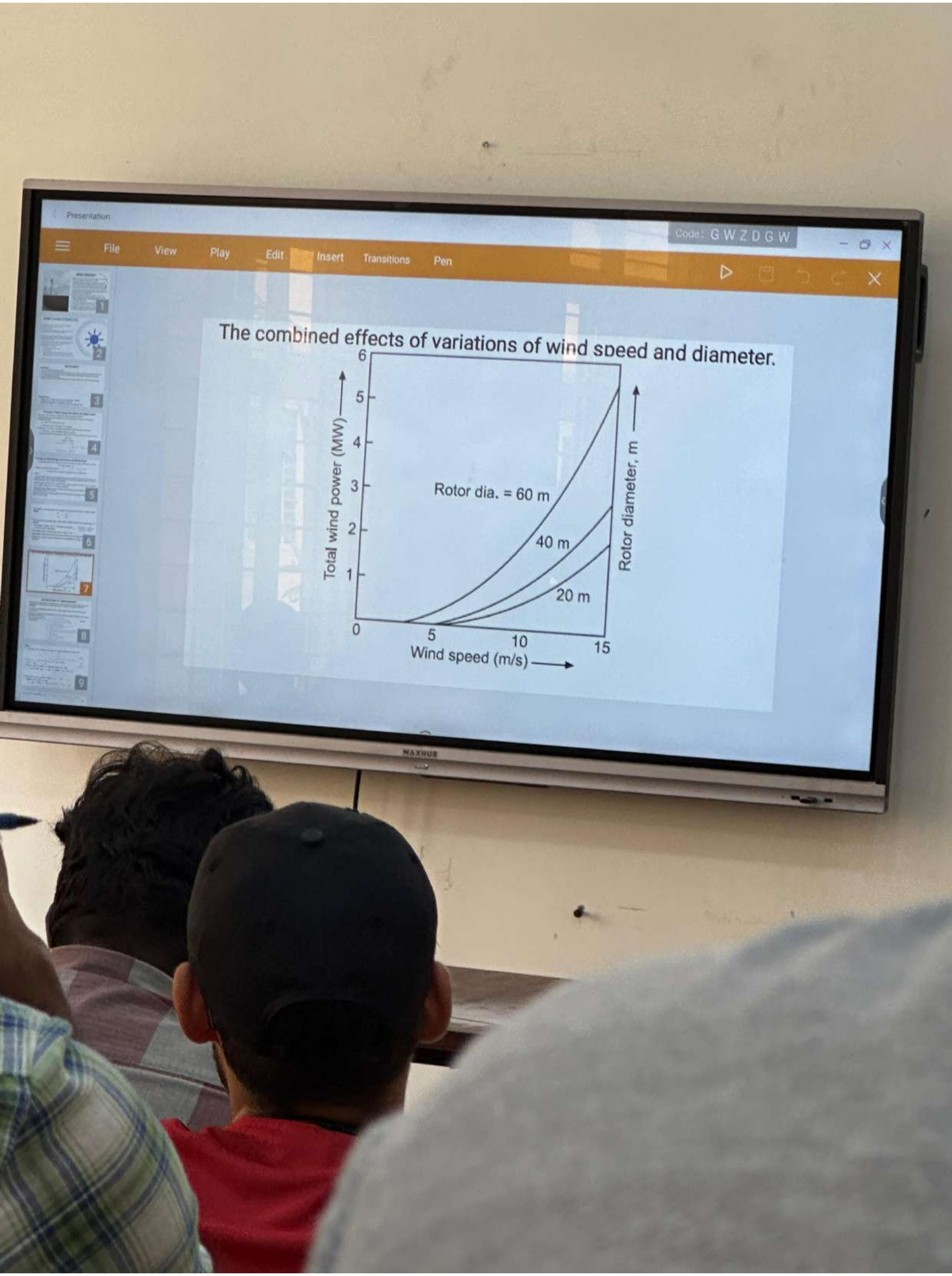
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The combined effects of variations of wind speed and diameter.
Total wind power (MW)
Rotor diameter, m
Rotor dia. = 60 m
40 m
20 m
Wind speed (m/s)
0
5
10
15
1
2
3
4
5
6

Principle of Wind Energy Conversion and Wind Power

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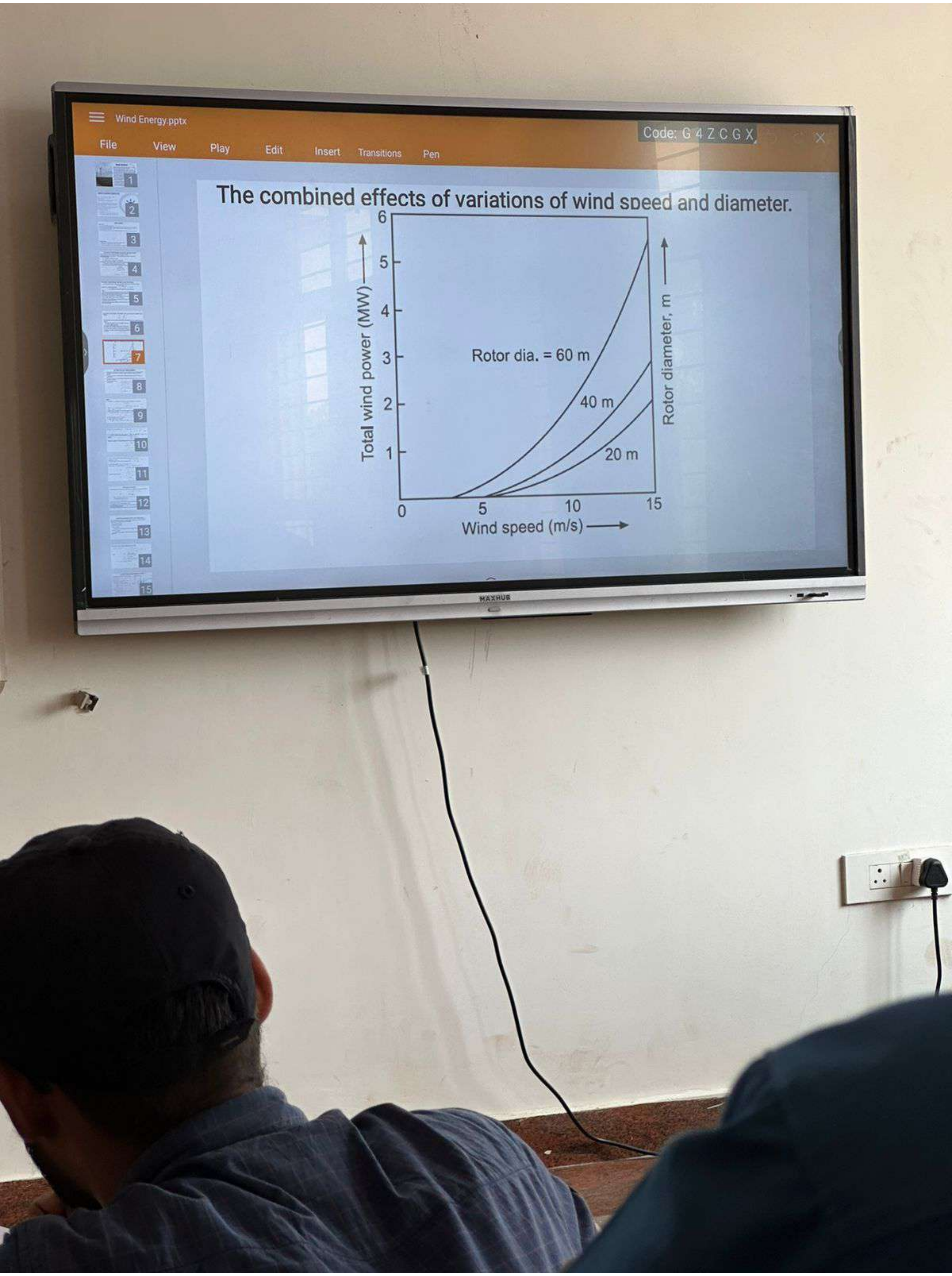
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The combined effects of variations of wind speed and diameter.
Total wind power (MW)
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Wind speed (m/s)
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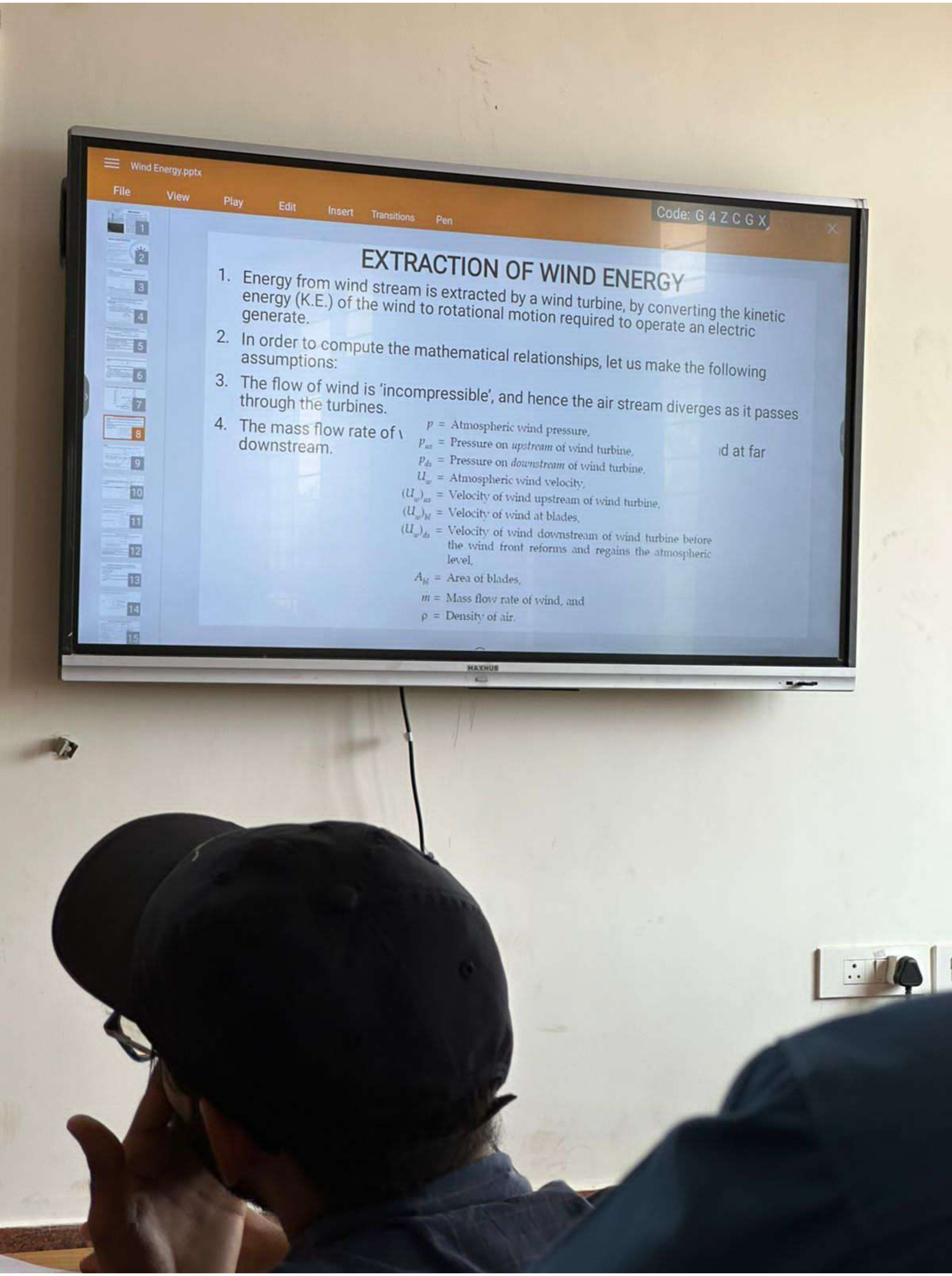
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EXTRACTION OF WIND ENERGY
1. Energy from wind stream is extracted by a wind turbine, by converting the kinetic energy (K.E.) of the wind to rotational motion required to operate an electric generate.
2. In order to compute the mathematical relationships, let us make the following assumptions:
3. The flow of wind is 'incompressible', and hence the air stream diverges as it passes through the turbines.
4. The mass flow rate of w
d at far downstream.
p = Atmospheric wind pressure,
p_{us} = Pressure on upstream of wind turbine,
p_{ds} = Pressure on downstream of wind turbine,
U_w = Atmospheric wind velocity,
$(U_w)_{us}$ = Velocity of wind upstream of wind turbine,
$(U_w)_{bl}$ = Velocity of wind at blades,
$(U_w)_{ds}$ = Velocity of wind downstream of wind turbine before the wind front reforms and regains the atmospheric level,
A_{bl} = Area of blades,
$\dot{m}$ = Mass flow rate of wind, and
ρ = Density of air.
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l downstream of turbine for unit mass flow, $\dot{m} = 1$.

