Technologies for Sustainability in Energy and the Environment

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Edited by

Martin Mkandawire, Allen J. Britten
and R. Chandra Devi

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FOREWORD

Since the Brundtland Commission report was unveiled in 1987, the world has struggled to operationalize the concept of sustainable development for agriculture and fisheries, mining, energy, manufacturing, climate action, and so many other important sectors. The world is now on the verge of a tipping point where conflicts between energy, the environment and the economy demand critical attention.

The editors and chapter authors of "Technology for Sustainability in Energy and the Environment" offer important insights on how to think about the consumption of the planet's resources while being mindful of the needs of future generations. Martin Mkandawire is a native of Malawi who spent a few decades working in Germany and the last 12 years in Canada; Allen Britten is a Canadian but worked on numerous technical assignments in Southern India; and Chandra Devi Raman represents an emerging generation of exceptional young women having studied engineering in India and England and collaborated on research in Canada. This multi-cultural team of editors along with their chapter authors have the vision and professional experience to shape this important book and offer a fresh, global view of energy and environment linkages and on how to sustain the environment and also to produce clean energy.

A particular strength of the papers in this book, among many, is how they zoom in on important sustainability challenges; using analytical chemistry, nanotechnology, biotechnology, biomimicry and other techniques; then zoom out to reflect on the problems created by high natural resource consumption in advanced economies of the North and low consumption in emerging economies of the South. The juxtaposition of zooming in, then zooming out while considering both the North and the South related to energy and the environment, offers an insightful and timely perspective.

Edwin MacLellan, PhD. (Prof (EM))

PREFACE

The global human population exceeded eight billion in 2023, far beyond the earth's natural carrying capacity. Only technological advancement is sustaining the high population, but at the expense of ecological balance. Consequently, the increasing human population has resulted in an increased need for resources. in doing so, we are reducing and encroaching into habitats of the co-existing organisms and destroying terrains that needed preservation. Our population growth has led to high waste production, emissions, and pollution. The resources and energy required for industrialization have resulted in the degradation of the environment and in global warming.

There is a general acknowledgment that the modern approach to technological advancement should focus on conserving the earth by halting or reducing negative environmental activities. This book looks specifically at the direction of technologies and innovations in research including those technologies just entering the market for abating, rehabilitating, and restoring degraded environments. Contamination and over-exploitation of resources, restoring the degraded landscape, catchment area and water sources, reducing the carbon footprint and energy production are investigated.

Specifically, we discuss from scientific and engineering perspectives the promising technologies in (a) sustaining acceptable environmental conditions, which are cost-effective and efficient with the potential to reach the most underprivileged world economies and (b) clean energy production, which is either renewable or has low- or zero-carbon emissions so that we attain carbon neutrality.

We look at how technologies benefiting from advances in different science and engineering fields like biomimicry, nanotechnology, and biotechnology-based techniques would help to conserve and abate the environmental damages. The first chapter is dedicated to generally introducing contemporary technology trends and the strategies based on these trends in the past and present decades, as well as predicting the direction of technological advancement. We include chapters that provide examples of scientific and policy strategies that would benefit developing technologies for sustainability in the energy and the environment. Case studies from Canada and India are highlighted.

A focus on energy storage and photovoltaic techniques, which discuss advances in, among other things, the development of supercapacitors is included. In another chapter, the book discusses some seminal trending technologies and their enablers in environmental remediation, like waste valuation, nanomaterial-solar-based water treatment, and solid-state fermentation. A chapter on analytical methods provides some insight on how we can evaluate these new technologies.

We hope that the various contributions from the authors, and the interdisciplinary approach of this book, will help to educate with respect to contemporary ideas in technology and sustainability. The editors thank the authors for their enlightening contributions but acknowledge that their work and opinions are their own and not necessarily those of the editors.

Martin Mkandawire, Allen J. Britten
and Chandra Devi Raman

31 December 2023

INTRODUCTION

MARTIN MKANDAWIRE
AND ALLEN J. BRITTEN[1]

The focus of technological development has changed from the initial goal of sustaining life to improving the quality of life. As a result, this change in focus has led to excessive use of fossil fuels and depletion of resources. The consequences are being manifested as challenges to environmental and energy sustainability.

Concept of Sustainability

According to the Oxford Dictionary, sustainability, in the broadest sense, refers to maintaining or supporting a process continuity over time. In this book, the definition of sustainability is confined to human development, which, according to the United Nations (the UN's) Brundtland Commission Report of 1987 – Our Common Future – is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability is often broken into three core concepts or pillars: **economic, environmental, and social**.

Economic sustainability focuses on conserving the natural resources that provide renewable physical inputs for economic production. A sustainable economic system should conserve natural and financial resources to last far into the future with minimal negative impacts. **Environmental sustainability** emphasizes the support systems (the atmosphere, soil, and water) that must be maintained for life. It includes the capacity to improve the quality of human life while living within the carrying capacity of the earth's supporting ecosystems. **Social sustainability** focuses on attempts to eradicate poverty and hunger and combat inequality.

