

GE1040 A Culture of Sustainability

AY 25/26 Sem 1 — github/omgeta

1. Unsustainable Development

Unsustainable development harms the ability of future generations to meet their needs due to the degradation of our climate, life-support systems and resources.

- i. Global Environmental Indicators: Planetary boundaries have already been exceeded (climate change, biodiversity loss, nitrogen cycle).
- ii. Stability Landscape: Ecosystems may lose resilience - once thresholds are crossed (valley basins), systems may not return to their original state.
- iii. Changing Climate: We are living in a changing climate. We need to mitigate impacts on us and ecosystem, or otherwise become more adaptable

Ecological Footprint

Terminology:

- i. Bioproductivity: amount and rate of production occurring in an ecosystem over a period of time.
- ii. Biocapacity = Area × Biocapacity: quantifies nature's capacity to produce renewable resources, provide land for built-up areas and provide waste absorption services such as carbon uptake.
- iii. Ecological Footprint (gha) = Population × Consumption/Person × Footprint Intensity: quantifies biological productive area needed for provision of renewable resources, or require absorption of CO₂ waste.
- iv. Footprint and biocapacity can be ranked by countries, enabling them to learn from each other.
- v. Ecological Deficit: ecological footprint > biocapacity (currently exceeded by 50%).

Earth Overshoot Day is the date when annual footprint exceeds annual biocapacity:

- i. Occurs earlier each year (first at 1970)
- ii. COVID-19 caused ecological footprint to contract
- iii. #MoveTheDate: push overshoot to December via sustainable cities, resilient systems, etc.

Causes

Overpopulation due to exponential population growth:

- i. 8.1b (2025) → 9.5b (2050) → 11b (2100)
- ii. Pressure on land, soil degradation, and biodiversity
- iii. Prior to Industrial Revolution, growth was resource-limited but now largely unchecked
- iv. Various demands by billions for a comfortable life, but everyone should have the equal right to health

Unsustainable Resource Use:

- i. Affluenza: oversumption in affluent societies
- ii. Developing countries fixated on GDP as sole success metric ignoring environmental costs

Poverty links to environment in a downward spiral:

- i. Direct reliance on food, water, fuel for survival
- ii. Degenerate forests, soil, grasslands and wildlife causing environmental degradation
- iii. Degraded environment further impoverishes people

Excluding Environmental Costs:

- i. Market prices ignore externalities such as ecosystem loss, health impacts and pollution
- ii. Ex. Timber companies pay to clear forests but not for environmental degradation and loss of habitat
- iii. Ex. Fishing companies pay to catch fish but not for depletion of fish stocks
- iv. Taxes and fines aim to fix this but not enough

Tragedy of the Commons

Tragedy of the commons is the overuse of a common property or free-access resource causing depletion for all.

- i. Mentality of "If I do not use it, someone else will. The little bit I use or pollute doesn't matter".
- ii. Solutions:
 - Responsible usage of shared renewable resources at rates well below sustainable yields
 - Convert open-access renewable resources to private ownership

IPAT Model

IPAT quantifies environmental impact as $I = P \times A \times T$ where P is population, A is affluence, T is technology:

- i. Population: not dominant factor
- ii. Affluence: $\frac{\text{Goods & Services}}{\text{Person}}$ can harm through high consumption, pollution and resource wastage but also produce funding for innovative R&D (e.g. Denmark, India's ethanol-blended gasoline)
- iii. Technology: $\frac{\text{Impact}}{\text{Goods & Services}}$ reduces impact
- iv. Ex.: Gasoline = cars × miles/car × gasoline/mile

Pollution

Pollution is the introduction of contaminants into the natural environment that adversely affects a resource.

- i. Point Source: single, identifiable source (e.g. smokestack, drainpipes)
- ii. Nonpoint Source: dispersed and difficult to identify (e.g. fertilizer and pesticide runoff into lakes - first flush effect after dryspell)

Health Effects:

- i. Headache and Fatigue
- ii. Respiratory Illness
- iii. Cardiovascular Illness
- iv. Cancer Risk
- v. Nausea and Gastroenteritis
- vi. Skin Irritation

Management Methods:

- i. Cleanup (end-of-pipe): clean/dilute contaminants
 - Temporary; growth in consumption may offset pollution control tech
 - Often relocates pollutants to another area
 - Costly to clean dispersed pollutants
- ii. Prevention (front-of-pipe): reduce/stop production

Environmental Viewpoints

Planetary Management:

- i. View: We are apart from the rest of nature and can manage it to meet our increasing demands.
- ii. Resources: We will not run out, due to our ingenuity and technology.
- iii. Economy: Potential for economic growth is essentially unlimited.
- iv. Success: Depends on how well we manage the earth's life-support systems for our benefit.

Stewardship:

- i. View: We have an ethical responsibility to be caring stewards of the earth.
- ii. Resources: We will probably not run out, but they should not be wasted.
- iii. Economy: Encourage environmentally friendly economic growth and discourage harmful forms.
- iv. Success: Depends on our managing the earth's life-support systems for our and nature's benefit.

Environmental Wisdom:

- i. View: We are part of and totally dependent on nature, and nature exists for all species.
- ii. Resources: Limited and should not be wasted.
- iii. Economy: Encourage earth-sustaining economic growth and discourage earth-degrading forms.
- iv. Success: Depends on learning how nature sustains itself, integrating them into how we think and act.

2. Principles and Practical Applications of Sustainability

Environmentally sustainable societies meet present needs without compromising future generations' own needs:

- i. Without destroying the environment
- ii. Without endangering the future welfare of the planet and its people
- iii. In a just and equitable manner

Sustainability is the ability of Earth's natural systems, cultural systems and economies to survive and adapt to changing environmental conditions indefinitely. 3 Pillars:

- i. Environment (ecological integrity)
- ii. Economy (economic viability)
- iii. Society (equity)

Sustainable Development Goals (SDGs)

UN Sustainable Development Goals (SDGs) were adopted in 2015 by 2500 scientists from 190 nations, providing a global framework to steer towards a safe and just operating space for society to thrive in until 2030:

- 1. No Poverty
- 2. Zero Hunger
- 3. Good Health and Well-being
- 4. Quality Education
- 5. Gender Equality
- 6. Clean Water and Sanitation
- 7. Affordable and Clean Energy
- 8. Decent Work and Economic Growth
- 9. Industry, Innovation and Infrastructure
- 10. Reduce Inequality
- 11. Sustainable Cities and Communities
- 12. Responsible Consumption and Production
- 13. Climate Action
- 14. Life below Water
- 15. Life on Land
- 16. Peace and Justice Strong Institutions
- 17. Partnerships to achieve the Goal

International Spillovers

Spillovers are transboundary negative impacts generated by one country on others, which can undermine their ability to achieve the SDGs, measured by Spillover Score. Types of spillovers:

- i. Environmental: use of natural resources and pollution, including transboundary effects embodied in trade, and direct cross-border flows in air and water
- ii. Economic/Financial/Governance: international development finance, unfair tax competition, banking secrecy, and labor standards
- iii. Security: negative externalities such as arms trade and organized crime destabilizing poorer countries; positive spillovers include conflict-prevention and peacekeeping investments

Natural Capital

Natural capital (natural resources + natural services) refers to the stock of natural resources and ecosystem services that sustain human life :

- i. Natural Resources: includes air, water, soil, land, life (biodiversity), nonrenewable resources, renewable energy and nonrenewable energy
- ii. Natural Services: includes air purification, water purification, water storage, soil renewal, nutrient recycling, food production, conservation of biodiversity, wildlife habitat, forest renewal, waste treatment, climate control, population control and pest control
- iii. Degradation of natural capital undermines long-term sustainability
- iv. Preserving natural capital is essential for intergenerational equity

Sustainability Concepts

Shifting Emphasis:

- i. Pollution cleanup → Pollution prevention
- ii. Waste disposal → Waste prevention and reduction
- iii. Species protection → Habitat protection
- iv. Environ. degradation → Environ. restoration
- v. Increased resource use → Less wasteful resource use
- vi. Population growth → Population stabilization by decreasing birth rates
- vii. Depleting and degrading natural capital → Protecting natural capital, living off bio-interest

Lessons from Nature:

- i. Runs on renewable solar energy → Rely mostly on renewable solar energy
- ii. Recycles nutrients and wastes (little waste) → Prevent/reduce pollution, recycle & reuse resources
- iii. Uses biodiversity to maintain and adapt to environmental change → Preserve biodiversity by protecting ecosystem services, habitats and species
- iv. Controls species' population size and resource use → Reduce births and wasteful resource use to prevent environmental overload, and depletion and degradation of resources

Challenges:

- i. Depletion of finite resources (fossil fuels, soil, minerals, species)
- ii. Overuse of renewable resources (forests, fish & wildlife, soil fertility, public funds)
- iii. Pollution (air, water, soil)
- iv. Inequity (economic, political, social, gender)
- v. Species loss (endangered species and spaces)

Solutions:

- i. Cyclical use of resources (emulate nature; 3R's)
- ii. Safe reliable energy (conservation, renewable energy, substitution, interim measures)
- iii. Human well-being interests (health, creativity, learning, cultural and spiritual development)

Research & Development (R&D)

Examples of sustainability-oriented research and indigenous technology development:

- i. Power Generation: Biogas integrated with waste management/Co-Gen systems
- ii. Construction Materials: Local, non-toxic, reusable materials; water as material for thermal walls
- iii. Water Supply: Rainwater harvesting for groundwater recharge and building cooling
- iv. Water Treatment: Natural biomaterials for turbidity removal; UV disinfection from sunlight; fabric filtration for point-of-use treatment
- v. Storm-water Management: Green roofs for runoff reduction, reduced energy use, and cooling effect
- vi. Building Design: Passive solar design, right-sized homes, cost-effective ventilation, maximize storage and comfort with minimal energy

Green Roofs are intensive (thick substrate, shrubs/trees) or extensive (thin substrate, smaller plants):