$$W = (K.E.)_{us} - (K.E.)_{ds}$$

or,

$$W = \frac{1}{2}\left[(U_w)_{us}^2 - (U_w)_{ds}^2\right] \qquad \text{--- (9)}$$

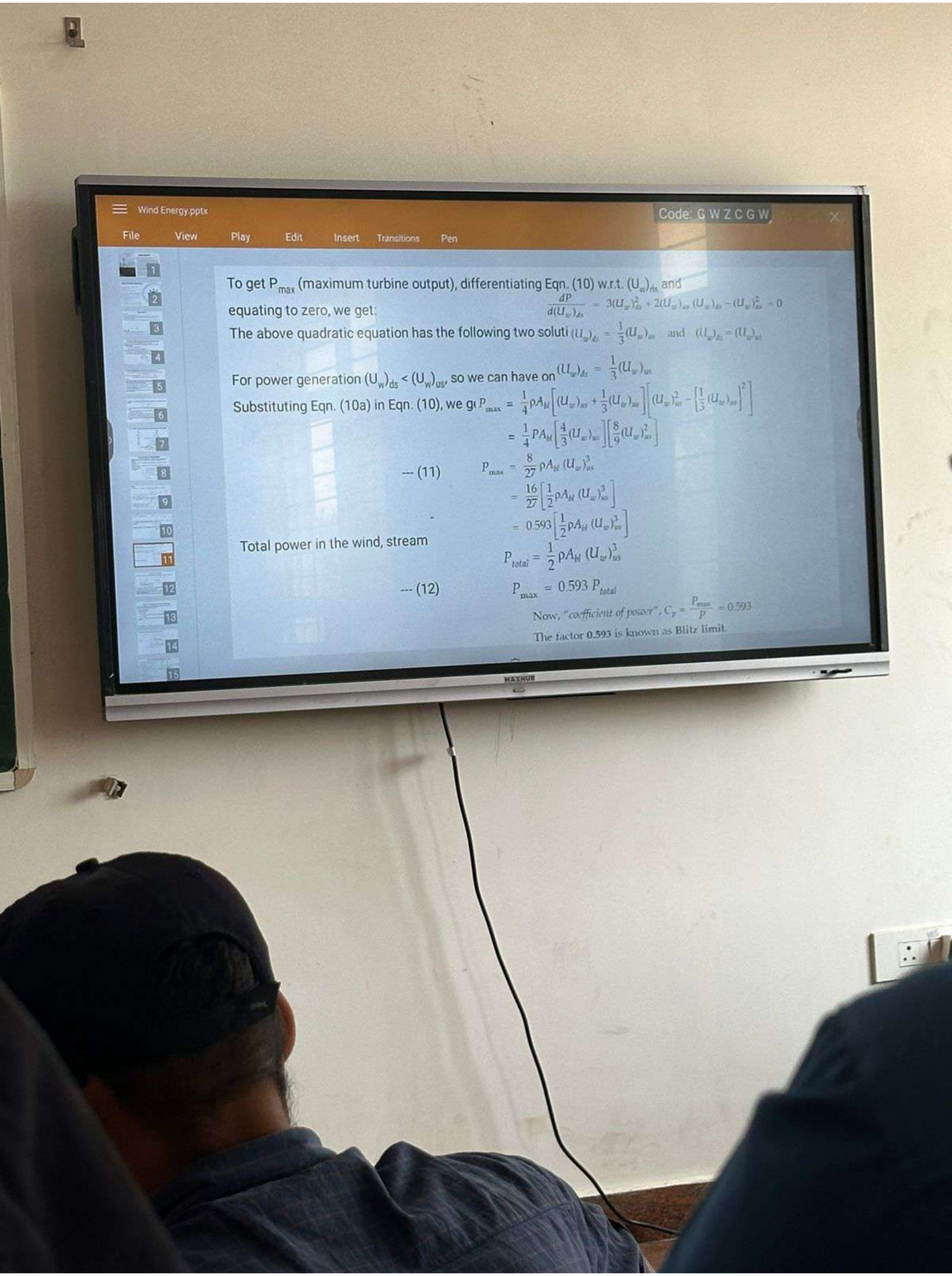
'P' of wind turbine (rate of doing work) is given as:

$$P = \frac{1}{2}\dot{m}\left[(U_w)_{us}^2 - (U_w)_{ds}^2\right] = \dot{m}\left[\frac{(U_w)_{us}^2 - (U_w)_{ds}^2}{2}\right]$$

$$= \rho A_{bl}\left[\frac{(U_w)_{us} + (U_w)_{ds}}{2}\right]\left[\frac{(U_w)_{us}^2 - (U_w)_{ds}^2}{2}\right]$$

$$\left[\because \dot{m} = \rho A_{bl}\,(U_w)_{bl} = \rho A_{bl}\left\{\frac{(U_w)_{us} + (U_w)_{ds}}{2}\right\}\right] \quad \text{Using Eq. (8)}$$

$$P = \frac{1}{4}\rho A_{bl}\left[(U_w)_{us} + (U_w)_{ds}\right]\left[(U_w)_{us}^2 - (U_w)_{ds}^2\right] \qquad \text{--- (10)}$$