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Human development and economic growth are inseparable - tied to technological industrialization. For a long time, environmental protection was deemed to impede economic growth. Prioritizing environmental sustainability was in apparent conflict with the needs of a growing industrialized society. Economic growth is temporary and unsustainable when the environment and society are ignored. Sustainability is achievable when the equilibrium of economic, environmental, and social sustainability is well-balanced.

The strains exerted by the stress of conflict between population growth and the environment are very apparent. With limited resources, in a biophysical context, the growth of the human population competes with that of nonhuman species. Although improving the quality of life for a portion of the human population, current technologies have not addressed the demise of nonhuman species.

All resources feeding technological industrialization come from the earth and are obtained only through two means – farming or mining. The extraction of resources depletes or destroys the environment. At some point, even in localized areas, the loss of farming will lead to the collapse of the economy and social and ecological health. A higher energy demand than ever is leading to more polluted environments and depleted natural resources.

Sustainable Technologies Vs. Technologies for Sustainability

Sustainable technology is not the same as technology for sustainability. Loosely, sustainable technology would be one that can be maintained at the same level for eternity. These technologies would benefit from a healthy environment with perpetual resources and energy supply. Sustainable technology can be an umbrella term for describing innovations that consider natural resources and foster economic and social development.

In contrast, technologies for sustainability support the pillars of sustainability, namely economic, environmental, and social. These technologies aim to reduce environmental and ecological risks, conserve resources and mitigate or reverse the effects of human activity on the environment. Such technologies are expected to support a healthy environment, resource and energy availability, suspend climate change, and satisfy three parameters:

- Substitution – The ability of a technology to foster a shift from non-renewable to renewable resources;
- Prevention – The ability of technology to prevent deterioration of the environment; and,

- Efficiency – The technology is efficient in its use of energy and resources.

Sustainability in Energy

The energy consumption rate threatens the sustainability of energy availability. A push for sustainability has focused on finding new energy sources to reduce the drawdown on existing reserves. These sources have accounted for a very small percentage of the total energy resource and have done little to mitigate environmental issues and climate change.

Using the definition of sustainability (given above and used in this book), sustainability in energy would mean maintaining the energy supply and availability perpetually at the level that meets the global energy demand and needs. It can be achieved by combining improved energy efficiency with renewable energy sources. The energy produced from resources that naturally sustain or replenish themselves over time can be considered renewable. For renewable energy to be sustainable, the rate of replenishment of the primary energy resource should be equal to or more than the rate at which energy is consumed. For instance, traditional resources like coal and oil, which take millions of years to form, are strictly speaking renewable, but because of the timeline, they are not sustainable energy.

Renewable energy and sustainable energy are often wrongly used interchangeably. Although there is some overlap between the two, these two are not the same. Sustainable energy is inexhaustible and will never be used up or depleted. Several forms of energy can be considered sustainable, mostly sourced from wind, solar, and water. Bioenergy and geothermal energy are also alternatives to unsustainable sources. Energy sources should be considered sustainable when obtained without environmental pollution, global warming, and landscape disturbance.

Although harnessing sunlight for energy can always be replenished, it is not always clean due to the source of material used to harness it. Bioenergy is renewable. However, it contributes to greenhouse gases when energy is obtained through combustion, and as its consumption emits climate-affecting greenhouse gases. Furthermore, farming biofuel plants leads to the clearing of forests, thereby reducing greenhouse gas sinks and creating spatial competition for biodiversity habitats.

Sustainability in the Environment

Global warming is a significant challenge to the continuity of life-supporting systems on earth. Although global warming is largely blamed on the overuse of greenhouse gas-emitting fossil fuels, a significant cause of global warming is the reduction of carbon sinks. The extraction and combustion of fossil fuels release more carbon than nature could previously capture (sunk) by nature.

Environmental sustainability is when humans responsibly interact with the planet to maintain natural resources and not jeopardize the ability of future generations to meet their needs. Sustainability in the environment can only come if the global atmospheric carbon can be reduced to the levels of the 1950s. Only then can we look to reaching net zero. This means we need to capture the excess carbon already released from the sinks. According to the United Nations, reducing emissions by about 45% by 2030 should keep global warming to no more than 1.5°C.

Minerals never replenish after extraction. Mineral resource extraction is generally not sustainable, but if care is taken, mineral resource use can be done sustainably. Even the technology using such resources can be made to support sustainability principles by strategically moving away from a linear economy towards a circular economy, where the extracted resources are reused or repurposed at the end of the product life cycle. For example, although photovoltaic (solar) panels are promoted as a solution to meeting carbon neutrality, they have a life span of only 25 years. If the current linear economy of photovoltaics continues, the world is already on the verge of a new eco-disaster of solar panel waste and junk. Additionally, the storage of solar energy requires batteries, which have a limited life and are, therefore, a source of environmental pollution. Technology design should incorporate sustainable methods of the whole lifecycle of the products and extend their re-usability.