- i. Aesthetically pleasing
- ii. Reduce storm-water runoff
- iii. Reduce urban heat island effects
- iv. Reduce air conditioning costs
- v. Negate acid rain effects
- vi. Reduce CO₂ impact
- vii. Create habitats for certain plants and animals
- viii. Cooling Effect: protects from solar radiation, stabilizes roof temperature, cools building interiors
- ix. Water Quality: depends on substrate layer, vegetation type, fertilisation quality, roof age, surrounding area type, local pollution sources

Key Carbon Considerations:

- i. Embodied: emissions from construction materials
- ii. Operational: emissions from running processes

Case Study: NUS Sustainability Initiative

Current Practices:

- i. Integrated into education, research, campus operations, and leadership
- ii. Contributes directly to multiple SDGs such as climate action, clean energy, and sustainable cities

Future:

- i. Driving sustainability via collaboration with other sectors (internal and external partners)
- ii. Building climate resilience by linking research across climate, urban, economic, and social areas

Case Study: Punggol Digital District (PDD)

Current Practices:

- i. 17 Green Mark Platinum and 3 Super Low Energy Buildings (e.g. Mass Engineered Timber with 98% lower embodied carbon)
- ii. Smart Energy Grid: real-time data management optimisation saves 1,700 tonnes CO₂ annually; rooftop PV panels generate 3,000 MWh annually
- iii. Open Digital Platform (ODP): collect and analyse environmental and building data to improve energy efficiency, reduce costs and minimise impact
- iv. Digital Twin: real-time planning-simulation model
- v. Centralised Cooling System: cooling towers with underground distribution reduce energy use by 30% and 3,700–4,000 tonnes CO₂ annually
- vi. Carlite District: prioritises low-emission transport

Future:

- i. Environmental Modelling
- ii. Use of recycled materials for construction
- iii. Fuel Cell System for Lifts
- iv. Regenerative Lift converts motions into energy
- v. Centralized Chutes for Recyclables
- vi. "Develop an eco-town with a human settlement that enables its residents to live a good quality of life while using minimal natural resources."

Case Study: Singapore Story

Vision of "Clean, Green and Good Living Environment" for present and future generations, balancing economic development, social progress and environmental protection (strong commitment from the top).

Fundamental Principles:

- i. Control pollution at source
- ii. "Polluter Pays" principle
- iii. Pre-empt and take early action
- iv. Innovation and technology
 - Ex. Semakau Landfill as first man-made offshore landfill, Ulu Pandan NEWater Plant
- v. Resource conservation
 - Ex. Waste recycling, energy efficient energy
- vi. Environmental ownership
 - Ex. Involvement of 3P (private, public, people) with communication, engagement and empowerment

Key Strategies:

- i. Integrated land-use planning and development control (e.g., Singapore River clean-up)
- ii. Environmental infrastructure (e.g., integrated solid waste; water and wastewater treatment)
- iii. Environmental legislation and enforcement (pragmatic, progressive controls)
- iv. Environmental monitoring (assess level of pollution, track trends, inform standards and planning)
- v. Environmental education (instil awareness via campaigns, training, dialogues)

Future Challenges:

- i. Small tropical island, high population density, limited natural resources
- ii. Rising consumerism and environmental expectations; need to sustain standards

3. Circular Economy

Circular economy is a regenerative system where resource input, waste, emissions, and energy leakage are minimised by slowing, closing, and narrowing resource loops.

- i. Replaces the end-of-life concept with long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling
- ii. Regenerate natural systems by returning valuable nutrients to ecosystems
- iii. Supports economic, environmental, and social dimensions of sustainable development
- iv. Mimics nature's cyclical systems

Economy Progression:

- i. Linear Economy: take → make → dispose (single-use, wasteful)
- ii. Recycling Economy: partial recovery through recycling but still wasteful
- iii. Circular Economy: design for closed loops, resources kept in circulation, waste designed out

Energy and Matter

High-quality energy is concentrated, good for useful work.
Low-quality energy is dispersed, bad for useful work.

Three Big Ideas:

- i. There is no "away": matter cannot be destroyed, only converted (Law of Conservation)
- ii. Cannot get something for nothing; cannot get out more energy than in (1st Law of Thermodynamics)
- iii. Cannot break even; energy conversion from one form to another reduces energy quality or less usable energy (2nd Law of Thermodynamics)

Economy Types:

- i. High-throughput economy: unsustainable, high-waste, promotes pollution
- ii. Low-throughput economy: matter-recycling and reuse; mimics nature and reduces pollutants but may be insufficient for growing populations

Industrial Symbiosis

Industrial symbiosis is a business relationship focused on sharing resources between industrial facilities/companies where wastes or byproducts from one become raw materials for another.

- i. Subset of Industrial Ecology: shift from linear to cyclical (closed-loop) systems
- ii. Mutually beneficial cooperation which reduces environmental impact while improving business competitiveness
- iii. Key enabling business model for advancing the move to a circular economy
- iv. Ex. Kalundborg, Denmark: cooperation among 8 industries sharing energy, water, and materials

Applications and Innovations

- i. Bioplastics: key enabler of low-carbon circular economy; allow closed resource cycles and cascading reuse especially when being reused or recycled
- ii. Design for longevity: durability, easy repair, remanufacturing
- iii. Closed resource cycles: minimize virgin resource extraction via reuse and recovery
- iv. Resource Recovery: convert waste streams into valuable resources (e.g., waste-to-energy, nutrient recovery, material cascading)

4. Sustainable Urbanization

Urbanization is inevitable as societies advance, but it poses significant environmental and social challenges. Sustainable cities aim to balance growth with ecological integrity, equity, and efficiency.

- i. > 50% of the world's population lives in cities, with further growth projected esp. developing countries
- ii. Urban living → higher literacy, education, health, social services, cultural and political participation.
- iii. Trends:
 - Proportion of urban global population growing
 - Number and sizes of urban areas mushrooming
 - Rapid increase in urban populations in developing countries
 - Urban growth slower in developed nations
 - Increasing poverty and inequality (75% of cities more unequal now than 20 years ago)

Disadvantages of Urbanization:

- i. Unsustainable systems
- ii. Lack of vegetation
- iii. Water problems
- iv. Pollution and health problems
- v. Noise pollution
- vi. Climate and artificial light
- vii. Urban heat island
- viii. Light pollution

City Expansions:

- i. Compact Cities: Limited land area with high population density, thus growing vertically. Most people get around by walking, biking or public transport.
 - Ex: Hong Kong, Singapore, Tokyo
- ii. Dispersed Cities: Ample land area available for outward expansion. Residents mostly depend on motor vehicles for transportation.
 - Ex: Australia, Canada, United States

Urban Sprawl

Urban sprawl is the uncontrolled, low-density outward expansion of cities into surrounding undeveloped or agricultural land, often characterised by low-density housing, single-use zoning and increasing reliance on private automobiles.

Causes:

- i. Prosperity
- ii. Ample and Affordable Land
- iii. Automobile
- iv. Cheap Gasoline
- v. Poor Urban Planning

Problems (Natural Capital Degradation):

- i. Land and Biodiversity: loss of cropland, forests, grasslands, wetlands and habitats
- ii. Water: increased use/pollution of surface and groundwater, runoff and flooding, decreased natural sewage treatment
- iii. Energy, Air and Climate: increased energy waste, air pollution, greenhouse gas emissions
- iv. Economic: decline of downtown business districts, increased unemployment in central, loss of tax base in central

Regulating:

- i. Smart Growth: policies promoting compact, high-density, mixed-use development with access to mass transit
- ii. Greenbelts: surrounding large cities with open space for recreation, forestry, or sustainable uses
- iii. Urban Growth Boundaries: strict limits beyond which urban development is prohibited
- iv. Cluster Development: concentrate high-density housing on part of land while preserving shared open space on the rest of the land (often 40-50%)
- v. Satellite Towns: smaller metropolitan areas outside the main city, reducing pressure on the core

Megacities

Megacities are metropolitan regions with populations exceeding 10 million people. They represent areas of high risk due to their complexity, scale, and vulnerability to environmental, economic, and social stresses.

- i. Growth: By 2030, 41–53 megacities are projected worldwide. Asia alone is expected to host 30 megacities by 2025
- ii. Sustainability Risks:
 - Rapid urban expansion without adequate planning drives resource depletion
 - Environmental degradation and loss of ecosystem services
 - Intensified greenhouse gas emissions from dense populations

Challenges:

- i. Enormous demand for water, energy, waste management, and housing
- ii. High risks of congestion, pollution, and infrastructure strain
- iii. Extreme levels of poverty, social inequality, and vulnerability
- iv. Fragmentation across economic, societal, and geopolitical dimensions

Solutions:

- i. Promote resource efficiency through policy (e.g., compact cities, smart growth)
- ii. Invest in sustainable infrastructure, mass transit, and renewable energy
- iii. Develop strong institutional frameworks for governance and resilience
- iv. Encourage inclusive urban planning to reduce inequality

Sustainable City Models

Environmentally Sustainable Cities:

- i. Centralize the population within a given area
- ii. Use renewable energy as much as possible
- iii. Build and design people-oriented cities
- iv. Use energy and matter efficiently
- v. Prevent pollution and reduce waste
- vi. Recycle, reuse, and compost
- vii. Protect and encourage biodiversity
- viii. Promote urban gardens and farmers markets
- ix. Zone for environmentally stable population levels

Eco-cities model self-reliant resilient ecosystems:

- i. Includes inhabitants and their ecological impacts
- ii. Focus: eliminate carbon waste, run on 100% renewable energy
- iii. Goal: incorporate environment into the city, reduce poverty, higher population densities, improve health

Smart cities use information and communication technologies:

- i. Focus: increase operational efficiency, share information with public
- ii. Goal: improve quality of government services and citizen welfare

Case Study: Vauban, Freiburg (Germany)

Current Practices:

- i. Connected, efficient, green transport: trams near every home, pedestrian and bicycle paths, trains every 7.5 minutes with subsidised tickets
- ii. Combined Heat and Power (CHP) plant fueled by woodchips for district heating
- iii. Buildings designed to low-energy and positive-energy standards
- iv. Anaerobic digestion of organic waste: ecological sewage treatment from household waste creates biogas for cooking
- v. Green infrastructure: 600 hectares of parks, 3,800 garden plots, and strong local food economy of farmshops, wineries, butcheries, bakeries, etc.
- vi. Renewable energy production encouraged with federal tax credits and regional utility subsidies