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To get P_{max} (maximum turbine output), differentiating Eqn. (10) w.r.t. $(U_w)_{ds}$ and
equating to zero, we get: $\frac{dP}{d(U_w)_{ds}} = 3(U_w)_{ds}^2 + 2(U_w)_{us}(U_w)_{ds} - (U_w)_{us}^2 = 0$
The above quadratic equation has the following two soluti $(U_w)_{ds} = \frac{1}{3}(U_w)_{us}$ and $(U_w)_{ds} = (U_w)_{us}$
For power generation $(U_w)_{ds} < (U_w)_{us}$, so we can have on $(U_w)_{ds} = \frac{1}{3}(U_w)_{us}$
Substituting Eqn. (10a) in Eqn. (10), we g $P_{max} = \frac{1}{4}\rho A_H\left[(U_w)_{us} + \frac{1}{3}(U_w)_{us}\right]\left[(U_w)_{us}^2 - \left\{\frac{1}{3}(U_w)_{us}\right\}^2\right]$
$= \frac{1}{4}\rho A_H\left[\frac{4}{3}(U_w)_{us}\right]\left[\frac{8}{9}(U_w)_{us}^2\right]$
--- (11) $P_{max} = \frac{8}{27}\rho A_H (U_w)_{us}^3$
$= \frac{16}{27}\left[\frac{1}{2}\rho A_H (U_w)_{us}^3\right]$
$= 0.593\left[\frac{1}{2}\rho A_H (U_w)_{us}^3\right]$
Total power in the wind, stream
$P_{total} = \frac{1}{2}\rho A_H (U_w)_{us}^3$
--- (12) $P_{max} = 0.593\, P_{total}$
Now, "coefficient of power", $C_p = \frac{P_{max}}{P} = 0.593$
The factor 0.593 is known as Blitz limit.
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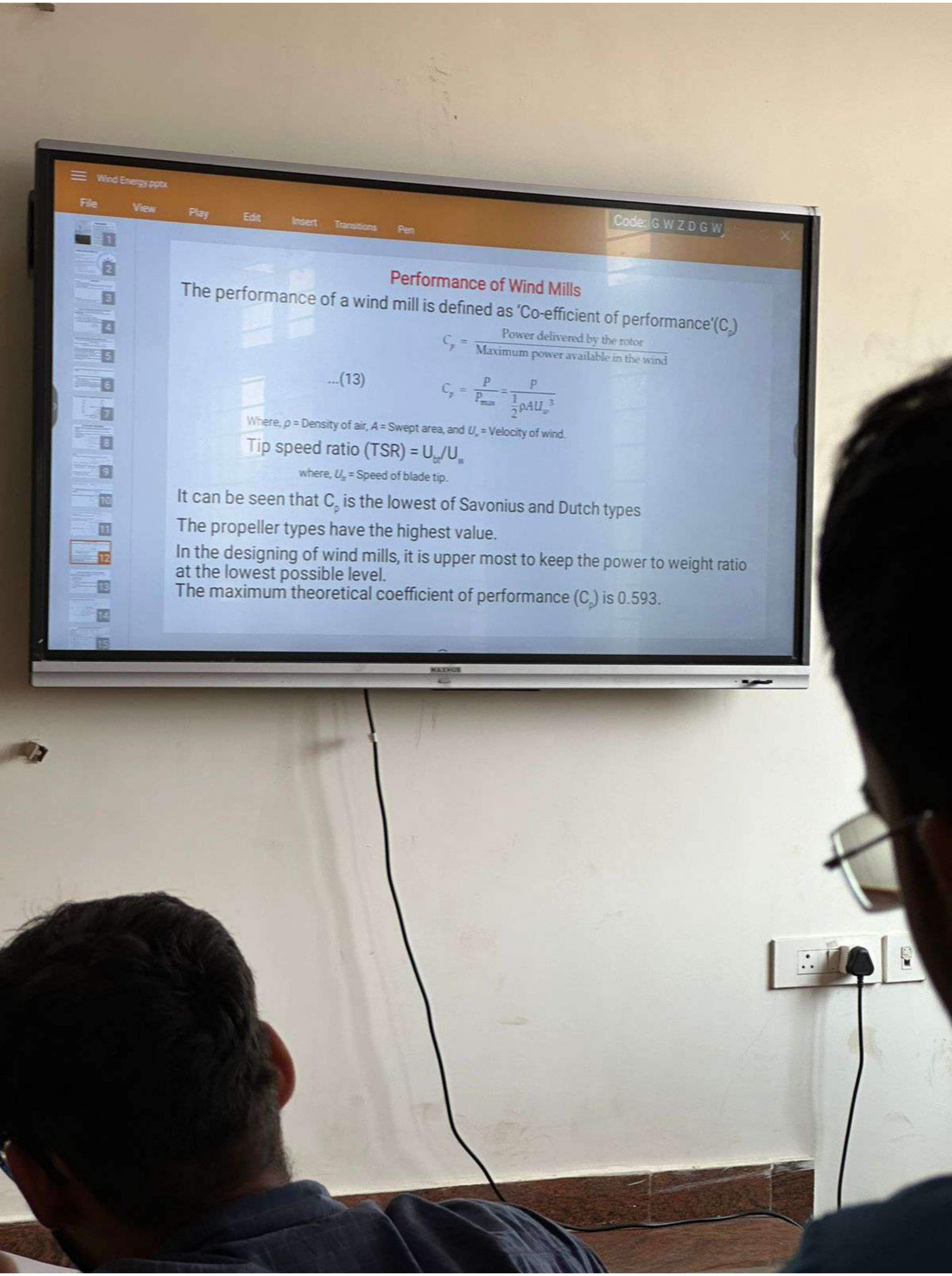