CHAPTER ONE

TRENDING TECHNOLOGIES FOR ENERGY AND THE ENVIRONMENT

MARTIN MKANDAWIRE AND SAMAR ZAHRA ALI[1]

This chapter defines the trending technology and the factors fueling the development. The chapter shows that technological growth is changing from merely sustaining the human population, which has grown beyond the Earth's carrying capacity and resulting in conflict with the environment and other ecosystems' compartments, to reducing carbon footprint to reverse climate change.

1.1 Introduction

1.1.1 Background

Before the 18th century Industrial Revolution, the global human population had never exceeded 200 million. The checks and balances of starvation and pestilence controlled population growth.[1] Since the late 1600s, the world's population has increased by more than 15-fold.[2,3] In 2020, it was estimated at 7.7 billion and continues to grow by around 80 million people annually.

Population sizes of living organisms are limited by environmental factors such as adequate food, shelter, water, and mates. If these needs are unmet, the population will decrease until resources rebound. The Industrial Revolution facilitated technological advancements and innovations for humanity that have eliminated most of these environmental limitations. It led to new chemical manufacturing and iron production processes, the increasing use of steam and waterpower, the development of mechanical tools and the rise of the

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mechanized factory system. Technological and medical advances continue to enable people to live longer, healthier lives.

The global human population of about 8 billion seems to exceed the Earth's natural carrying capacity, yet it has been sustained thus far due to technological advancements. Carrying capacity is the average population size of a species in a particular habitat. Thus, technological advances are a driving force for the development and sustenance of humans on Earth. However, ensuring continual technological advancements requires a sustainable supply of resources, mainly energy, raw materials, and space.

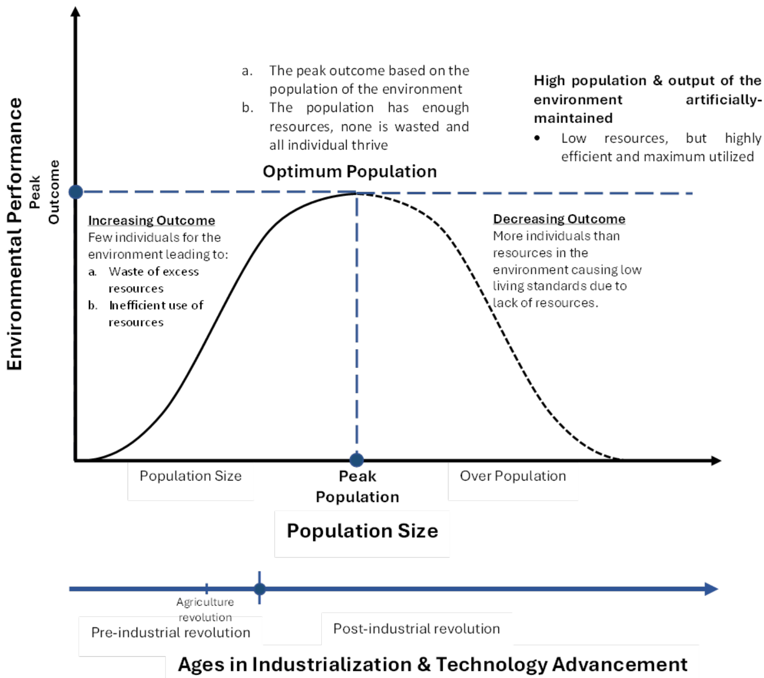

Fig. 1. The concept of optimum population and Earth's carrying capacity shows (a) where the human population can balance maintaining a maximum population size with optimal *living standards* for all people and (b) how industrialization and technological advancement maintain the high human population.

Consequently, there is a continuous cycle between population growth, technological advances, increasing demand for resources and energy, and environmental degradation. All resources, including raw materials and over 90% of energy directly or indirectly, come from the Earth and are obtained only in two ways – either by farming or mining. If they can be planted or farmed, they are exploited as minerals. The obvious consequences of resource extraction by either method have led to their overexploitation, environmental degradation, increased competition for space, leading to conflict between humans and other species for living habitat, and reduced carbon storage. Thus, technological advances have never been static but dynamic, constantly changing to adopt more energy-efficient methods of sustaining our daily lives by integrating variable renewables and developing new technologies and techniques.

1.1.2 The focus of contemporary discourse

Technology constantly evolves, requiring constant technique, strategy, and focus adaptation. The gist of contemporary technological development is sustaining the high quality of human living against the pressure exerted by the human population. The aim is to conserve the Earth by reducing negative environmental footprints and attempting to halt and possibly reverse the environmental degradation caused by exploiting resources and energy to drive industrial-technological systems.