Case Study: Stockholm, Sweden

Current Practices:

- i. Green roofs bind rainwater, solar cells convert solar energy and heat water
- ii. Ecological fashion for environmentally aware
- iii. Household refuse is sucked into automatic underground waste collection systems
- iv. Heat exchangers in water treatment
- v. Street rainwater is treated locally and flows into lakes instead of treatment plants
- vi. Combustible waste is used for district heating and electricity; organic waste turned into biogas
- vii. Low-flushing toilets and tap aerators reduce water consumption by half

Case Study: Singapore Green Plan 2030

Aims:

- i. City in Nature: plant 1 million more trees by 2030, develop green spaces, adding new 1000ha by 2035
- ii. Green Government: public sector leads sustainability
- iii. Sustainable Living: strengthen green efforts in schools, development of nationwide car-lite transport system, reduce waste to landfill per capita and household water consumption
- iv. Energy Reset: clear-energy vehicles and EV-ready towns, achieve 80% green buildings by 2030, reduce energy consumption in HDBs, 4x solar energy
- v. Green Economy: incentivise sustainable industries, develop carbon services, seek investments in sustainability, and create jobs
- vi. Resilient Future: safeguard coastlines against rising sea levels, improve food security, reduce urban heat

Case Study: CO₂ Accounting in China

Findings:

- i. Shanghai: highest per capita GDP and consumption-based CO₂ emissions
- ii. Beijing & Tianjin: similar per capita consumption-based emissions despite Beijing's local per-capita territorial emissions
- iii. Chongqing: lowest per capita consumption-based emissions due to lower development
- iv. Capital formation is the largest contributor to emissions, driven by rapid growth, infrastructure, and government policy
- v. Household consumption ranks second, with a smaller share than in developed countries
- vi. Beijing has large government expenditure as capital
- vii. Imports outweigh exports in embodied emissions, dominated by construction
- viii. Food imports are high in Shanghai, Beijing, and Tianjin, but minimal in Chongqing
- ix. Emissions rise with infrastructure demand, transport networks, and higher incomes

5. Carbon Management

Carbon management in built environment is critical to reduce greenhouse gas emissions, since the building and construction sector accounts 36% of final energy use and 39% of energy- and process-related CO₂ emissions in 2018.

- i. Operational Carbon: emissions from building use such as heating, cooling, lighting, and appliances.
- ii. Embodied Carbon: emissions from materials and construction, including extraction, manufacturing, transport, and assembly.
- iii. Life Cycle Stages: raw materials, transport, manufacturing, construction, operation, and end-of-life (reuse, recycling, landfill, incineration).
- iv. Footprint: the total carbon impact is the sum of embodied and operational emissions.

Energy-Efficient Buildings

Passive Design reduces energy demand:

- i. Natural Ventilation
- ii. Sunlight Shading and Daylighting
- iii. Dynamic Facade

Active Design improves system efficiency:

- i. Energy Efficient Chiller
- ii. Energy Recovery System
- iii. Evaporative Cooling
- iv. LED Lights

Smart Energy Management uses technology to monitor, control, and optimize energy use:

- i. Intelligent Building Management System (BMS)

Renewable Energy Integration generates power on-site, often combined with other strategies to maximise energy generation:

- i. Photovoltaic Panels
- ii. Wind Energy
- iii. Tidal Energy
- iv. Geothermal Energy

Types of Buildings:

- i. Zero Energy Buildings (ZEB): produce as much energy as they consume annually.
- ii. Super Low Energy Buildings (SLEB): operate with much lower energy use than conventional buildings.
- iii. Positive Energy Buildings (PEB): generate surplus energy that can be stored, shared, or sold.

Surplus Energy from PEBs can be:

- i. Stored: in batteries for later use
- ii. Shared/Sold: exported to the grid or shared with others; a Renewable Energy Certificate (REC) is a tradeable proof of 1 MWh of renewable energy fed into the grid
- iii. Integrated: in smart grids for efficient distribution

Design for Manufacture and Assembly (DfMA)

Fundamentals of DfMA:

- i. Simplifies design for efficient manufacture and assembly.
- ii. Identifies and eliminates waste and inefficiency.
- iii. Enables end-of-life pathways such as reuse and recycling through design for disassembly.

EOL Scenarios:

- i. Landfill: frame is disposed, contributing to waste and environmental impact
- ii. Downcycle: frame is recycled into lower-value products, extending life but reducing utility
- iii. Incinerate: frame is burned, generating energy but releasing emissions and reducing material recovery
- iv. Re-use: frame is directly reused in new projects, preserving value and minimising waste

Implementation:

- i. Minimize number of components
- ii. Modular construction (e.g. prefab units, modules)
- iii. Simplify joints (e.g. plug-in connections)
- iv. Top-down vertical assembly with self-aligning parts

Prefabricated Prefinished Volumetric Construction (PPVC)

PPVC modules are manufactured and finished off-site before being transported and assembled on-site.

- i. Improves construction productivity and efficiency
- ii. Ensures higher quality through controlled factory conditions
- iii. Reduces dust, noise, and on-site disruption
- iv. Requires fewer workers on-site, enhancing safety
- v. Speeds up project timelines through parallel off-site fabrication and on-site preparation

Reducing Embodied Carbon

Concrete and steel are major sources of embodied emissions. Reductions can be achieved through:

- i. Material substitution:
 - GGBS - 30–50% replacement of cement
 - PFA - 15–30% replacement of cement
 - RCA - 10% replacement (coarse fraction)
 - WCS - 10% replacement (fine fraction)
- ii. Optimizing material use via efficient structural design
- iii. Procuring low- or zero-carbon alternatives
- iv. Designing for re-use and recycling at end-of-life

Life Cycle Assessment (LCA) of Materials:

- i. Embodied carbon is released at the start of a building's life, "locking in" emissions for decades
- ii. Early-phase reductions are critical to avoid long-term carbon lock-in
- iii. Operational carbon accumulates over the use phase and can be reduced through retrofits and energy efficiency upgrades

6. Air Quality

Air quality is linked to earth's climate and ecosystems.

- i. Ambient Air: surrounds us outdoors and to which we are constantly exposed.

Atmosphere Layers:

- i. Thermosphere (~500km): contains >99.9% of atmospheric gases
- ii. Mesosphere (~100km)
- iii. Stratosphere (~50km): contains 90% of atmospheric ozone, which acts a protective layer against the sun's harmful UV radiation
- iv. Troposphere (~10km): weather conditions are mainly controlled by physical processes here

Air Pollutants

Air pollutants are substances which are unnatural or have higher than normal concentration. They can be transferred to other sectors of the environment (i.e. biosphere, hydrosphere, lithosphere).

Physical forms:

- i. Particulate matter (e.g. ash, dust, smoke)
- ii. Gases (e.g. sulfur dioxide, carbon monoxide)

Classification of Air Pollutants:

- i. Primary Pollutants: found in atmosphere in the same chemical form as when it was emitted.
 - Ex. carbon monoxide, nitric oxide, hydrogen sulfide, sulfur dioxide, halogen compounds
- ii. Secondary Pollutants: formed in the air as result of chemical transformation of primary pollutants.
 - Ex. nitrogen dioxide from nitric oxide, ozone from photochemical reactions of nitrogen oxides, sulfuric acid droplets from sulfur dioxide

Clean Air Act

US Environmental Protection Agency (EPA) in 1970 addresses environmental problems; Clean Air Act (CAA) passed to safeguard public health by regulating emissions.

- i. EPA is authorized to set standards protecting public health and welfare, and to regulate emissions
- ii. CAA is one of most comprehensive air quality laws

Sources of Air Pollutants:

- i. Fires release harmful chemicals and haze:
 - Ex. forest fires, deforestation, agri. burning
- ii. Industrialization and modernization have increased air pollution due to increased demand for power
 - Ex. Bhopal, India: Gas leak on 2 Dec. 1984 at UCIL Pesticide plant which exposed >500,000 people to MIC gas and other chemicals. Approximately 5,200 deaths and several thousand permanent or partial disabilities.
 - Ex. Chernobyl, Ukraine: Nuclear accident on 26 Apr. 1986 releasing large quantities of radioactive particles and a radioactive cloud, killing 30 workers from acute radiation poisoning and exposing >6000,000 recovery workers.
- iii. Mobile sources
 - Ex. automobiles, diesel trucks, buses, planes
 - Ex. New Delhi, India: most polluted city - WHO; vehicles account for 75% of pollution
- iv. Stationary sources
 - Ex. industrial and power plants
- v. Air pollution episodes and accidents
- vi. Thermal inversion occurs when warm air settles over cooler air near the ground, holding down the cool air, stopping pollutants rising and scattering
 - Ex. Donora, Pennsylvania: temperature inversion on Oct. 1948 caused a wall of smog killing 20 and sickening 7,000, due to fluoride emissions from zinc and steel plants.
 - Ex. Great Smog of London: in Dec. 1952 caused by black smoke from homes and factories killing 12,000 and bringing transport to a standstill.

Criteria Pollutants

US National Ambient Air Quality Standards (NAAQS) sets limits for 6 common air pollutants which are most prevalent and harmful to health and the environment, if concentration in ambient air is above certain levels.

Carbon Monoxide (CO) is a colorless, odorless gas from incomplete combustion of carbon:

- i. Sources: cigarette smoking; incomplete burning of fossil fuels; ~77% (up to 95% in cities) from motor-vehicle exhaust.
- ii. Health: binds to hemoglobin reducing O₂ delivery; impairs perception/reflexes; headaches, drowsiness; can trigger angina/heart attacks; harms fetal/child development; aggravates chronic bronchitis, emphysema, anemia; coma, brain damage, death.

Nitrogen Dioxide (NO₂) is a reddish-brown irritant, converts to nitric acid (HNO₃) acid rain component:

- i. Sources: fossil-fuel burning in motor vehicles (49%) power plants & industries (46%).
- ii. Health: lung irritation/damage; aggravates asthma & chronic bronchitis; increases susceptibility to respiratory infections (children/elderly).
- iii. Environmental: reduces visibility; HNO₃ damages trees, soils, aquatic life; corrodes metals/stone; NO₂ damages fabrics.