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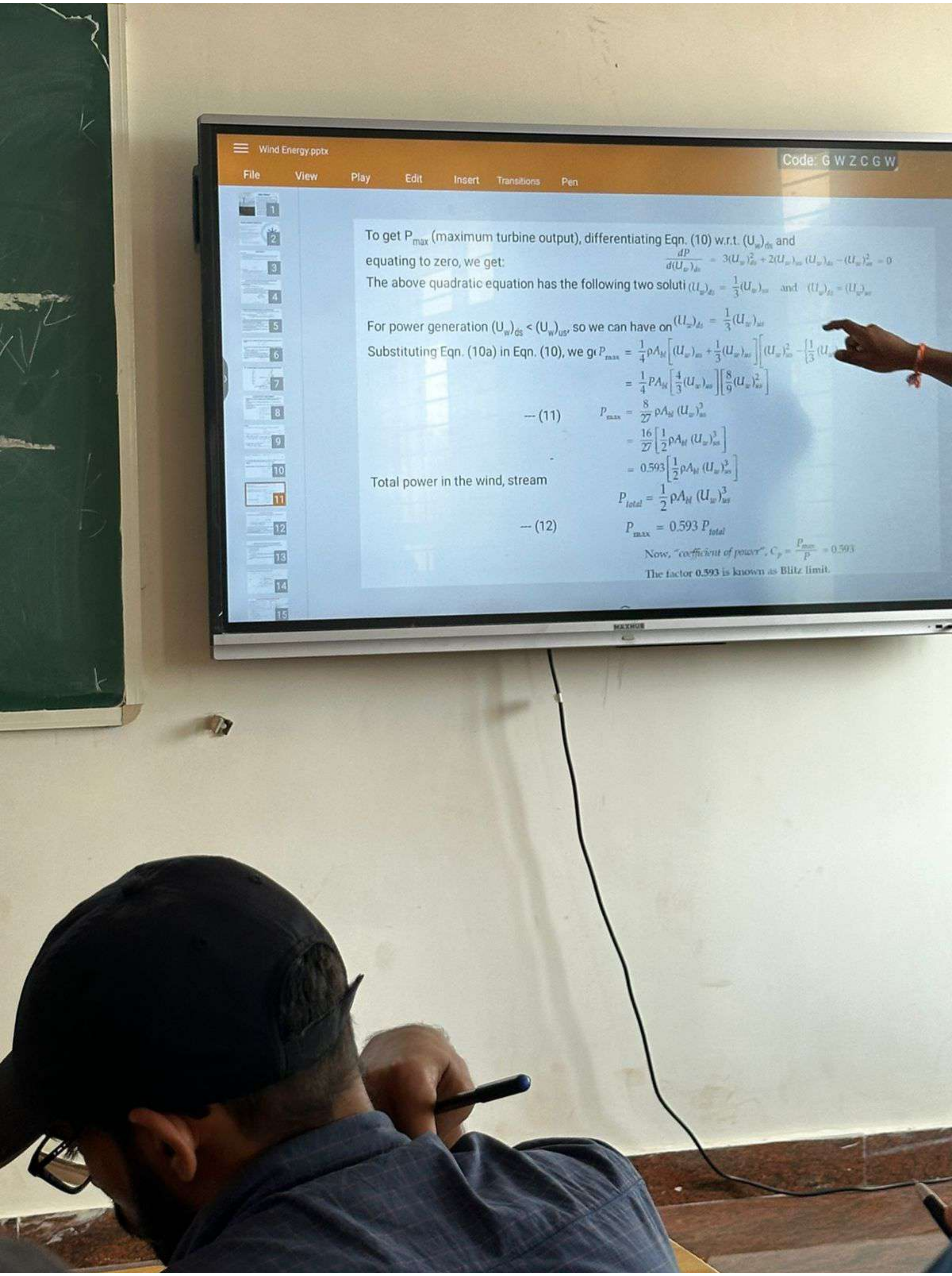
Performance of Wind Mills
The performance of a wind mill is defined as 'Co-efficient of performance'(C_p)
$C_p = \dfrac{\text{Power delivered by the rotor}}{\text{Maximum power available in the wind}}$
...(13)
$C_p = \dfrac{P}{P_{max}} = \dfrac{P}{\frac{1}{2}\rho A U_w^3}$
Where, ρ = Density of air, A = Swept area, and U_w = Velocity of wind.
Tip speed ratio (TSR) = U_{bt}/U_w
where, U_{bt} = Speed of blade tip.
It can be seen that C_p is the lowest of Savonius and Dutch types
The propeller types have the highest value.
In the designing of wind mills, it is upper most to keep the power to weight ratio at the lowest possible level.
The maximum theoretical coefficient of performance (C_p) is 0.593.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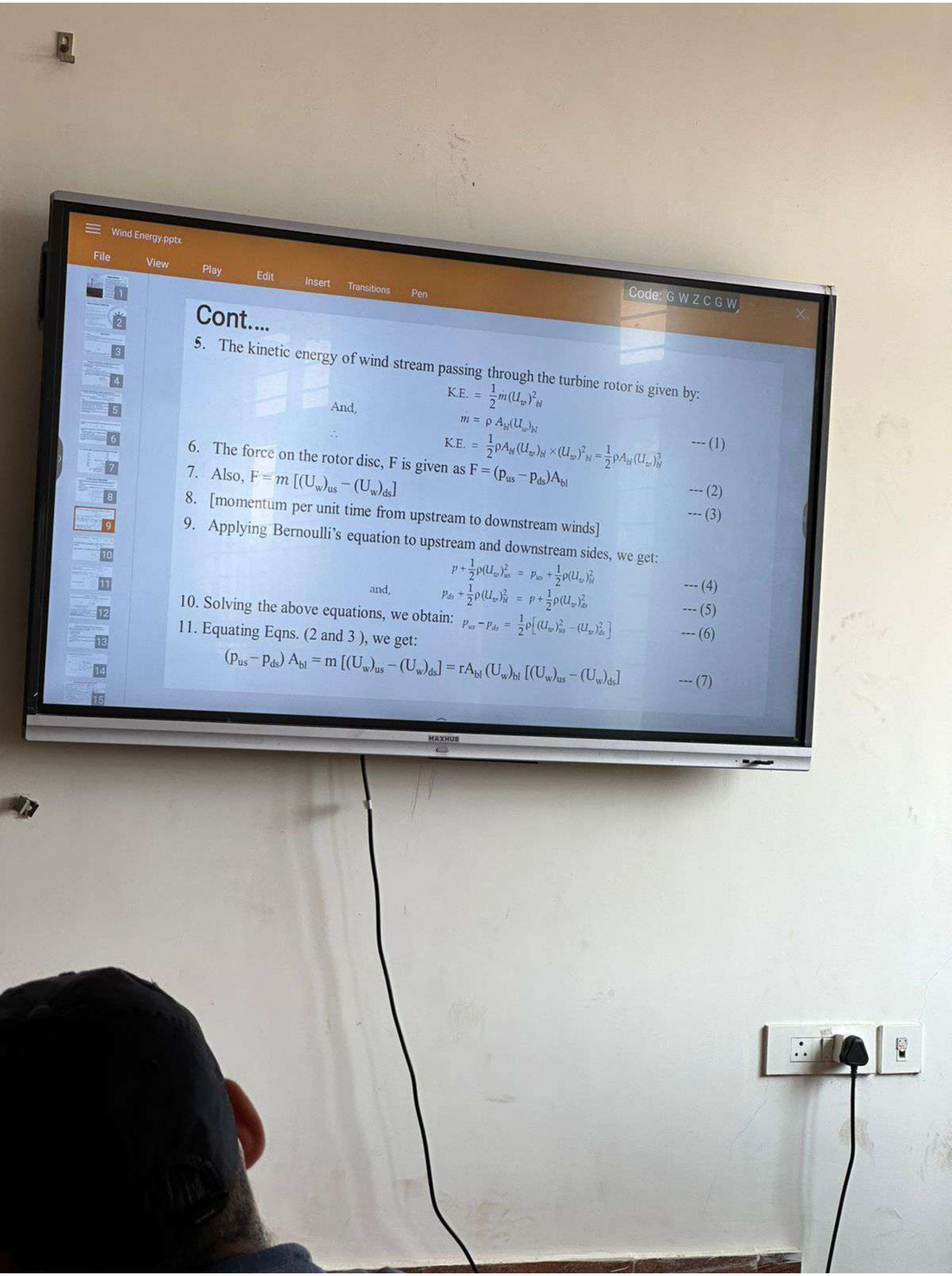
To get Pmax (maximum turbine output), differentiating Eqn. (10) w.r.t. (Uw)ds and
equating to zero, we get:
The above quadratic equation has the following two soluti
For power generation (Uw)ds < (Uw)us, so we can have on
Substituting Eqn. (10a) in Eqn. (10), we g
--- (11)
Total power in the wind, stream
--- (12)
Now, "coefficient of power", Cp = Pmax / P = 0.593
The factor 0.593 is known as Blitz limit.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Cont....
5. The kinetic energy of wind stream passing through the turbine rotor is given by:
$K.E. = \frac{1}{2}\dot{m}(U_w)^2_{bl}$
And, $\dot{m} = \rho A_{bl}(U_w)_{bl}$
$\therefore$ $K.E. = \frac{1}{2}\rho A_{bl}(U_w)_{bl} \times (U_w)^2_{bl} = \frac{1}{2}\rho A_{bl}(U_w)^3_{bl}$ --- (1)
6. The force on the rotor disc, F is given as $F = (p_{us} - p_{ds})A_{bl}$ --- (2)
7. Also, $F = m\,[(U_w)_{us} - (U_w)_{ds}]$ --- (3)
8. [momentum per unit time from upstream to downstream winds]
9. Applying Bernoulli's equation to upstream and downstream sides, we get:
$p + \frac{1}{2}\rho(U_w)^2_{us} = p_{us} + \frac{1}{2}\rho(U_w)^2_{bl}$ --- (4)
and, $p_{ds} + \frac{1}{2}\rho(U_w)^2_{bl} = p + \frac{1}{2}\rho(U_w)^2_{ds}$ --- (5)