Thus, it is essential to look at the direction of technologies and innovations in research or those entering the market for rehabilitating and restoring the degraded environment, especially from contamination and energy production. Specifically, the discussion should centre on the promising technologies in environmental remediation from scientific and engineering perspectives, which are cost-effective and efficient and can potentially reach the most underprivileged world economies. They also provide clean energy production by being either renewable or having low- or zero-carbon emissions. It is recognized that the quest for energy and resources to support the technology industry is responsible for environmental pollution and degradation. Therefore, they cannot be treated separately because they go hand-in-hand.

This first chapter introduces contemporary technology trends and the strategies based on these trends in the past and present decades.

1.2 Science, Engineering and Technology

Before the 20th century, the term “technology” was uncommon in the English language. Some have defined technology as the use of science in industry or engineering to invent useful things or solve problems such as machines, pieces of equipment, devices, and methods. Other definitions of the concept include (a) practice, the way we do things around here, (b) the pursuit of life by means other than life, and (c) organized inorganic matter. A standard definition among scholars today, especially social scientists, is that technology includes all tools, machines, utensils, weapons, instruments, housing, clothing, communication, transporting devices, and the skills we produce and use. Scientists and engineers generally prefer to define technology as an applied science rather than what people make and use.

In this chapter (and possibly in the book), technology refers to a collection of techniques. In this context, technology is the state of humanity's knowledge of combining or manipulating resources to produce desired products, solve problems, fulfil needs, or satisfy wants, including technical methods, skills, processes, techniques, tools, and raw materials. Thus, technology is often a consequence of science and engineering, although technology as a human activity precedes the two fields.4-6 Science is about creating the meaning of natural phenomena, engineering is based on scientific knowledge (e.g., creating new devices, tools and processes), and technology is about creating a collection of engineered and tested tools for humankind (illustrated in Fig. 2). Therefore, technology can form or change culture. Technology predates science and engineering as a cultural activity, each formalizing aspects of technological endeavour connected with artistic endeavours.

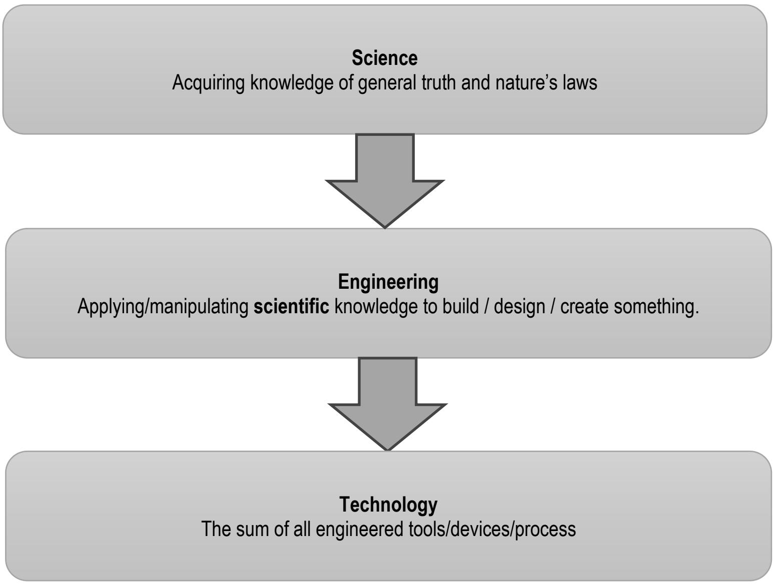

Fig. 2. The relationship and differences between science, engineering, and technology: Science is about creating the meaning of the natural phenomenon, Engineering is about creating new devices, tools and processes, and Technology is about creating a collection of engineered and tested tools for humankind. (Adapted from an unknown source)

Engineering is the goal-oriented process of designing and making tools and systems to exploit natural phenomena for practical human means, often (but not always) using scientific results and techniques. Technology development may draw upon many fields of knowledge to achieve practical results, including scientific, engineering, mathematical, linguistic, and historical knowledge.

1.3 Contemporary Technology Trends

Recent changes have focused on shaping technology towards meeting needs ranging from improving quality of life (e.g., transportation, medical advances, food security, telecommunications, affordable energy, and the digital world) to using technology as a tool for economic development and growth, protection/conservation of biodiversity, sustainable land use, and innovations for combating global warming and climate change. Since the last quarter of the 1900s, the manifestation of climate change due to global warming has been self-evident. Therefore, technological trends are now incorporating climate change adaptation techniques.

1.3.1 From climate change mitigation to adaptation techniques

Technological advances, particularly the discovery and use of fossil fuels, have contributed to climate change. The rising average temperature of the Earth is primarily blamed on greenhouse gas emissions that trap radiation in the atmosphere, which would otherwise escape into space.[7,8] The global climate summit at the Paris Conference (*aka* COP21) in 2015 adopted the Paris Climate Accords to halt global temperature rise to 1.5 degrees Celsius above preindustrial averages, which will require cutting net emissions of greenhouse gases roughly in half by 2030 and zero by 2050.

