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 occuring 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 CO_2 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 degredation, 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 renewed 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, subtitution, 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 CO_2 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 CO_2 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 CO_2 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. Involvment of 3P (private, pubic, 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 farmships, 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 millon more trees by 2030, develop green spaces, adding new 1000ha by 2035
ii. Green Government: public sector leads sustainablty
iii. Sustainable Living: strengthen green efforts in schools, development of nationwide car-lite transport system, reduce waste to landfill per capta and household water consumption
iv. Energy Reset: clear-energy vehicles and EV-ready towns, achieve 80% gren buildings by 2030, reduce energy consumtpion in HDBs, 4× 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: CO_2 Accounting in China

Findings:

i. Shanghai: highest per capita GDP and consumption-based CO_2 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 CO_2 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 ($\sim$500km): contains >99.9% of atmospheric gases
ii. Mesosphere ($\sim$100km)
iii. Stratosphere ($\sim$50km): contains 90% of atmospheric ozone, which acts a protective layer against the sun's harmful UV radiation
iv. Troposphere ($\sim$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

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.

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

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; $\sim$77% (up to 95% in cities) from motor-vehicle exhaust.
ii. Health: binds to hemoglobin reducing O_2 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 (NO_2) is a reddish-brown irritant, converts to nitric acid (HNO_3) 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; HNO_3 damages trees, soils, aquatic life; corrodes metals/stone; NO_2 damages fabrics.

Sulfur Dioxide (SO_2) is a colorless irritant mainly from burning sulfur-containing fuel, converts to sulfuric acid (H_2SO_4) 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; H_2SO_4 damages trees, soils, lakes; SO_2 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. Enivornmental: 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 vegatation 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, marketting 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 chloroflurocarbons (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. CO_2 is the major driver of recent warming (observed rise in CO_2 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 CO_2.

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 $25 - 27°C$

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 CO_2 growth will lead to dangerous temperature increases; aggressive decarbonisation is needed to avoid 2 degrees of danger, requiring cutting emissions by > half.

ii. 2023 CO_2 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°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-CO_2 Gases: methane leak detection/repair (LDAR), agricultural CH_4/N_2O reductions, refrigerant management.

v. Nature-Based: afforestation/reforestation, peatland and mangrove restoration, improved soils.

Carbon Capture, Utilisation & Storage

Pipeline:

i. Capture: selective removal of CO_2 from point sources (power, cement, steel) or air (DAC).

ii. Transport: compression and movement via pipelines (regional) or ships (long distance).

iii. Utilisation: CO_2 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 CO_2/CH_4; 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 ~40% of global electricity at inexpensive cost, with potential to cover global energy needs into 22^{nd} century.
ii. Well-developed technology, with air pollution reducible by improved technology
iii. Burned industrially for iron, steel and other products
iv. Major CO_2, SO_2 emitter, along with soot, and toxic industructible 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 H_2, CO, CO_2).
ii. Liquefaction: forms methanol/synthetic gasoline.

Oil

Crude oil is a black liquid of different combustible hydrocarbons, trappened 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 consued 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 viscious/heavy so buoyant forces are insufficient to expel them from the reservoir and requires more technology:

i. Oil Sands: extra heavy, viscious 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, Argentia, 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 breakthroughts, 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

Unconvential 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.

CO_2 Emissions

CO_2 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* CO_2 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% ^{238}U, 0.71% ^{235}U) enriched to ~3.5–5% ^{235}U → UO_2 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 electri motors with variable speed motors, recycling materials, swithing 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.

9. Renewable Energy

Renewable Energy (RE) is replenished by natural processes at a rate equal or exceeding rate of use.

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 anglessolar
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. evaporatn)
   - Topaz Solar Farm: 550 MW, powers ~160,000 homes; avoids ~377,000 t CO_2/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 CO_2, 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 purporses:

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 law materials like water and CO_2 into clean fuels and value-added chemicals (e.g. H_2, 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 CO_2 emissions in temperatee 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. Londay Array: biggest offshore farm; 630 MW
+ Moderate-high net energy, high efficiency, low environmental impact, no CO_2 emissions, easy expansion, can be located at sea
– Variable power suuply, 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 CO_2 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) → CH_4 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 CO_2 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 CO_2 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 H_2 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

11. Zero Waste

12. Environmental Hazards and Health