10. Solving the above equations, we obtain: $p_{us} - p_{ds} = \frac{1}{2}\rho\left[(U_w)^2_{us} - (U_w)^2_{ds}\right]$ --- (6)
11. Equating Eqns. (2 and 3), we get:
$(p_{us} - p_{ds})A_{bl} = m\,[(U_w)_{us} - (U_w)_{ds}] = rA_{bl}\,(U_w)_{bl}\,[(U_w)_{us} - (U_w)_{ds}]$ --- (7)
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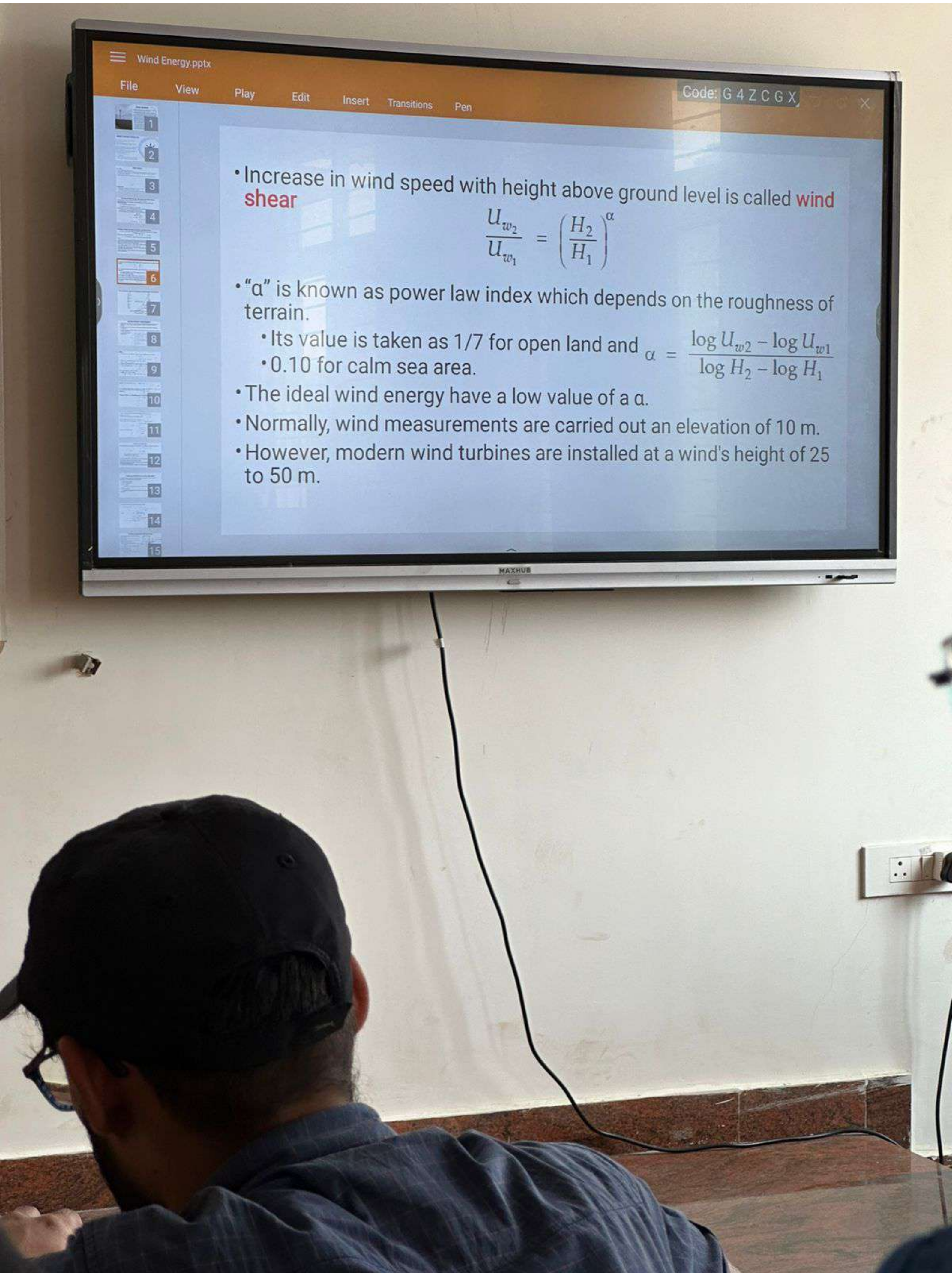
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• Increase in wind speed with height above ground level is called wind shear
$\frac{U_{w_2}}{U_{w_1}} = \left(\frac{H_2}{H_1}\right)^{\alpha}$
• "α" is known as power law index which depends on the roughness of terrain.
• Its value is taken as 1/7 for open land and
• 0.10 for calm sea area.
$\alpha = \frac{\log U_{w2} - \log U_{w1}}{\log H_2 - \log H_1}$
• The ideal wind energy have a low value of a α.
• Normally, wind measurements are carried out an elevation of 10 m.
• However, modern wind turbines are installed at a wind's height of 25 to 50 m.
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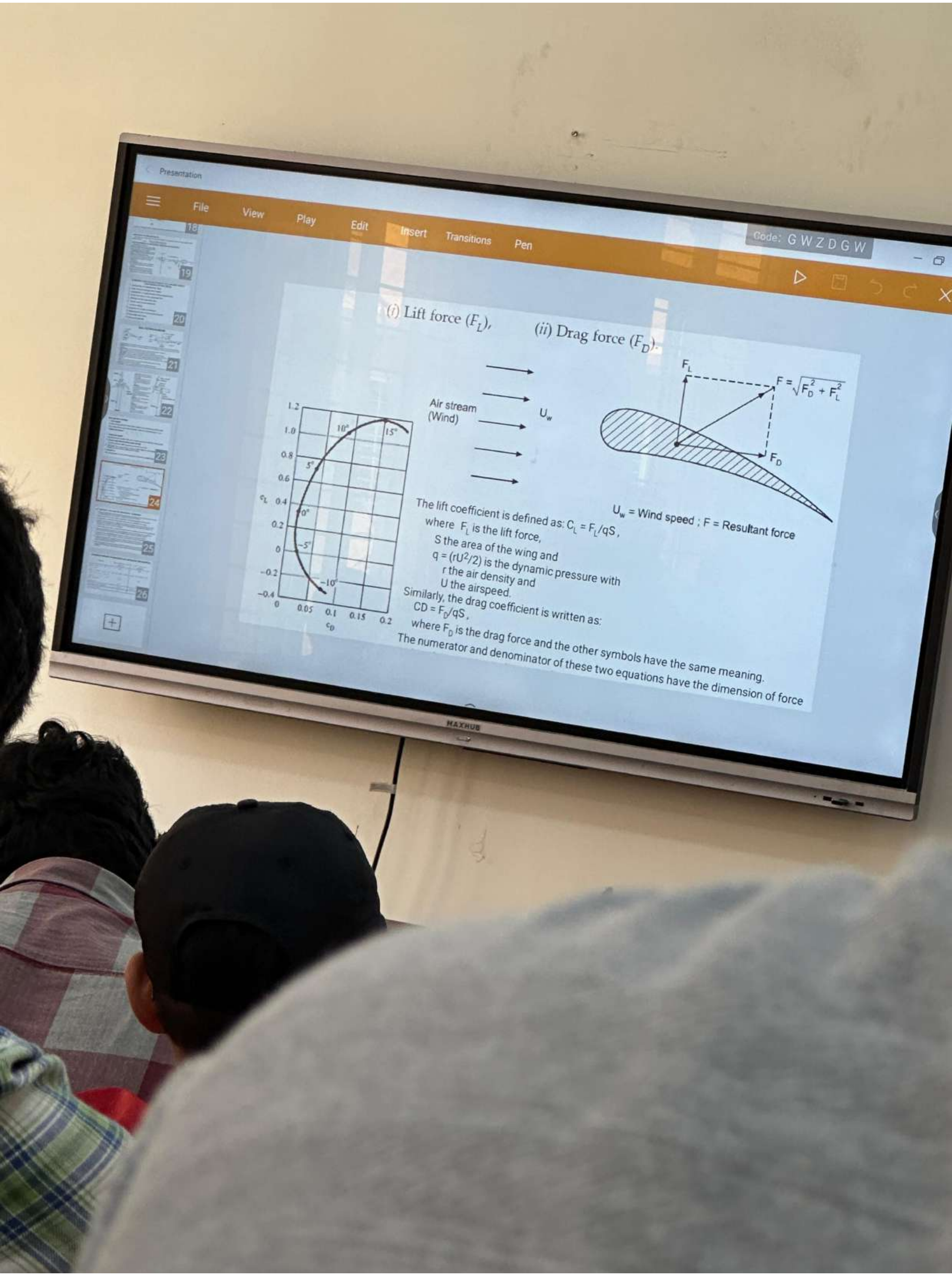
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(i) Lift force (F_L),
(ii) Drag force (F_D).
Air stream
(Wind)
U_w
F_L
$F = \sqrt{F_D^2 + F_L^2}$
F_D
U_w = Wind speed ; F = Resultant force
1.2
1.0
0.8
0.6
c_L 0.4
0.2
0
−0.2
−0.4
0
0.05
0.1
0.15
0.2
c_D
10°
15°
5°
0°
−5°
−10°
The lift coefficient is defined as: $C_L = F_L/qS$,
where F_L is the lift force,
S the area of the wing and
$q = (rU^2/2)$ is the dynamic pressure with
r the air density and
U the airspeed.
Similarly, the drag coefficient is written as:
$CD = F_D/qS$,
where F_D is the drag force and the other symbols have the same meaning.
The numerator and denominator of these two equations have the dimension of force
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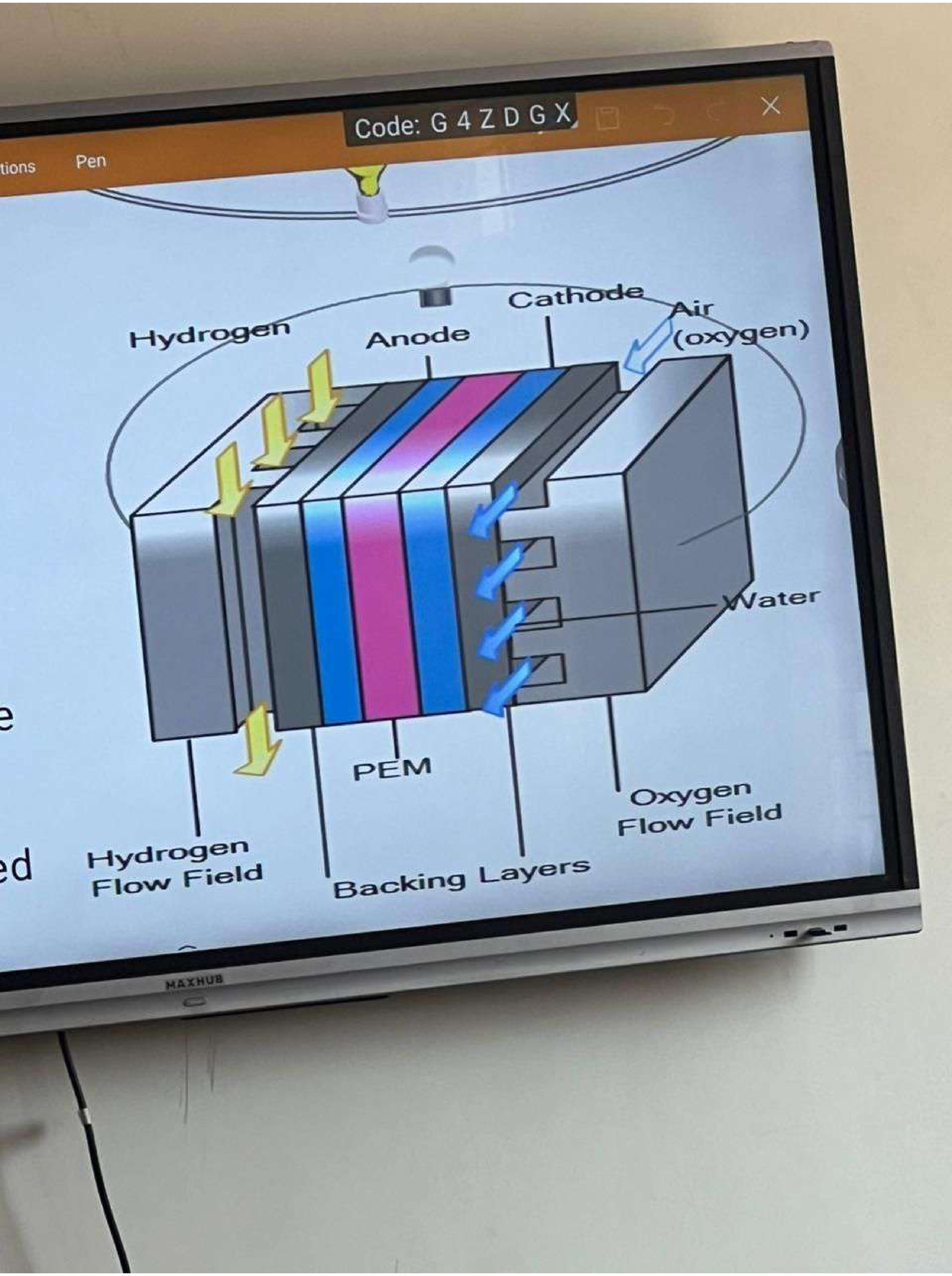
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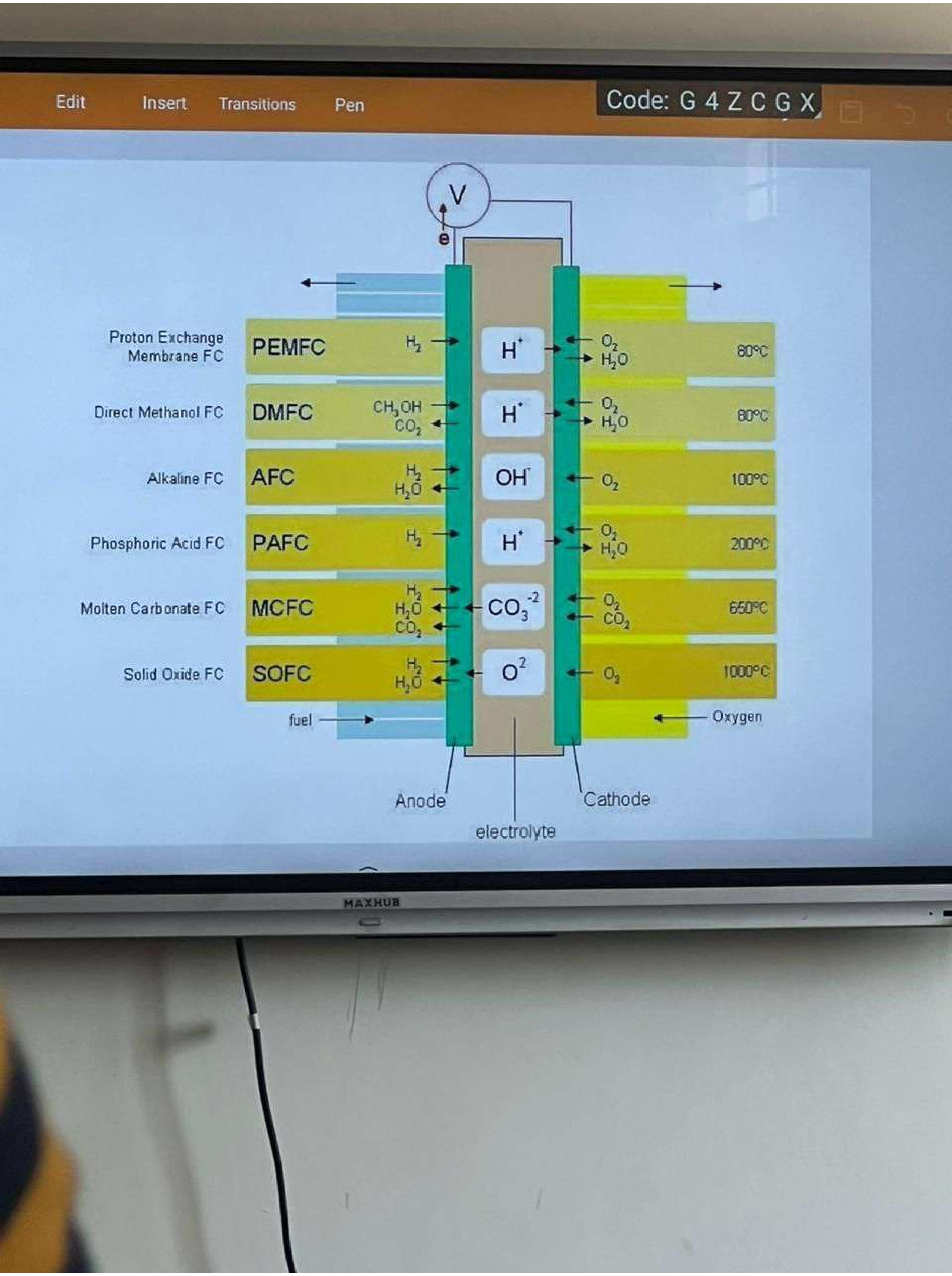
Pen
Hydrogen
Anode
Cathode
Air
(oxygen)
Water
PEM
Oxygen
Flow Field
Hydrogen
Flow Field
Backing Layers
MAXHUB