As a result, the trends in technological advancements from the beginning of the fourth quarter of the last century have been driven mainly by the quest to mitigate global warming. Unfortunately, efforts thus far have failed to reduce the impacts of global warming. Consequently, since the mid-1990s, the drivers for technological advancements are no longer just global warming mitigation but also adaptation to climate change. Some examples of climate change mitigation and adaptation techniques are outlined below.

(a) Techniques for controlling global warming

Greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (CFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), allow the sun's rays to pass through and warm the planet but prevent the warmth from escaping the atmosphere into space. The atmospheric concentrations of CO_2, CH_4, and N_2O – three important long-living greenhouse gases – have increased substantially since about 1750 – the Industrial Revolution.[1,9-11] Annual estimates from anthropogenic, natural sources and natural sinks that remove CO_2, CH_4, and N_2O from the atmosphere are summarized in **Fig.** 3. CO_2 is among the most significant greenhouse gases. It has risen by almost 50% since the Industrial Revolution.[11] The most abundant greenhouse gas in the atmosphere is water vapour. SF_6 is the most potent greenhouse gas – almost 60000 times as potent in heat-trapping than CO_2 – but fortunately, the concentration in the atmosphere is minimal. CH_4 is more than 25 times as potent as carbon dioxide at trapping heat in the atmosphere, but its atmospheric concentration is four times less than CO_2.

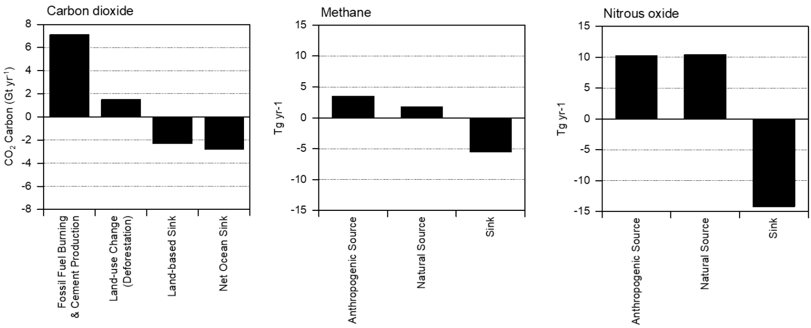

Fig. 3. The sources and sinks' contribution to the annual amount of greenhouse gases in the atmosphere *are* not included. Units are in grams (g) or metric tons (tonne: international symbol t = 10^3 kg = 10^6 g). Multiples used in the figures are: Gt (gigatonne) = 10^9 t = 10^{15} g; Tg (teragram) = 10^{12} g = 10^6 t; and Gg (gigagram) = 10^9 g = 10^3 t. Source: estimated from data extracted from IPCC Fourth Assessment Report (2007)[12]

Technological trends in climate change mitigation have focused on integrating techniques of natural climate solutions, which consist of conservation, restoration, and land-management actions that either prevent emissions or remove greenhouse gases, mainly carbon dioxide and methane, from the atmosphere. The innovations that have dominated this field can be categorized but are not limited to the following:

i. ***Trapping Greenhouse Gases***

Since CO_2 is the most prominent driver of climate change, contemporary innovations oscillate in reducing CO_2 emissions, including carbon capture, utilization, and storage technologies. For example, some technologies focus on capturing natural gases at oil wells instead of wastefully burning them off and dumping the resulting CO_2 into the atmosphere. In addition, technology is being used to develop a method of capturing CO_2 produced in industrial processes and power plants and transporting these emissions through a pipeline to offshore storage sites several kilometres beneath the oceans and seas. The CO_2 sequestered in secure areas deep beneath the sea would no longer contribute to the greenhouse effect and could even be synthesized into new fuels for transportation systems.

Another technique of capturing and sequestering CO_2 is mineral carbonation. Mineral carbon dioxide sequestration is an exothermic chemical reaction of a metal–bearing oxide, usually calcium (Ca), magnesium (Mg), or iron (Fe), with CO_2 to form stable solid carbonates. Natural minerals and industrial by-products are rich in Ca, and Mg can undergo the carbonation reaction through direct or indirect mineral carbonation processes.[13,14] Direct aqueous carbonation of red gypsum results in $CaCO_3$ and $FeCO_3$ production.[15] Indirect carbonation of red gypsum involves a reaction with an alkaline solution extraction, like NaOH and NH_4OH. Subsequently, the formation of solid $Ca(OH)_2$, which is dissolved in water and allowed to react with CO_2, produces $CaCO_3$. Carbonation is also promising in CO_2 curing, a technology for the concrete industry that introduces recycled CO_2 into fresh concrete. The process turns CO_2 from a gas to a mineral, creating solid carbonates that improve the strength of concrete and result in structures needing less cement. In addition, mineral carbonation provides a permanent and leakage-free CO_2 disposal method in that the produced carbonates are environmentally benign and stable.[13,15]

ii. ***Conserving Energy***

The most effective technological solution to climate change is reducing energy consumption. Energy is conserved by reducing waste, improving efficiency through technical upgrades, and enhancing operation and maintenance. Energy conservation is a part of the concept of Eco-sufficiency.[16-18] The quest for technological upgrades is another driver of technological trends. These technologies are divided into three distinct energy consumption areas: saving at home and in buildings, saving in industries and transportation.