Sulfur Dioxide (SO₂) is a colorless irritant mainly from burning sulfur-containing fuel, converts to sulfuric acid (H₂SO₄) acid rain component:

- i. Sources: coal-burning power plants (88%); industrial processes (10%).
- ii. Health: breathing problems; airway restriction in asthmatics; chronic exposure cause bronchitis-like
- iii. Environmental/Property: visibility loss; H₂SO₄ damages trees, soils, lakes; SO₂ damages paint, paper, leather; both corrode metals, erode stone.

Particulate Matter (PM) are particles and droplets (aerosols) light enough to remain suspended; cause smoke, dust, haze:

- i. Sources: coal burning (40%); diesel/other fuels in vehicles (17%); agriculture (plowing, field burning), unpaved roads, construction.
- ii. Health: nose/throat irritation, lung damage, bronchitis; aggravates bronchitis/asthma; shortens life; toxic particulates (Pb, Cd, dioxins) can cause mutations, reproductive problems, cancer; damage severity depends on particle size, inhaled number, and individual health; fine/ultrafine penetrate deep lungs (some to bloodstream).
- iii. Environmental: reduces visibility; H_2SO_4 droplets harm trees/soils/aquatic life; corrodes metal; soils/discolors buildings, clothes, fabrics, paints; affects photosynthesis and precipitation (more condensation nuclei).

Ground-level Ozone (O_3) is highly reactive irritant and major component of smog:

- i. Sources: Nitrogen oxides and volatile organic compounds (mostly cars/industry) react in sunlight
- ii. Health: breathing problems; coughing; eye/nose/throat irritation; aggravates asthma, bronchitis, emphysema, heart disease; reduces resistance to colds/pneumonia; speeds lung aging.
- iii. Environmental: damages plants more than many other pollutants; smog reduces visibility; damages rubber, fabrics, paints; large mortality globally.

Lead (Pb) is a toxic metal; emitted to air attached to particulate matter:

- i. Sources: old-house paint, smelters (metal refineries), lead manufacture, storage batteries, (legacy) leaded gasoline.
- ii. Health: bioaccumulates; brain/nervous-system damage and mental retardation (esp. children); digestive/other health problems; carcinogenic.
- iii. Environmental: can harm wildlife

Mathematical dispersion modeling estimates concentration of pollutants at various distances from a source.

Acid Deposition (Acid Rain)

Acid deposition is the accumulation of acids in land, water, or in vegetation as a result of acid rain or direct absorption from atmosphere.

- i. Acid rain increases the concentration of Al^{3+} in groundwater, adversely affecting plant growth.
- ii. Large sections of established forests have been severely damaged in eastern US.

Hazardous Air Pollutants (HAPs)

Toxic pollutants known or suspected to cause cancer or other serious health effects:

- i. Highest levels closest to source
- ii. Standards set based on availability of control tech
- iii. Ex. asbestos, vinyl chloride, benzene, arsenic

Indoor Air Pollution

Indoor air pollution is ubiquitous, taking many forms, especially in developing countries and in mixtures of volatile compounds in modern buildings:

- i. Sources: solid-fuel cooking (e.g. wood) in poorly ventilated homes causes high pollutant levels.
- ii. Health: irritation of eyes, nose, throat; headaches, dizziness, fatigue; respiratory diseases; heart disease; cancer; predominantly targets women and young children
- iii. Ex. Outbreak of Legionnaires' disease at Philadelphia, Pennsylvania

Greenhouse Gases (GHGs)

Greenhouse gas accumulation can also lead to adverse effects on the global climate:

- i. Concerns arise over polar ice caps, coastal flooding, and blocking of sun's rays triggering mini ice age
- ii. Kyoto Protocol, adopted in Kyoto, Japan, on 11 December 1997, proposed that industrialized nations must reduce their collective greenhouse gas emissions by 5.2% between 2008 to 2012.

Pollution Prevention

Pollution prevention hierarchy (least to most preferable): dispose → treat → recover → recycle → reuse → reduce → avoid

Pollution reduction or prevention come with a price and may require process alteration, change of fuel, marketing by-products, and temporary plant shutdowns.

Good Ozone Depletion

Gradual thinning of Earth's stratospheric ozone layer caused by human-released gases containing chlorine and other halogens.

- i. Causes: Chlorofluorocarbons (CFCs) and other ozone-depleting substances (ODS) such as HCFCs, halons, methyl chloroform, and carbon tetrachloride.
- ii. Ozone Hole (Antarctica): Dramatic springtime loss in the lower stratosphere, most pronounced over the polar regions (Antarctica).
 - Largest observed on 24 Sep 2006 (areas with >50% ozone decrease).
 - Polar vortex: isolated, concentric flow around Antarctica with strong westerlies and little meridional transport.
 - Springtime phenomenon observed in satellite records (e.g., TOMS/OMI daily minima).
 - Polar stratospheric clouds form at very cold temperatures and enable reactive chlorine chemistry.
- iii. Impacts: More UV reaches Earth's surface → increased skin cancer, cataracts, and genetic/immune system damage; broader environmental effects.
- iv. Policy & Recovery: Montreal Protocol (1987; amended 1990, 1992) phases out production/consumption of ODS (targeted by 2000); also yields climate benefits since many ODS are potent greenhouse gases; global ozone shows recovery stages.

7. Climate Change

Climate is the statistical description of weather conditions and their variations. Climate change is a shift in the average pattern of weather over long periods.

- i. Greenhouse gases (GHGs) cause the greenhouse effect, trapping infrared radiation from the sun
 - Ex. water vapour, carbon dioxide, methane, nitrous oxide, and some industrial gases such as chlorofluorocarbons (CFCs)
- ii. IPCC Report: human activity has increased global surface temperature (1.09°C comparing 2011-20 vs. 1850–1900; 1.5°C limit in Paris Agreement likely breached in few decades, with overshoot temporary only if emission cuts are immediate & sustained.
- iii. CO₂ is the major driver of recent warming (observed rise in CO₂ and global temperature, 1880–2010).
- iv. Urbanization: by 2050, ~70% of people will live in cities; cities already consume ~80% of global material/energy and produce >70% of CO₂.

OCBC Climate Index

OCBC Climate Index was developed to capture local climate attitudes and actions:

- i. Singaporeans have high awareness of environmental issues, but adoption levels not on par
- ii. Cost and inconvenience cited as top reasons for low adoption; could be due to needs of an individual according to life stages
- iii. Singaporeans love food, struggling most in terms of adoption here but likely to advocate green practices
- iv. Change in mindset is needed to kill bad habits

Lessons Learnt:

- i. Transport: prefer public transport, Park Connector Networks and safe cycling routes
- ii. Home: use AC responsibly between $25 - 27^{\circ}\text{C}$
- iii. Food: buy local vegetables, eat less meat
- iv. Goods: think before purchasing, prefer quality long-lasting items, repair if possible

Effects

Project and Observed Impacts:

- i. Sea Level Rise: saltwater intrusion raises groundwater salinity; amplifies storm-surge/high-wave impacts on coasts.
- ii. Extreme Weather Events: more frequent/severe events in recent decades.
- iii. More Heat Extremes: Small mean warming → large increase in heat extremes; fewer cold extremes.
- iv. Heavier Rain: warmer air holds more exponentially vapor; when it rains, more falls at once.
- v. Drought: higher water evaporation not offset by precipitation (e.g. western US), snowpack down, runoff spikes from intense events.
- vi. Wildfire: increasing area burned; fires now #1 PM_{2.5} source in western US; offsets air-quality gain.
- vii. Human Health: serious threats to well-being from climate crisis.

Future:

- i. Continued CO₂ growth will lead to dangerous temperature increases; aggressive decarbonisation is needed to avoid 2 degrees of danger, requiring cutting emissions by > half.
- ii. 2023 CO₂ emissions +1.1% (IEA); 2020-23 increase driven by Global South; coal ~65% of rise.

Mitigation

- i. Energy Efficiency: buildings (design, insulation, A/C setpoints $25-27^{\circ}\text{C}$), industry (heat recovery), transport (EVs, mode shift).
- ii. Clean Power: solar, wind, hydro, geothermal; retire inefficient coal; flexible grids and storage.
- iii. Fuel Switching: coal → natural gas (as a transition), electrification of end-uses.
- iv. Non-CO₂ Gases: methane leak detection/repair (LDAR), agricultural CH₄/N₂O reductions, refrigerant management.
- v. Nature-Based: afforestation/reforestation, peatland and mangrove restoration, improved soils.

Carbon Capture, Utilisation & Storage

Pipeline:

- i. Capture: selective removal of CO₂ from point sources (power, cement, steel) or air (DAC).
- ii. Transport: compression and movement via pipelines (regional) or ships (long distance).
- iii. Utilisation: CO₂ for enhanced oil/gas/coal-bed recovery (EOR/EGR/ECBM), synthetic fuels/chemicals, mineralisation.
- iv. Storage: secure geologic formations with physical/chemical trapping; monitoring, reporting, verification (MRV).

Government Role

Strategies:

- i. Regulatory: set performance standards for CO₂/CH₄; phase out inefficient coal plants.
- ii. Carbon Pricing: carbon taxes or cap-and-trade; recycle revenues to households/innovation.
- iii. Subsidy Shifts: phase out fossil subsidies; support efficiency, renewables, clean industry, sustainable agriculture.
- iv. Finance & R&D: scale public/private investment; de-risk projects; accelerate technology transfer.
- v. Land Use: protect forests; monitor and finance anti-deforestation; sustainable food systems.

Adaptation

- i. Coasts: raise/flood-proof assets; restore dunes/mangroves; managed retreat in hotspots.
- ii. Heat: cool roofs/urban greening; early-warning systems; heat-health action plans.
- iii. Water: diversify sources (reuse, desalination), conserve, improve storage; flood-resilient drainage.
- iv. Food: climate-smart agriculture, drought/heat-tolerant crops; reduce loss/waste.
- v. Health: surveillance of climate-sensitive diseases; protect vulnerable populations.

8. Nonrenewable Energy

Nonrenewable Energy (NRE) comes from finite sources and is consumed much faster than can be naturally replenished.