Fuel cell Basic Chemistry & Thermodynamics

- Fuel + oxidant → H_2O + other products + electricity
- $H_2 + ½\ O_2 \rightarrow H_2O$, $\Delta H = 286$ kJ/mol
- Enthalpy that can be converted to electricity in a fuel cell corresponds to Gibbs free energy.
- $\Delta G = \Delta H - T\Delta S$
- $W_{el} = qE = nFE$
- $W_{el} = -\Delta G$
- $E_{theo} = \frac{-\Delta G}{nF} = \frac{237{,}340\ J/mol}{2\times 96{,}485\ As/mol} = \mathbf{1.23\ V}$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V
e
Proton Exchange Membrane FC
PEMFC
H2
H+
O2
H2O
80°C
Direct Methanol FC
DMFC
CH3OH
CO2
H+
O2
H2O
80°C
Alkaline FC
AFC
H2
H2O
OH-
O2
100°C
Phosphoric Acid FC
PAFC
H2
H+
O2
H2O
200°C
Molten Carbonate FC
MCFC
H2
H2O
CO2
CO3-2
O2
CO2
650°C
Solid Oxide FC
SOFC
H2
H2O
O2
O2
1000°C
fuel
Oxygen
Anode
Cathode
electrolyte
MAXHUB

Characteristics of Fuel Cells

Fuel Cells	Attractive Attributes	Undesirable Attributes
Phosphoric Acid Fuel Cell (PAFC).	-Low temperatures suitable for portable device applications -Ability for variable power output -Broad fuel choice	-Uses expensive platinum as a catalyst. -Electrolyte is poor conductor at low temperatures
Proton Exchange Membrane Fuel Cell (PEM).	-Low operating temperature suitable for transportation and portable devices -High power density	-Uses expensive platinum as a catalyst -Sensitivity to fuel impurities
Molten Carbonate Fuel Cell (MCFC)	-High operating temperature improves efficiency for base load power plants.	-Not suitable for small-sized applications
Solid Oxide Fuel Cell (SOFC)	-High operating temperature improves efficiency for base load power plants. -Solid electrolyte improves conductivity	- Electrolyte is made from ceramics and solid zirconium oxide that is a rare mineral
Alkaline Fuel Cells (AFC)	-Low temperature and high fuel-to-electricity efficiency	-Requirement of pure hydrogen and allergic to carbon dioxide
Direct Methanol Fuel Cells (DMFC).	-Eliminates need for fuel reformer drawing hydrogen directly from the anode -Low temperatures suitable for portable devices	-Fuel crossing from anode to cathode without producing electricity

Classification of Fuel cells:

1. **Primary fuel cell:** The reactants are passed through the cell only once and the products of the reaction being discarded. (H_2 - O_2 fuel cell)
2. **Secondary fuel cell:** The reactant are passed through the fuel cell many times because they are generated by different methods. (Nitric oxide – Chlorine fuel cell)

According to the Application:

1. Stationary,
2. Portable
3. Mobile

According to the Operating temperature:

1. Low temperature (25 to 100°C)
   Proton exchange membrane fuel cell (PEMFC), Direct methanol fuel cell (DMFC)
2. Medium temperature (100 to 500°C)
   Alkaline Electrolyte fuel cell, Phosphoric acid Fuel cell (PAFC)
3. High temperature (500 to 1000°C)
   Molten Carbonate fuel cell (MCFC), Solid Oxide Fuel Cell (SOFC)
4. Very high temperature (>1000 °C)

According to the type of electrolyte:

1. Aqueous
2. Non-aqueous
3. Molten or solid

According to the physical state of fuel:

1. Gas (Hydrogen, Lower hydrocarbons)
2. Liquid (Alcohols, Hydrazine, higher hydrocarbons)
3. Solid (metals)

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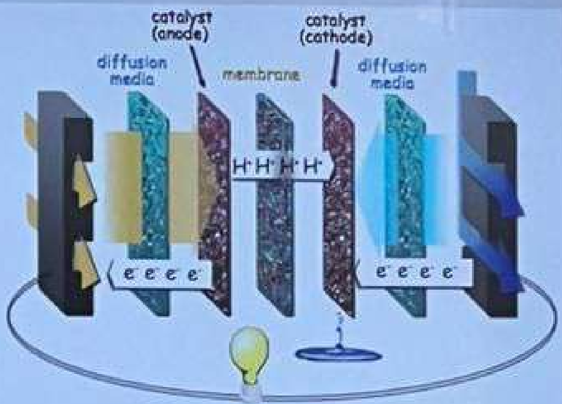
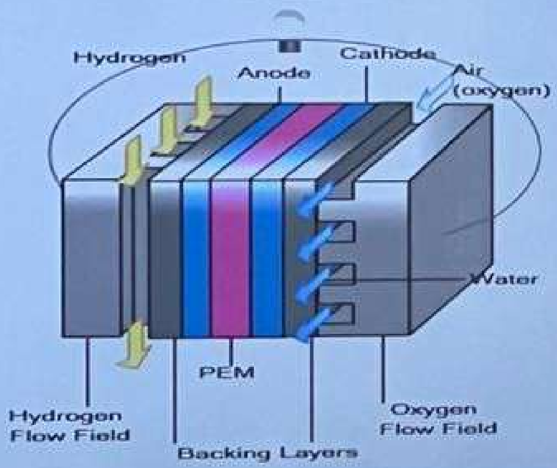
The primary components of a FCs are:

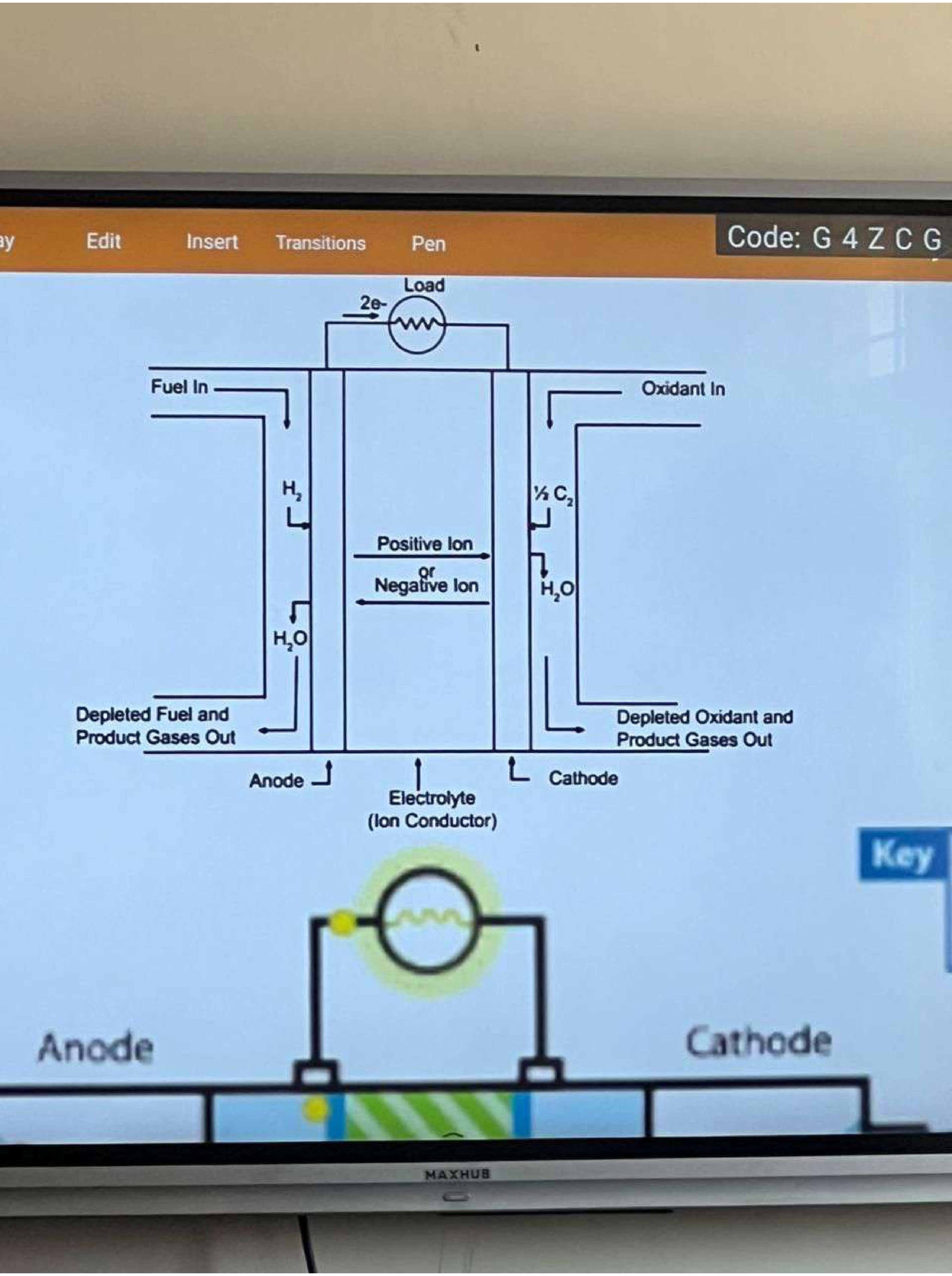
1. an ion conducting electrolyte,
2. a cathode, and
3. an anode,
4. as shown schematically in Figures

1. Together, these three are often referred to as the simply a single-cell fuel cell.

Electrode: a thin catalyst layer pressed between the ionomer membrane and porous, electrically conductive substrate.
Electrolyte: A chemical compound that conducts ions from one electrode to the other inside a fuel cell.
Catalyst: A substance that causes or speeds a chemical reaction without itself being affected.
Bipolar plates: connecting the anode of one cell to the cathode of the adjacent cell.
Gas diffusion layer: a layer between the catalyst layer and bipolar plates, also called electrode substrate or diffusor/current collector







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Load
2e-
Fuel In
Oxidant In
H_2
$\frac{1}{2} C_2$
Positive Ion
or
Negative Ion
H_2O
H_2O
Depleted Fuel and Product Gases Out
Depleted Oxidant and Product Gases Out
Anode
Electrolyte (Ion Conductor)
Cathode
Key
Anode
Cathode
MAXHUB

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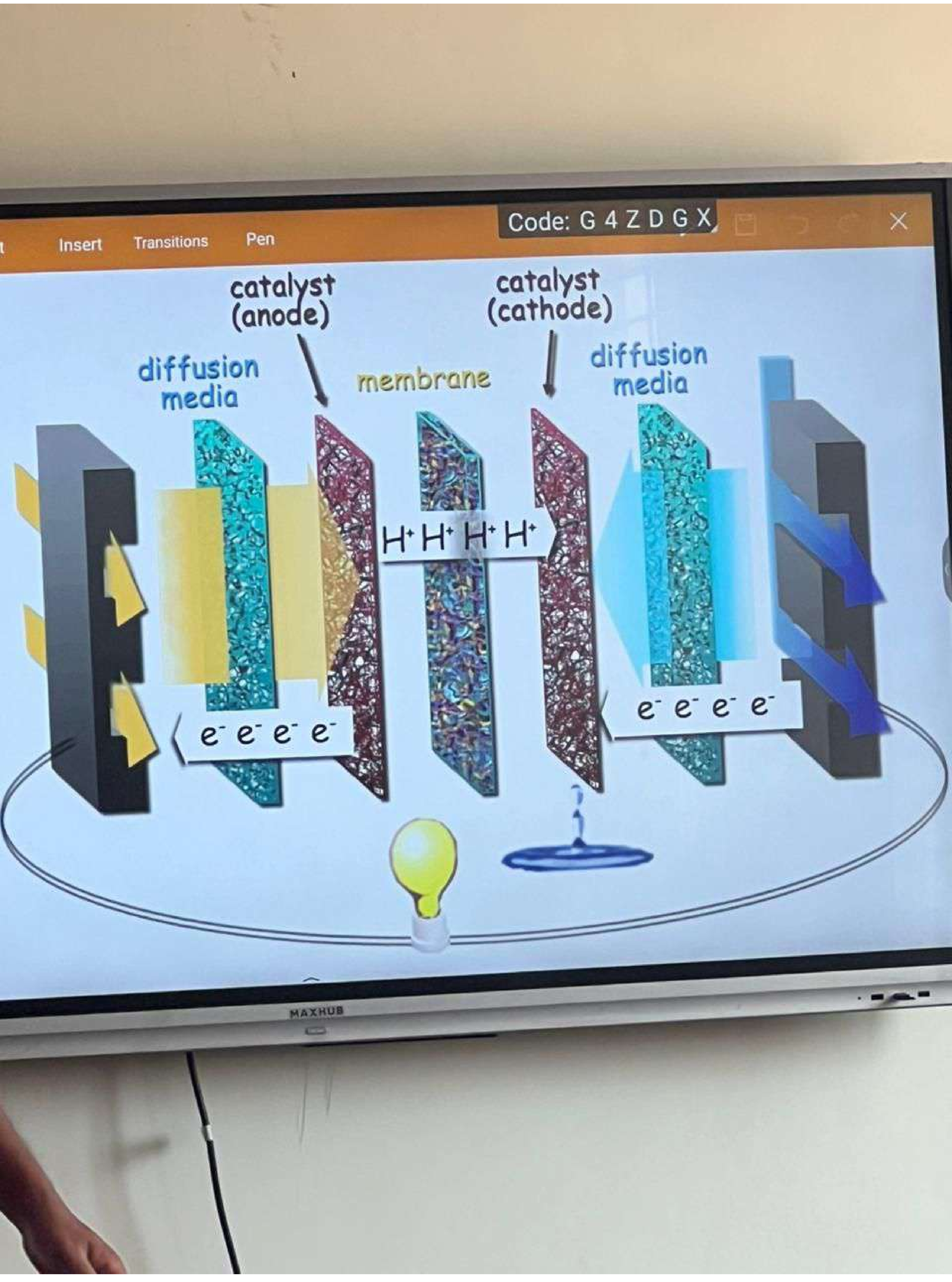
Fuel Cell	Electrolyte	Qualified Power (W)	Working Temperature (°C)	Electrical Efficiency	Status
Alkaline fuel cell	Aqueous alkaline solution (e.g., potassium hydroxide)	10 kW to 100 kW	60-120	35-55	Commercial/Research
Direct methanol fuel cell	Polymer membrane (ionomer)	100 kW to 1 mW	60-200	20-30	Commercial/Research
Phosphoric acid fuel cell	Molten phosphoric acid (H_3PO_4)	up to 10 MW	150-220	40	Commercial/Research
Molten carbonate fuel cell	Molten alkaline carbonate (e.g., sodium bicarbonate $NaHCO_3$)	100 MW	600-650	>50	Commercial/Research
Solid oxide fuel cell	O^{2-}-conducting ceramic oxide (e.g., zirconium dioxide, ZrO_2)	up to 100 MW	700–1000	>50	Commercial/Research
Proton exchange membrane fuel cell	Polymer membrane (ionomer) (e.g., Nafion® or Polybenzimidazole fiber)	100 W to 500 kW	50-100	35-45	Commercial/Research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Pen
catalyst
(anode)
catalyst
(cathode)
diffusion
media
membrane
diffusion
media
H+ H+ H+ H+
e- e- e- e-
e- e- e- e-
MAXHUB

12th Unit: Fuel Cell vehicles

Fuel cells: Introduction

Fuel cell characteristics

Thermodynamics of fuel cells

Fuel cell types

emphasis on PEM fuel cell

What Is a Fuel Cell?