Since energy can only be transformed from one form to another (e.g., heat energy to motive power in vehicles or kinetic energy of water flow to electricity in hydroelectric power plants), the quest for efficient energy transformation without wastage into non-harnessable forms is at the forefront in most technological upgrades. From everyday electronics to sources of heat, lighting, and power, many factors influence energy usage in domestic and industrial buildings. New technologies for conserving energy include adapting smart techniques and low energy-consuming appliances. These techniques include self-programming smart thermostats to regulate temperature preferences in a schedule, allowing for integrating portable electronics (e.g., smartphones) and providing monthly savings reports. Several advanced light bulbs are replacing the traditional lighting system. These are predominantly LEDs (Light Emitting Diodes), using 90% less energy than incandescent light bulbs, followed by Induction Powered Light Bulbs and CFLs (Compact Fluorescent Light Bulbs), using 75% and 70% less energy than incandescent light bulbs, respectively. Other technologies for energy efficiency incorporated in building designs include sensors for monitoring and performing an energy audit, an inspection and analysis of energy use and flow, and elements of passive solar design, in which windows, walls, and floors are made to collect, store, and distribute solar energy in the form of heat and reject solar heat when required.[19,20]

iii. Shrinking Carbon Footprint of the Transportation Sector

The transportation sector consumes the second-highest amount of energy, behind the industrial sector, but it generates the largest share of greenhouse gas emissions.[11,12,21] Greenhouse gas emissions from transportation primarily come from burning fossil fuels, of which over 90% are petroleum-based, including gasoline and diesel.[22] Shrinking the carbon footprint would mean reducing the use of fossil fuels and redesigning transport vessels and vehicles for efficiency.

In road transportation systems, vehicles will continue to undergo substantial technological changes, introducing new powertrain designs, alternative fuels, advanced materials, and other significant changes to the vehicle body over the next several decades. Other technological trends include alternative methods to propel and fuel vehicles and alternative modes of transportation, including autonomous vehicles.

Some of the energy-efficient technologies that are currently available in performance-enhancing and fuel-saving technologies that can reduce greenhouse emissions include [23-26]:

(a) Engine Technologies:

- Cylinder deactivation saves fuel by "turning off" some cylinders when not needed, increasing efficiency by up to 5%;
- Turbochargers increase engine power, allowing the use of smaller engines without sacrificing performance or are used to increase performance without lowering fuel economy, increasing efficiency up to 8%;
- Gasoline Direct Injection (GDI) delivers higher performance with lower fuel use, increasing efficiency by1%; and,
- Valve Timing and Lift Technologies improve engine efficiency by optimizing the flow of fuel and air into the engine for various engine speeds, improving the efficiency by 3%–4%

(b) Transmission Technologies

- Additional gears allow the engine to operate at efficient speeds more often, which increases the efficiency by 2%–4%;
- Continuously Variable Transmissions (CVTs) have an infinite number of "gears," providing seamless acceleration and improved fuel economy by 3%–4%; and,
- Dual-clutch transmissions, similar to manual transmissions but adding automated shifting, improve efficiency by 3%–4%.

(c) Hybrid Technologies

- Stop-Start systems stop the engine when the vehicle comes to a stop and automatically restart it to resume driving, reducing wasted fuel from idling by 2%.
- Mild hybrids use Stop-Start technologies and a small regenerative braking system that can recover and reuse small amounts of energy lost from braking, increasing efficiency by 3%–6%.
- Hybrids use Stop-Start, regenerative braking, and larger electric motors and batteries to reduce fuel use, especially stop-and-go driving, increasing efficiency up to 27%–35%.

Other Technologies include weight reduction and powertrain downsizing, which can significantly improve fuel economy by up to 1%–3% per 5% reduction in weight. In addition, low-rolling resistance tires reduce the parasitic energy loss from tires rolling under load and are estimated to improve efficiency by up to 4%.

The aviation sector is a major contributor to human-made greenhouse gases. However, the development of electric planes is limited by battery-weight challenges, where it is estimated that jet fuel produces about 14 times more energy than the equal mass of a battery.[27,28] With much effort invested in reducing the weight-to-power ratio, E-planes are moving closer to taking off but have not yet advanced enough to replace fossil fuel in aviation. Thus, aviation is seeking new technologies, designs and materials that can sustainably increase fuel efficiency and produce less CO_2. The trend is to improve engines, enhance aerodynamics and use lighter materials.