- i. Nonrenewable energy fuels $\sim \frac{3}{4}$ of the world's commercial energy.
- ii. Global energy demand is projected to increase 28% between 2015-40
- iii. Net energy is the only energy that counts: usable energy minus energy automatically wasted in finding, processing and transporting it to users.

Coal

Coal is the world's most abundant fossil fuel:

- i. Generates $\sim 40\%$ of global electricity at inexpensive cost, with potential to cover global energy needs into 22nd century.
- ii. Well-developed technology, with air pollution reducible by improved technology
- iii. Burned industrially for iron, steel and other products
- iv. Major CO₂, SO₂ emitter, along with soot, and toxic indistructible mercury and radioactive materials
- v. Major factor in development of emerging and developing economies.
- vi. Process: heat generated boils water to produce steam which spins a turbine to product electricity. Steam can be recooled, condensed and reused.

Synfuels burn cleaner than coal, but lower net energy and higher cost per unit of energy than conventional coal:

- i. Gasification: forms syngas (of H₂, CO, CO₂).
- ii. Liquefaction: forms methanol/synthetic gasoline.

Oil

Crude oil is a black liquid of different combustible hydrocarbons, trapped under crust or under the seafloor, requiring drilling and refining.

- i. Crude oil is biggest source of commercial energy (85 million barrels of oil /day), oil is consumed 4× faster than being discovered, crude oil will be depleted over 80% between 2050-2100.
- ii. High net energy yield, easy to transport, low land use, and well developed tech
- iii. Need to find substitutes within 50 years, with fluctuating market price and high pollution
- iv. Organisation of Petroleum Exporting Countries (OPEC): 13 countries holding 78% of proven reserves; long-time supply influence.
- v. Process: Fractional distillation by boiling points; yields fuels & petrochemicals (plastics, fibers, solvents, medicines, etc.).

Unconventional Oil is found in poorly connected poors, or is too viscous/heavy so buoyant forces are insufficient to expel them from the reservoir and requires more technology:

- i. Oil Sands: extra heavy, viscous crude oil trapped in unconsolidated sand; most in Canada and Venezuela; expensive and emission intensive
- ii. Oil Shales: fine grained sedimentary rocks containing kerogen from which shale oil and gas are produced; mainly in US, Australia, China, Brazil, Estonia
- iii. Tight Oil: light crude oil in formations of low permeability; mainly in Russia, US, China, Argentina, Libya
- iv. Hydraulic Fracturing: extracts tight oil/gas; carries environmental risks (water, seismicity, fugitive emissions).

Natural Gas

Natural gas is a mixture of gases (50-90% methane) and other hydrocarbons (e.g. propane, butane) often found above crude oil.

- i. Known reserves should last 62-125 years, with high net energy yield, abundance, transport and usage breakthroughs, energy security concerns
- ii. Low net energy density complicates handling
- iii. Process: refine to remove impurities/NGLs
- iv. Liquefied Petroleum Gas (LPG): when natural gas is tapped, propane and butane gases are liquefied and removed

Unconventional Gas:

- i. Tight Gas: trapped in low-permeability sandstones/limestones; mainly US or North Sea.
- ii. Shale Gas: trapped in shale (acts as source and reservoir); produced via horizontal drilling + hydraulic fracturing.
- iii. Coal Bed Methane (CBM): methane adsorbed in coal seams; co-produces significant water which must be removed (adds cost/handling).
- iv. Methane Hydrates: methane trapped in ice lattices under seafloor/permafrost; large potential but technical & environmental risks.

CO₂ Emissions

CO₂ emissions per unit of electrical energy:
Coal-fired electricity > Coal synfuel > Coal > Tar sand > Oil > Natural gas > Nuclear > Geothermal

Nuclear Power

Nuclear power is the only nonrenewable clean energy, formed from nuclear fission:

- i. Role: large-scale baseload with *no direct CO₂* at the plant; constrained by cost, low net energy yield (full fuel cycle), radioactive wastes, safety/security concerns.
- ii. Basics: induced fission chain reaction in a controlled reactor; moderators and control rods sustain steady power.
- iii. Fuel Cycle: natural uranium (99.28% ²³⁸U, 0.71% ²³⁵U) enriched to ~3.5–5% ²³⁵U → UO₂ pellets → fuel rods/assemblies.
- iv. Process: reactor heat → steam → turbine; cooling via once-through water or cooling towers.
- v. Accidents: Three Mile Island (1979), Chernobyl (1986), Fukushima (2011) led to upgraded safety standards and regulatory scrutiny.

Energy Efficiency

A large share of commercial energy is wasted; roughly half is avoidable through better tech/operations.

Techniques:

- i. Industry: cogeneration/ combined heat and power (CHP), replacing energy-wasting electric motors with variable speed motors, recycling materials, switching to LED lighting
 - ii. Transport: hybrids/EVs, lightweighting, aerodynamics, public transit & mode shift; hydrogen fuel cells.
 - iii. Buildings: solar heating, superinsulation for heating, high-efficiency HVAC, green roofs, daylighting, sustainable building materials, straw bale houses.
- Waste still exists due to artificially cheap fossil fuels (due to subsidies and exclusion of environmental costs), few incentives and inadequate energy-efficiency building codes and appliance standards.
- i. Drivers: growing energy demand, environmental concerns, economic benefits, energy security, cost competitiveness
 - ii. Needs: grid flexibility (storage, demand response, transmission), modern market design, land and water management, biodiversity trade-offs.

Solar Energy

Solar is the largest energy source, inexhaustible, and captured as heat (absorption by gases/liquids/solids) or photoreaction (photon-driven electron flow).

Photovoltaic (PV)/ Solar cells generate electricity through the photovoltaic effect; sunlight on semiconductor releases electrons, and current flows through an external circuit:

- i. Cosine Effect: solar irradiance is maximal when sun is directly overhead, and reduced at angle solar
- ii. Variance: solar irradiance varies with latitudes (high variance at high altitudes, low in tropics); dependent on season and weather
- iii. Tilt: face the equator; summer tilt < latitude to maximize capture; winter tilt > latitude for higher need months
- iv. Applications: rooftop (residential/commercial), utility-scale ground-mount, building-integrated PV, floating PV on reservoirs (dual use, red. evaporation)
 - Topaz Solar Farm: 550 MW, powers ~160,000 homes; avoids ~377,000 t CO₂/yr.
 - Marina Barrage Solar Park: 405 modules; ~76,000 kWh/yr for onsite loads.
 - Floating PV: Huainan 40-150 MW; Yamakura Dam 13.7 MW; Sanshan 8.5 MW.
 - + High net energy yield, quick installation, easily expanded, no CO₂, long lasting
 - Need access to sun, need electricity storage system or backup, environmental costs not included, expensive, high land use, must convert DC to AC

Concentrating Solar Power (CSP) is the generation of electricity through optical concentration of solar energy, producing high temperature fluids or materials:

- i. Resultant output is used to drive heat engines and electrical generators

Solar Thermal uses solar energy for heating purposes:

- i. Solar panels of evacuated tubes or plate-plate collectors heat up water tanks, or for space heating

Solar Fuels involve conversion of sunlight into storable chemical fuels (e.g. hydrogen or synthetic hydrocarbons) through photochemical/photobiological, artificial photosynthesis or thermochemical:

- i. Artificial Photosynthesis: converts raw materials like water and CO₂ into clean fuels and value-added chemicals (e.g. H₂, and hydrocarbons)
- ii. Photocatalytic water splitting converts water into hydrogen ions and oxygen, and is an active research area in artificial photosynthesis.
- iii. Can also be used as feedstock in (the chemical) industry.
- iv. Combined with fuel cell tech which convert fuel to electricity and heat, can power a building or small community

Hydropower

Converts potential/kinetic energy of water to electricity.

- + Moderate-high net energy, high efficiency, large untapped potential, low-cost, long lifespan, no CO₂ emissions in temperate areas, can provide flood control, provides irrigation water
- High construction cost, environmental impacts (flooding, fish), danger of collapse, social displacement, silting reduces efficiency

Wind Energy

Converts kinetic energy of air into electricity via lift on rotating blades in wind turbines.

- i. Ex. Gansu, China: largest wind farm; 6,000 MW as of 2012, goal of 20,000 MW by 2020
- ii. Ex. London Array: biggest offshore farm; 630 MW
- + Moderate-high net energy, high efficiency, low environmental impact, no CO₂ emissions, easy expansion, can be located at sea
- Variable power supply, needs backup systems, plastic components produced from oil, high land use, visual pollution, noise, can kill birds and disrupt migratory patterns

Geothermal Energy

Converts generated steam to drive turbines:

- i. Direct Uses: district heating, industry, greenhouses; ground-source heat pumps for efficient HVAC.
- + Moderate net energy at accessible sites, very high efficiency, moderate environmental impact, lower CO₂ emissions, low land use, low cost at some sites
- Scarcity of suitable sites, can be depleted, moderate to high local air pollution, noise and odor, usually high cost

Ocean Energy

Harnesses waves, tidal range (barrages), tidal currents, ocean currents, ocean thermal energy (OTEC), and salinity gradients (osmosis).

- i. Ex. oscillating water columns, point absorbers, attenuators (wave); barrages/lagoon schemes and in-stream turbines (tidal); warm-cold cycle heat engines (OTEC).
- + Predictable tides, proximity to coastal loads, large potential; complements solar/wind
- High cost, harsh marine environment, ecological constraints

Bioenergy

Energy from biomass/biogas and liquid biofuels.

- i. Biomass: residues/wood pellets for heat/power.
- ii. Biogas: anaerobic digestion (wastewater, landfills, agri/food waste) → CH₄ for CHP or upgrading to biomethane.
- iii. Biofuels: ethanol (sugar/starch), biodiesel (oils/fats), advanced drop-in fuels (cellulosic, SAF).
- + Valorises wastes, cut landfill methane; lower net CO₂ if sustainably sourced; rural jobs and energy
- Water use, fertilizer runoff, competition for food, land availability, destruction of forests, conversion technology issues

Hydrogen Energy

Hydrogen is a fuel produced by using energy, storable in fuel cells:

- + Producible with water, low environmental impact, renewable, no CO₂ from water production, good substitute for oil, competitive price considering env. cost, easy storage, safety, nontoxic, high efficiency
- Not found in nature, energy is needed to produce it, negative net energy, will need generated by renewable fuels, technology immature, excessive H₂ leaks hurt ozone

Grid Integration & Storage

Flexibility tools to match variable RE with demand.