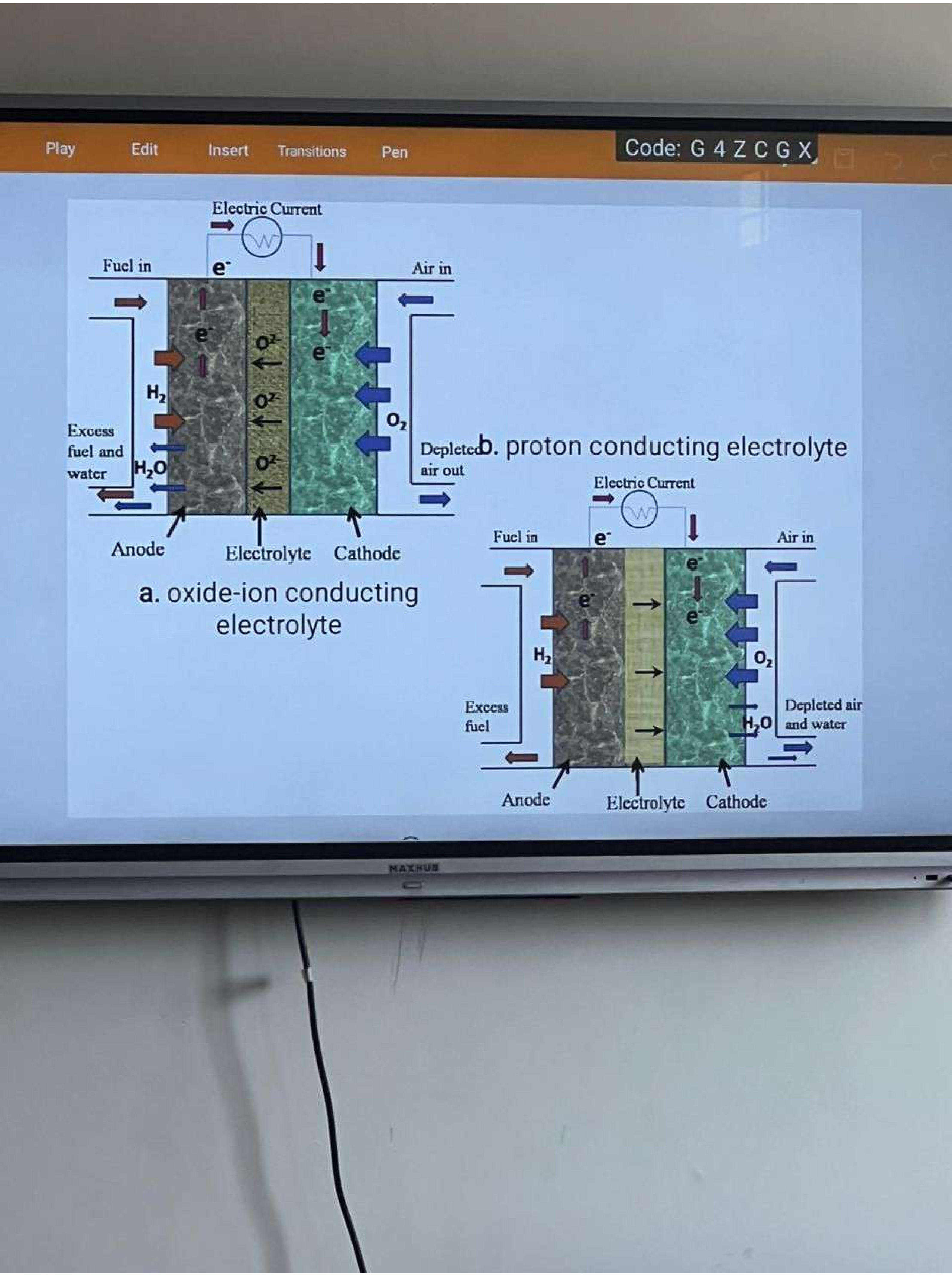
Early 1839 William Grove discovered the basic operating principle of fuel cells, by reversing water electrolysis to generate electricity from Hydrogen and Oxygen.

The principle that he discovered remains unchanged today.

A fuel cell is an electrochemical "device" that continuously converts chemical energy into electric energy (and some heat) for as long as fuel and oxidant are supplied.

Unlike engines or batteries, a fuel cell does not need recharging, it operates quietly and efficiently.

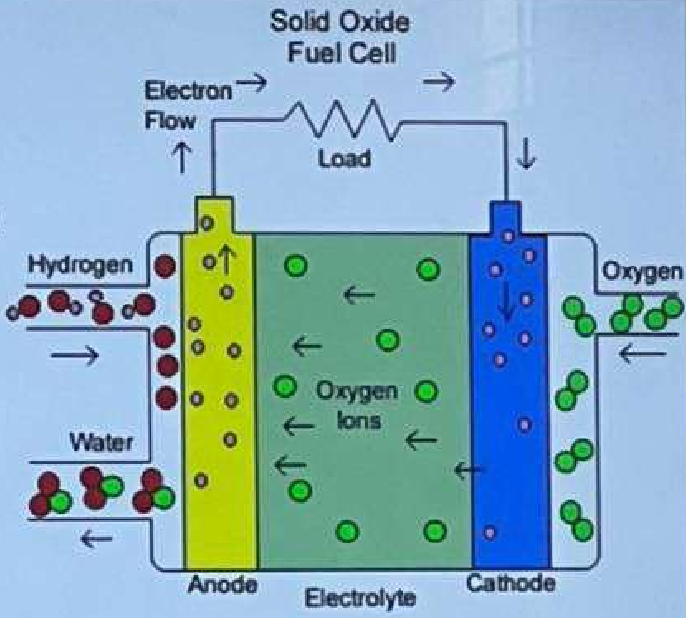
When hydrogen is used as fuel it generates only power & drinking water, so emissions are zero


Play
Edit
Insert
Transitions
Pen
Code: G 4 Z C G X
Electric Current
Fuel in
e⁻
Air in
e⁻
e⁻
e⁻
O²⁻
O²⁻
O²⁻
H₂
O₂
Excess fuel and water
H₂O
Depleted air out
Anode
Electrolyte
Cathode
a. oxide-ion conducting electrolyte
b. proton conducting electrolyte
Electric Current
Fuel in
e⁻
Air in
e⁻
e⁻
e⁻
H₂
O₂
Excess fuel
H₂O
Depleted air and water
Anode
Electrolyte
Cathode
MAXHUB

1. The **anode**, the **negative** post of the fuel cell, has several jobs.
2. It conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. It has channels etched into it that disperse the hydrogen gas equally over the surface of the catalyst.
3. The cathode, the positive post of the fuel cell, has channels etched into it that distribute the oxygen to the surface of the catalyst.
4. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water.
5. The electrolyte is the proton exchange membrane.
6. This specially treated material, which looks something like ordinary kitchen plastic wrap, only conducts positively charged ions.
7. The membrane blocks electrons. For a PEMFC, the membrane must be hydrated in order to function and remain stable.
8. The catalyst is a special material that facilitates the reaction of oxygen and hydrogen.
9. It is usually made of platinum nanoparticles very thinly coated onto carbon paper or cloth.
10. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen.
11. The platinum-coated side of the catalyst faces the PEM.

How does Fuel cell work:

1. It is an electrochemical energy conversion device.
2. This works like batteries, but they do not run down or need recharging.
3. They produce electricity and heat if fuel is supplied.
4. A fuel cell consists of two electrodes - a negative electrode (or anode) and a positive electrode (or cathode) - sandwiched around an electrolyte.
5. The atoms are stripped of their electrons in the anode.
6. The positively charged protons pass through the membrane to the cathode and the negatively charged electrons are forced through a circuit, generating electricity.
7. After passing through the circuit, the electrons combine with the protons and Oxygen from the air to generate the fuel cells by products water and heat.



The fuel cell can be represented as:

1. At anode $H_2 \rightarrow 2H^+ + 2e^-$
2. At Cathode $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
3. Overall reaction $H_2 + \frac{1}{2} O_2 = H_2O$