The most significant contributions to aeronautic fuel efficiency are designing a new wing shape – the supercritical wing, characterized by its flattened upper surface, highly cambered ("downward-curved") aft section, and sizeable leading-edge radius – that significantly increases efficiency at high speeds and eliminated weight. Similarly, aircraft with upturned wingtips improve airplane performance by reducing drag by 10% to 15%. In addition, they can cut emissions by 6%.[29,30] Winglets are devices mounted at the tip of the wings and are used to improve the aerodynamic efficiency by the flow around the wingtip to create additional thrust.

Reducing the overall weight of the airplane is always a top priority to increase fuel efficiency. This area is promising to use 3D printing technology in additive manufacturing, carbon fibre materials, and shape memory alloys (SMA), which can reduce aircraft weight while increasing customization and overall construction efficiency. SMA responds to a specific temperature when the alloy metal transforms into different shapes. In addition, they are being explored as vibration dampeners for jet engines.

The maritime transport sector is the backbone of the increasingly globalized economy and the international trade system. However, maritime shipping emissions contribute 2.5% of global CO_2 because most big ships burn tons of low-quality "bunker fuel."[31,32] A trending technology in transitioning to clean energy is the development of ships powered by hydrogen fuel cells, which create energy from hydrogen gas and release only water.[33] The hydrogen will be green, sourced from splitting water molecules with wind or solar energy. Another technique is to adopt nuclear-powered engines, commonly used in a submarine.

iv. Advancing Renewable Energy

Intense efforts have been invested in developing techniques to harness renewable natural resources for energy production, naturally replenished on a human timescale. There are several potential renewable sources, but the most prominent are sunlight, wind, rain, tides, waves, and geothermal heat.[34] Renewable energy often provides energy in four critical areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services. The leading mainstream technologies are:

a. Hydropower

This renewable energy source predominantly generates electric power (i.e., hydroelectric power) by natural water flow. The conventional hydropower method involves generating hydroelectric power from the potential energy of dams and reservoir water to drive a water turbine and generator. The power extracted from the water depends on the volume and the difference in height between the source and the water's outflow. Run-of-the-river hydroelectric generation derives energy from rivers without creating a large reservoir. However, a constant supply of water from a lake or existing reservoir upstream is a significant advantage in run-of-the-river. The water is typically conveyed along the side of the river valley, using channels, pipes, or tunnels until it is high above the valley floor. After that, it can fall through a penstock to drive a turbine.

A new hydropower method is extracting power from the kinetic energy of ocean tides, currents, and waves. Tidal power makes use of the daily rise and fall of ocean water. Some water bodies have underwater currents which can be harnessed for hydroelectric generation. Wave power captures the energy of ocean surface waves. Tidal power is viable in a relatively small number of locations worldwide.

Further, hydropower is also being used in energy storage using the pumped-storage technique. The technique produces electricity to supply high peak demands, especially solar and wind energy, by using excess energy to move water between reservoirs at different elevations. The excess generation capacity pumps water into the higher reservoir during low electrical demand. When the demand increases, water is released back into the lower reservoir through a turbine. Pumped storage is not an energy source.

b. *Wind power*

The power available from the wind is a function of the cube of the wind speed. So, when wind speed increases, power output increases up to the maximum output for the turbine. As a result, wind energy is becoming one of the leading renewable sources of electricity, meeting more than 40% of electricity demand in some developed countries.[34,35] Globally, the long-term technical potential of wind energy is estimated to be 40 times the current electricity demand, assuming all practical barriers are overcome. This would require wind turbines to be installed over large areas, particularly in areas of higher wind resources, such as offshore and high-altitude terrains. Generally, offshore wind speeds average ~90% greater than land, and offshore resources can contribute substantially more energy than land-stationed turbines.[36] One major drawback is the unpredictable winds to match demand, thus requiring a good energy storage system for a time of high wind energy but low demands. For instance, when winds are gusting during storms, the energy demand is generally very low as most production is closed due to inclement weather.

c. *Solar energy*

The energy from the sun reaches the Earth as solar radiation, part of the electromagnetic radiation spectrum. Solar radiation includes visible, ultraviolet, infrared, radio waves, X-rays, and gamma rays. Solar radiation is harnessed using various technologies, which either passively or actively capture, convert, and distribute solar energy. Passive solar techniques involve designs or choice of material that naturally facilitate thermal mass or light dispersing properties, like orienting a building to the sun and designing spaces that naturally circulate air.[37,38]

Active solar technologies encompass solar thermal energy, solar collectors for heating, and solar power, converting sunlight into electricity either directly using photovoltaics (PV) or indirectly using concentrated solar power (CSP), concentrator photovoltaics (CPV), solar architecture and artificial photosynthesis.[39-43]