- i. Storage: batteries (short-duration), pumped hydro (long), thermal (molten salt, chilled/heat), emerging hydrogen storage.
- ii. System tools: demand response, forecasting, interconnection/transmission, curtailment, smart inverters (volt/VAR, grid-forming).
- iii. Hybrids: solar+storage, wind+storage, RE+diesel (remote), virtual power plants (aggregate distributed resources).
- + Improves reliability and RE penetration; provides ancillary services; lowers curtailment; enables resilient microgrids
- Capital cost and siting (batteries, pumped hydro, lines); permitting/interconnection delays; operational complexity at high RE shares

Economics & Policy

Enablers for scaling RE deployment.

- i. Costs & learning: PV/wind/batteries show strong cost declines; at high shares, BOS/soft costs dominate.
- ii. Markets & finance: competitive auctions/PPAs reduce WACC; rooftop export rules (net billing) shape adoption.
- iii. Standards & incentives: RPS/RECs, FITs, tax credits; streamlined permitting and grid interconnection.
- iv. Externalities: carbon/pollution pricing aligns private with social costs; just transition and workforce policies.
- + Faster, cheaper scale-up; investment certainty; innovation and domestic industry growth
- Policy risk and inconsistency; equity/affordability concerns if design is poor; rebound or land-use conflicts without safeguards

10. Sustainable Water Resources

Water is vital for all aspects of life but is poorly managed:

- i. ~71% of Earth's surface is water, with 96.5% held in oceans.
- ii. Only ~3% is freshwater; < 1% readily available in rivers, lakes and streams.
- iii. Water cycle continually collects, purifies, recycles and redistributes water, but human activities purposefully and unintentionally alter it.

Issues:

1. Economic: vital for reducing poverty and producing food and energy
2. National and Global Security: increasing tensions with limited shared water resources
3. Environmental: excessive withdrawal from rivers and aquifers results in dropping water tables, shrinking lakes and loss of wetlands

Groundwater

Groundwater is the water in soil pore spaces and in rock fractures below ground:

- i. Water table: level below which all pores are water-filled; above which is air-filled.
- ii. Zone of Saturation: region below water table where all pores are completely filled with water.
- iii. Aquifers: underground caverns and porous layers of sand, gravel or bedrock through which groundwater flows. Most are replenished by natural recharge (precipitation percolating down), others by lateral recharge (nearby rivers and streams).
- iv. Pollution: can be contaminated when polluted surface water with nutrients or chemicals drains into the groundwater environment.

Surface Water

Surface water is the water from precipitation and snowmelt that flows over land into lakes, wetlands, streams, rivers, estuaries and ultimately oceans:

- i. Surface runoff: precipitation that does not infiltrate the ground or return to atmosphere by evaporation.
 - Reliable surface runoff: $\sim \frac{1}{3}$ of annual runoff available as freshwater for human use (rest is lost in seasonal floods).
- ii. Watershed / Drainage Basin: land from which surface water drains into a particular water body.

Global Water Use

Water can be extracted, used, recycled and reused. Consumption is the final use of water, after which reuse is not possible. Extraction has risen much faster than consumption, indicating intensified exploitation.

Causes of Water Scarcity:

- i. Dry climate and drought
- ii. Too many people sharing a supply
- iii. Wasteful, inefficient water use

Consequences of Water Scarcity:

- i. ~1 billion people lack regular access to clean water.
- ii. ~40% gap between demand and available water projected by 2030.
- iii. 1.8 billion people use drinking water sources contaminated by faeces.
- iv. $\geq 80\%$ of wastewater returns untreated to the environment.
- v. ~30% of global water abstraction lost via leakage.
- vi. Water scarcity already affects ~40% of the world.
- vii. 70–90% of water use is for agriculture; $\sim 70\%$ more food needed by 2050.
- viii. Business risks: environmental, political, operational and reputational risks propagate along supply chains from upstream suppliers to downstream customers.

Increasing Freshwater Supplies

Waste Reduction:

- i. Redesign manufacturing processes and recycle water in industry
- ii. Landscape with plants requiring little water, use drip irrigation, fix leaks, use water meters, use water-efficient appliances and fixtures
- iii. Raise water prices, require water conservation in water-short cities, purify and reuse water for houses and offices

Groundwater Withdrawal:

- + Useful for drinking and irrigation, available year-round, widely available, renewable if sustainable, no evaporation loss, cheaper to extract
- Overpumping can deplete aquifers and sink land, pollution of aquifers, saltwater intrusion into drinking water near coasts, reduced water flows into surface waters, increased cost and contamination from deeper wells

Dams and Reservoirs:

- + Provides irrigation water above and below dam and drinking water, recreation (fishing), hydropower, reduces downstream flooding.
- Flooded land destroys habitat or displaces people, large evaporation losses, deprives downstream habitat of nutrient-rich silt, risk of failure, disrupts fish migration

Desalination:

- i. Distillation: heat saltwater until evaporation and recondense as freshwater; less commercialised for large scale plants.
- ii. Reverse Osmosis: high pressure forces saltwater through membrane filter to remove salt; higher productivity and efficiency leads to high commercialisation for large scale plants.

Transporting surface area across regions

Case Study: Aral Sea

Issues:

- i. Rivers diverted for irrigation (cotton, crops) since 1960.
- ii. Lake shrank and became saltier, splitting into smaller lakes; salty desert left behind.
- iii. Consequences: economic collapse, health problems, severe ecological disruption.

Case Study: Dead Sea

Issues:

- i. As population increased, water diverted from Jordan River for drinking and irrigation → shoreline retreat, sinkholes.
- ii. Red Sea-Dead Sea Project: desalination in Aqaba on the red sea, with brine and/or water transfers to stabilise Dead Sea levels.

Sustainable Water Use

Solutions:

- i. Decrease waste and subsidise water conservation.
- ii. Preserve aquifers and water quality
- iii. Protect and restore wetlands, floodplains, watersheds and other natural systems storing and releasing water.
- iv. Regional agreements sharing surface water resources.
- v. Raise water prices.
- vi. Slow population growth.

Individual Actions:

- i. Use efficient water devices, and reduce usage.
- ii. Repair water leaks.
- iii. Reuse water for household chores.
- iv. Use recycled water and prefer services using recycling.
- v. Use drip irrigation and mulch for gardens.

Floodplains

Floodplains are low flatlands adjacent to rivers/streams, and periodically flooded and shaped by geomorphic and hydrologic processes. Benefits:

- i. Highly productive wetlands; natural flood and erosion control.
- ii. High water quality and groundwater recharge.
- iii. Water for irrigation, transport, recreation; flat land for settlements and infrastructure.

Floods:

- + Deposits nutrient-rich silt on floodplains
- + Recharge groundwater, supporting wetlands biodiversity and aquatic ecological services
- Kills thousands annually and cause property damage
- Human activities increase risk; e.g. removal of water-absorbing vegetation and building on wetlands which absorb floodwaters
 - Ex. Hurricane Katrina, 2005: damage intensified due to degradation or removal of coastal wetlands

Case Study: Bangladesh Floodplains

Issues:

- i. Densely populated coastal floodplain; moderate annual monsoon floods maintain soil fertility.
- ii. More frequent severe floods due to:
 - Population growth, deforestation, overgrazing, unsustainable farming on steep slopes in Himalayan watershed.
 - Loss of mangroves for fuel, farming and shrimp aquaculture.
- iii. Sea-level rise and stronger storms from climate change pose growing threats.

Water Pollution

Water Pollution is any change in water quality that harms organisms or makes water unsuitable for desired uses:

- i. Point sources: discharge at specific locations (e.g. factories, mines, oil tankers, sewage outfalls).
- ii. Nonpoint sources: diffuse inputs from broad areas (e.g. agricultural runoff, urban streets, logged forests, parking lots, lawns, golf courses).
- iii. Major pollutants: pathogens, oxygen-demanding wastes, plant nutrients (N, P), organic/inorganic chemicals, sediments, heavy metals, heat.
- iv. Endocrine disruptors (EDCs): chemicals (e.g. some pesticides, metals, additives, personal care products) that interfere with hormones in aquatic organisms, causing growth, reproductive abnormalities and sex changes.

Solutions:

- i. Prevent groundwater contamination
- ii. Reduce point source pollution
 - Clean Water Act (CWA), Water Quality Act (WQT): set standards for allowed levels of key water pollutants, and require pollutants to get permits limiting discharge
 - Discharge Trading Policy: permit holders can pollute more if credits bought from permit holders underpolluting; market forces reduce water pollution; could overpollute areas where credits are bought
- iii. Reduce nonpoint runoff
- iv. Treated wastewater and sewage for reuse
- v. Find substitutes for toxic pollutants
- vi. Reduce air pollution
- vii. Reduce poverty, and population growth

Individual Actions:

- i. Use manure/compost instead of inorganic fertilizer
- ii. Minimise pesticides, especially near water
- iii. Prevent yard wastes entering storm drains
- iv. Do not flush medicine/chemicals

Cleansing

Streams:

- i. Biodegradable wastes cause an oxygen sag curve, reducing organisms with high oxygen requirements.
- ii. Recovery downstream from oxygen demanding wastes or heated wastes with time, if not overloaded

Lakes and Reservoirs:

- i. Pollutants persist due to limited vertical mixing and low flow
- ii. Eutrophication: nutrient enrichment (nitrates, phosphates from runoff) → algal blooms, turbidity.
- iii. Cultural Eutrophication: human activity (farmland, fertiliser, sewage) accelerates algal/ cyanobacteria blooms, O₂ depletion and fish kills.

Groundwater:

- i. Pollutants (fertilisers, pesticides, gasoline, solvents) can seep into aquifers.
- ii. Slow flow, low dissolved O₂ and microbial activity; cold temperatures slow waste decomposition.
- iii. Natural cleansing may take decades-millennia; prevention is cheaper than cleanup.

Drinking Water

Developed Countries:

- i. Water stored in reservoirs to let particulates settle, increase dissolved O₂ and improve taste
- ii. Then treated in purification plants to meet drinking water standards

Developing Countries:

- i. Exposing clear plastic bottle to intense sunlight for solar disinfection
- ii. Portable devices, e.g. LifeStraw to convert contaminated water

Ocean Pollution

Issues:

- i. ~40% of people live near coasts; coastal population projected to double by 2050.
- ii. 80% of marine pollution originates on land; large shares of sewage enter oceans untreated.
- iii. Nutrient-rich runoff causes harmful algal blooms and oxygen-depleted (dead) zones.
- iv. Residential areas, factories and farms contribute to pollution of coastal waters and bays
- v. Oil spills:
 - Destroy insulation of fur and water-proofing of feathers, causing hypothermia and death.
 - Polycyclic aromatic hydrocarbons cause heart damage and developmental problems in fish.
- vi. Key control: reduce land-, air- and river-borne pollution entering the seas.

Sewage Treatment

Rural and Suburban:

- i. Sewage discharged into a septic tank
- ii. Grease and oil rise up, solids fall and are decomposed by bacteria

Urban:

- i. Raw sewage undergoes one or two levels of treatment
- ii. Primary: Remove large floating objects and allow suspended solid to settle out
- iii. Secondary: Aerobic bacterial removes 90% of dissolved and biodegradable, oxygen-demanding organic wastes

Case Study: Singapore & NEWater

Four National Taps provide robust, diversified and sustainable water supply:

- i. Local catchment water (35%)
- ii. Imported water from Johor (40%)
- iii. NEWater (high-grade reclaimed water) (15%)
- iv. Desalinated water (10%)

NEWater:

- i. Produced from treated used water via:
 - Microfiltration/Ultrafiltration
 - Reverse osmosis
 - Ultraviolet disinfection and pH adjustment
- ii. Exceeds WHO standards; >130,000 tests passed.
- iii. Major uses: wafer fabs, electronics, power generation, building cooling.
- iv. Small share blended into reservoirs and treated as potable water.
- v. Capacity expanding (aim: meet ~50% of demand by 2060); exploration of underground storage/drainage to address climate extremes.

11. Solid and Hazardous Waste

Solid waste is any unwanted or discarded material from industrial, commercial, mining, agricultural and community activities:

- i. Types:
 - Industrial solid waste: from mines, agriculture, industries (e.g. solvents, paints, metals, sludge).
 - Municipal solid waste (MSW): from homes and workplaces (paper, food, cans, bottles, e-waste).
- ii. E-waste: rapidly growing stream from discarded electronics; wastes resources and releases toxic metals and organics when poorly managed.
- iii. Hazardous Waste: threatens health/environment; poisonous, chemically reactive, corrosive, flammable (e.g. solvents, medical waste, batteries, ash).
 - Organic compounds: solvents, pesticides, PCBs, dioxins.
 - Toxic heavy metals: Pb, Hg, As, etc.
- iv. Unsustainable Pattern: most urban areas behave as high-throughput, high-waste systems.

Singapore Solid Waste Profile

- i. Waste types: construction debris, metals, wood, paper/cardboard, plastics, food, glass, horticultural waste, ash/sludge, textiles/leather, others.
- ii. Trend:
 - Recycling rate ~61% (2013) → ~52% (2023).
 - High recycling for construction debris, metals, slag, tyres ($\geq 95\%$).
 - Low recycling for plastics, textiles/leather, glass, food (single-digit or low-teen %).
- iii. Challenge: domestic and food waste growing; need stronger minimisation and recycling.

Waste Strategies

Waste Hierarchy sets priorities based on sustainability and preference:

- i. Reduce (lower waste produced)
- ii. Reuse (use materials repeatedly)
- iii. Recycle (use materials to make new products)
- iv. Recovery (recovery energy from waste)
- v. Landfill (safe disposal of waste)

Strategies:

- i. Waste Management:
 - Involves reducing environmental harm of waste
 - Involves mixing wastes and transferring them to different parts of the environment (e.g. landfills), but can contribute to air and water pollution and land degradation
- ii. Waste Reduction:
 - Involves producing much less waste and pollution
 - Wastes produced are considered potential resources for reuse, recycling or composting
- iii. Integrated Waste Management:
 - Involves variety of strategies for both waste reduction and management

Incineration

Waste-to-energy incinerators burn mixed solid waste and recover energy to produce steam for heating or electricity.

- + Reduces trash volume, reducing need for landfills
- + Low water pollution, low air pollution with modern pollution controls (filters, scrubbers)
- + Concentrates hazardous waste into ash for burial
- + Selling of metals; Sale of energy reduces cost
- Expensive, difficult to site
- Some air and CO₂ pollution
- Output approach encourages waste production
- Competes with recycling for burnables like paper

Gasification

Gasification converts waste into syngas by reacting with steam/ limited oxygen at high temperature (~1300°C):

- i. Plasma Gasification: uses plasma arc (> 2000°C) to break waste into syngas and inert slag

Sanitary Landfills

Sanitary landfills are engineered sites isolating waste from the environment until it is safe, i.e. degraded biologically, chemically and physically:

- i. Features: liners, leachate collection, gas collection, daily cover, monitoring.
- ii. Ex. Semakau, SG: ~3.5 km², capacity ~63 million m³ for incineration ash and some non-incinerables.
 - + No open burning, little odor
 - + Low groundwater pollution if sited well
 - + Built quickly with low operating costs
 - + Handles large amounts of waste
 - + Filled land can be reused
 - + No shortage of landfill space in many countries
 - Noise, traffic, dust and air pollution from toxic gases and trucks
 - Releases greenhouse gases (methane and CO₂)
 - Slow decomposition of wastes
 - Output approach encourages waste production
 - Eventual leaks can contaminate groundwater

Waste Reduction

5R's:

- i. Refuse: avoid unnecessary items.
- ii. Reduce: consume less; simplify lifestyle.
- iii. Reuse: repeatedly use products; buy secondhand, borrow or rent.
- iv. Repurpose: use items for new functions.
- v. Recycle: separate and recycle paper, metals, glass, plastics and buy recycled-content products.

Reuse

Reuse extends product life, saves resources and energy, cuts pollution and waste, and creates local jobs:

- i. Strategies: yard sales, flea markets, secondhand shops, online platforms, refillable bottles and containers.
- ii. Refillable glass and PET containers: technically feasible but often less favoured by corporations due to logistics and cost; bottle deposits and national bottle bills can promote reuse.

Recycling

Recycling reprocesses discard materials into new, useful products:

- i. Types of waste:
 - Preconsumer/internal: generated in manufacturing.
 - Postconsumer/external: generated after use.
 - ii. Recycling paths:
 - Primary/closed-loop: same product type (e.g. can → can).
 - Secondary: different product (e.g. tires → rubberised asphalt).
- + Reduces air, water pollution and GHG emissions
+ Saves energy, resources and landfill space
- Costs more than landfills, and may lose money for items such as glass and some plastics
- Source separation can be inconvenient

Waste Biomass are trees, grasses or other construction waste which can be recycled into fuels and materials:

- i. Cogeneration and material recycling (e.g. reconstituted particle board for construction) increase resource efficiency.
- ii. Composting:
 - Bacterial decomposition of yard trimmings and food scraps.
 - Produces soil amendment that supplies nutrients, reduces erosion and increases water-holding capacity.
 - Requires control of odours and exclusion of toxic materials.

Household Solid Waste:

- i. Materials Recovery Facilities (MRFs): machines/workers separate recyclables for sale as raw materials; residuals are landfilled or burned.
- ii. Source Separation: households/businesses pre-sort recyclables (glass, paper, metals, plastics, organics); higher quality and energy savings.
- iii. Pay-as-you-throw (PAYT): households pay per bag/bin of mixed waste but not for separated recyclables; strong incentive to reduce and sort.
- iv. Ex. Singapore: NEA initiatives for voluntary recycling by households and trade premises; national recycling bins and campaigns; focus on waste minimisation.

Plastics:

- i. High-value engineering plastics can be separated from complex goods (computers, appliances, autos) and converted to pellets.
- ii. Benefits:
 - Uses ~90% less energy than making virgin plastics.
 - Reduces GHG emissions and need for incineration/landfilling.
 - Plastics can be recycled multiple times (several "lives") before downcycling.

Waste Reduction

Government Policies:

- i. Increase subsidies/tax breaks for reusing and recycling; Decrease subsidies/tax breaks for exploiting virgin sources
- ii. Increase fee-per-bag waste collection system
- iii. Encourage or require government purchases of recycled products
- iv. Pass laws requiring companies to reuse or recycle packaging and e-Waste
- v. Public education

Industry Strategies:

- i. Redesign manufacturing processes and products to use less material and energy, and produce less waste and pollution
- ii. Develop products easy to repair, reuse, remanufacture, compost or recycle
- iii. Eliminate or reduce unnecessary packaging
- iv. Use fee-per-bag waste collection
- v. Establish cradle-to-grave responsibility laws
- vi. Restructure urban transportation systems

Hazardous Waste Management

Detoxification:

- i. Bioremediation: use bacteria/enzymes to break down toxic substances.
- ii. Phytoremediation: use plants to absorb, filter and remove contaminants from soil and water.
- iii. Incineration: heating up to 2000°C can break down or convert harmful chemicals
- iv. Plasma Arc Torch: passing electrical current through gas to generate an electric arc and very high temperatures can create plasma to decompose liquid or solid hazardous waste

Storage Options:

- i. Deep-well Disposal: pump liquid wastes under pressure into porous rock far below aquifers.
- ii. Surface Impoundments: lined ponds, pits or lagoons for liquid wastes (risk of leakage/overflow).
- iii. Long-term Retrievable Storage: drums stored in secure, monitored facilities for future treatment (for materials which cannot be detoxified or destroyed)
- iv. Secure Landfills: drums buried in carefully designed and monitored sites.

Mercury is a highly toxic element and potent neurotoxin:

- i. Released by coal burning, incineration, metal and cement production, mining, waste handling.
- ii. Highly mobile cycling between atmosphere and Earth's surface; bioaccumulates and biomagnifies, especially in aquatic food chains.
- iii. Control: reduce emissions, phase out mercury-containing products, advise on fish consumption, use safer alternatives.

Lead is a highly toxic metal and strong poison and neurotoxin which can build up in the body:

- i. Released in old lead-based paints, contaminated dust/soil, plumbing, legacy exhausts
- ii. Control: remove/encapsulate old lead paint, replace pipes, soil remediation, screening and treatment of children.

Food Waste

Issues:

- i. Globally $\sim \frac{1}{3}$ of food calories produced are wasted; enough to feed ~ 3 billion people.
- ii. Food waste $\sim 8\%$ of global GHG emissions; contributes to deforestation and water depletion.
- iii. Problems: contaminates recyclables, causes odour and vermin if mismanaged; adds load to incinerators and landfills.
- iv. Management options: source reduction, redistribution, separate collection for treatment (composting, anaerobic digestion), public education.
- v. Ex. Singapore: food waste $\sim 10\%$ of total waste and has grown by $\sim 40\%$ over 10 years.

Towards a Low-Waste Society

Policies:

- i. Grassroots Actions: keep large number of incinerators, landfills and hazardous-waste treatment plants from being built in local areas.
- ii. Environmental Justice: everyone deserves equal protection from environmental hazards.
- iii. International Treaties: phase out persistent organic pollutants (POPs) such as DDT, PCBs and dioxins.
- iv. New vision:
 - Everything is connected; there is no real "throw away".
 - Polluters/producers pay full costs.
 - Do not mix hazardous and recyclable wastes.
 - Mimic nature by reusing, recycling and composting.

12. Environmental Hazards and Health

Environmental hazards and health risks arise from various factors:

- i. Hazard: any source of potential damage, harm or adverse health effect (e.g. chemical, pathogen, energy source).
- ii. Risk: probability that exposure to a hazard will cause harm.
- iii. Risk Assessment: estimate how much harm a hazard can cause to human health or the environment.
- iv. Risk Management: decide whether and how to reduce risk, and at what cost.

Types of Hazards:

- i. Biological: pathogens (bacteria, viruses, parasites, fungi).
- ii. Chemical: harmful substances in air, water, soil, food, products.
- iii. Physical: fires, earthquakes, volcanoes, floods, storms, radiation.
- iv. Cultural: unsafe work, unsafe roads, crime, poverty, war.
- v. Lifestyle: smoking, unhealthy diet, lack of exercise, excessive alcohol, unsafe sex.

Routes of Exposure:

- i. Environmental media: air, drinking water, food, soil.
- ii. Entry pathways:
 - Inhalation (breathing in airborne contaminants)
 - Ingestion (drinking/eating contaminated water or food)
 - Dermal/eye absorption (through skin or eyes)
 - Injection (needles, bites, medical procedures)

Biological Hazards

Types:

- i. Non-transmissible Diseases: not caused by living organisms; do not spread person-to-person (e.g. cardiovascular disease, asthma, diabetes, most cancers).
- ii. Infectious Diseases: caused by pathogens that invade and multiply in the body (e.g. malaria, cholera, dengue).
- iii. Transmissible Diseases: infectious diseases that spread person-to-person (e.g. tuberculosis, flu, measles, COVID-19).
- iv. Epidemic: large outbreak in a region or country.
- v. Pandemic: epidemic that spreads globally (e.g. HIV/AIDS, COVID-19).
- vi. A small number of diseases account for a large share of global deaths (respiratory, digestive, cardiovascular, cancers and a few major infections).

Tuberculosis (TB)

Tuberculosis is spread by the TB bacterium:

- i. $\sim \frac{1}{3}$ of world population is infected with TB bacterium; most infections latent.
- ii. Challenges:
 - Underfunded screening and control programmes, especially in developing countries.
 - Most TB strains have developed genetic resistance to majority of antibiotics.
 - Crowded living conditions and increased air travel have increased person-to-person contacts.
 - New multidrug-resistant TB and extensively drug-resistant TB.
 - Low financial incentive to develop new TB drugs.

Viral Diseases

Viruses evolve quickly, are not affected by antibiotics and can kill many people:

- i. Influenza: global killer transmitted via droplets and aerosols.
- ii. HIV/AIDS: attacks and weakens immune system; no cure and limited vaccine coverage.
- iii. Hepatitis B: causes serious liver disease and cancer.
- iv. Emergent: West Nile, SARS, MERS and others.

Malaria

Malaria is caused by a parasite spread through Anopheles mosquitoes, and via blood transfusions and shared needles;

- i. $\sim 40\%$ of world population lives in malaria-risk areas; kills thousands daily (mainly children).
- ii. Climate change may expand mosquito ranges and lengthen transmission seasons.
- iii. Control strategies:
 - Antimalarial drugs and vaccines (under development/limited rollout).
 - Insecticide-treated bed nets and indoor residual spraying.
 - Environmental management to reduce mosquito breeding sites.

Preventing Infectious Diseases

Solutions:

- i. Increase research on tropical diseases and vaccines.
- ii. Improve nutrition and reduce poverty.
- iii. Improve sanitation, hygiene and access to safe drinking water.
- iv. Reduce unnecessary antibiotic use.
- v. Expand vaccination and basic healthcare.
- vi. Public education (handwashing, safe sex, food).
- vii. Strengthen surveillance and rapid response to outbreaks.

Antibiotic Resistance

Antibiotic resistance occurs when bacteria evolve to survive exposure to antibiotics.

Drivers:

- i. Overprescription and misuse (wrong drug, wrong dose, viral infections).
- ii. Not completing full antibiotic courses.
- iii. Routine use in animal feed to promote growth.
- iv. Poor infection control and hygiene.

Consequences:

- i. Infections become harder or impossible to treat.
- ii. Longer illness, hospital stays and higher medical costs.
- iii. Increased mortality from once-treatable diseases.
- iv. Antibiotic residues and resistant bacteria in wastewater, rivers, soils and sediments.
- v. Resistance genes spread via water, food chains, livestock and human travel.

Solutions:

- i. Antibiotic stewardship: stricter prescribing and regulation in medicine and agriculture.
- ii. Infection prevention: vaccination, hygiene, safer sex and food safety.
- iii. Improved waste and wastewater treatment to reduce environmental antibiotic loads.

Chemical Hazards

Types:

- i. Toxic Chemical: can cause temporary or permanent harm or death (e.g. arsenic, lead, benzene).
- ii. Hazardous Chemical: toxic and reactive and whose potential for injury is high if released (e.g. acetaldehyde, bromine chloride)
- iii. Carcinogens: cause or promote cancer (e.g. benzene, radon, UV).
- iv. Mutagens: cause or increase frequency of DNA mutations (e.g. nitrous acid).
- v. Teratogens: cause harm or birth defects in embryos or fetuses (e.g. cadmium, formaldehyde).

Bioaccumulation and Biomagnification:

- i. Persistent chemicals move through air, water, soil and food webs.
- ii. Bioaccumulation: build-up of chemicals in an organism when intake > breakdown/excretion.
- iii. Biomagnification: increasing chemical concentration at higher trophic levels in a food chain (i.e. predators higher up).
- iv. Fat-soluble, persistent chemicals are most prone to bioaccumulation and biomagnification.

Effects:

- i. Long-term, low-dose exposure can disrupt:
 - Immune system: weakened disease defence.
 - Nervous system: brain, spinal cord and nerves.
 - Endocrine system: hormone-producing glands.
- ii. Neurotoxins: damage nervous system (e.g. methylmercury, lead, pesticides, solvents).
- iii. Hormonally Active Agents (HAAs): mimic, block or alter hormones, disrupting endocrine system (e.g. aluminium, mercury, PCBs)
- iv. Many household and consumer products contain mixtures of potentially hazardous chemicals; low-level residues are found in human blood and tissues worldwide.

Toxicology

Toxicology studies the harmful effects of chemicals on humans and other organisms:

- i. Toxicity: measure of how harmful a substance is at a given dose.
- ii. Dose: amount of a substance a person takes in (ingested, inhaled or absorbed).
- iii. Response: health damage resulting from exposure to a certain dose.
- iv. Acute effect: rapid, short-term response to a single exposure or from multiple in a short time.
- v. Chronic effect: long-term response to repeated or continuous exposure.

Estimating toxicity:

- i. Laboratory tests:
 - Typically use rats, mice or other test organisms, extrapolated to humans with safety factors.
 - Alternative: cell/tissue cultures, computer models, epidemiological studies.
- ii. Dose-response Curve: describes change in effect on an organism caused by different exposure to a substance after a certain exposure time.
- iii. Lethal Dose: dose which kills animal
- iv. Median Lethal Dose, LD₅₀: dose that kills 50% of test animals in 18-day period.
- v. Uncertainties:
 - Genetic differences between individuals.
 - Mixtures of multiple chemicals.
 - Effects of low doses and long-term exposures.

Managing Chemical Risks

Solutions:

- i. Pollution Prevention:
 - Substitute safer, less toxic chemicals.
 - Redesign processes to minimise hazardous waste generation.
 - Recycle chemicals in closed loops to prevent environmental release.
- ii. Precautionary Principle:
 - When there is reasonable but incomplete evidence of serious or irreversible harm, take preventive action rather than wait for more proof.
- iii. Phase out Persistent Organic Pollutants (POPs):
 - Resistant to degradation, bioaccumulate and biomagnify (e.g. DDT, PCBs, dioxins, furans).
 - International treaties aim to phase out or restrict POPs.

Risk Evaluation

Risk Analysis:

- i. Risk Assessment: scientific study of risk magnitude and likelihood.
- ii. Risk Acceptance: social and personal judgement of how much risk is tolerable.
- iii. Risk Management: policy and economic decisions on how to reduce or share risk.

System Reliability = Tech. Reliability ×

Human Reliability:

- i. Even highly reliable technology can be undermined by human error.
- ii. Compare risks objectively using data.
- iii. Identify which risks are most serious and most controllable.
- iv. Focus policies on major lifestyle and environmental risks (e.g. smoking, air pollution) rather than minor hazards.