A PV system converts light into a direct electrical current, while CSP systems use lenses, mirrors, and tracking systems to focus a large area of sunlight into a small beam. CPV systems employ sunlight concentrated on photovoltaic surfaces for electricity generation. PV is currently installed in many solar farms. However, floating solar arrays, PV systems that float on drinking water reservoirs, quarry lakes, irrigation canals or remediation and tailing ponds are becoming popular. The systems have advantages over photovoltaics on land, including the land cost and fewer rules and regulations for structures built on bodies of water. The floating solar arrays achieve higher efficiencies than PV panels on land because water cools the panels. However, the panels must be specially coated to prevent rust or corrosion.

Another rapidly advancing solar technology is Perovskite solar cells, a type of solar cell that includes a perovskite-structured compound, most commonly a hybrid organic-inorganic lead or tin halide-based material, as the light-harvesting active layer. Perovskite materials, such as methylammonium lead halides and all-inorganic cesium lead halides, are affordable and straightforward to manufacture to increase solar cell efficiencies. Core problems and research areas include short- and long-term stability.

Artificial photosynthesis uses techniques, including nanotechnology, to store solar electromagnetic energy in chemical bonds by splitting water to produce hydrogen and using carbon dioxide to make methanol.[44] It requires designing molecular mimics of photosynthesis that use a broader region of the solar spectrum and employ catalytic systems made from abundant, inexpensive materials that are robust, readily repaired, nontoxic, stable in a variety of environmental conditions and efficient, allowing a greater proportion of photon energy to end up in the storage compounds.

Other technologies for harnessing solar energy include (a) a solar-assisted heat pump that integrates a heat pump and thermal solar panels in a single integrated system. A heat pump is a device that provides heat energy from a heat source to a heat sink. Heat pumps move thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one; (b) Solar updraft tower, which generates electricity from low-temperature solar heat as sunshine heats the air beneath an extensive greenhouse-like roofed collector structure surrounding the central base of a very tall chimney tower, resulting in convection of hot air updraft in the tower by the chimney effect. This airflow drives wind turbines in the chimney updraft or around the chimney base to produce electricity.

d. *Geothermal energy*

It is renewable energy extracted from the natural heat of the Earth. During the geological process of the planet's formation and the radioactive decay of minerals, heat is generated in both high enthalpy (i.e., volcanoes, geysers) and low enthalpy forms (i.e., thermal energy stored as thermal energy in rocks and fluids in the centre of the Earth).[34,35,45] Thermal energy can be tapped as geothermal energy. The geothermal energy can be from deep within the Earth, down to about 6,400 km in the Earth's core, where the temperatures can reach over 5,000 °C.[45] However, the geothermal gradient, created by the difference in temperature between the core and surface of the Earth, drives a continuous conduction of thermal energy in the form of heat from the core to the surface, heating rock and water in the crust, sometimes up to 371°C.[35,46] Thus, deep wells can be drilled into underground reservoirs to tap steam and very hot water that can be brought to the surface for various applications, mostly for heating or cooling and electricity generation.

Low-temperature geothermal uses the Earth's outer crust as a thermal battery to facilitate renewable thermal energy for heating and cooling buildings and other refrigeration and industrial uses. In this form, a geothermal heat pump and ground-coupled heat exchanger move heat energy into and out of the Earth for cooling and heating, respectively, on a varying seasonal basis. High-temperature geothermal energy is mostly used to extract steam to rotate a turbine, which activates a generator and produces electricity. There are three types of geothermal power plants: (i) dry steam, in which underground steam is piped directly from wells to the power plant, where it is directed into a turbine/generator unit; (ii) flash steam, which uses geothermal reservoirs of water with temperatures greater than 182°C, hot water flowing up through wells in the ground under its pressure. As it flows upward, the pressure decreases, and some of the hot water boils into steam, which is used to power a turbine/generator; and (iii) binary cycle that operates on the water at lower temperatures of about 107-182°C, which boils a working fluid, usually an organic compound with a low boiling point to turn a turbine.

Most geothermal energy within drilling reach is in dry and non-porous rocks. Such thermal energy is extracted using enhanced geothermal systems (EGS), a new technology that does not require natural convective hydrothermal resources. Instead, the energy is extracted through hydraulic fracturing of the hot rock. The EGS may be feasible anywhere globally, depending on the economic limits of drill depth. Good locations are over deep granite covered by thick (3–5 km) insulating sediments, which slow heat loss.[45,46]

e. *Marine energy*

The ocean's water movement creates a vast store of kinetic energy carried by ocean waves, tides, salinity, and ocean temperature differences, which can be harnessed to generate electricity. Commonly termed marine energy (also sometimes referred to as ocean energy), it encompasses both wave power – power from surface waves, and tidal power – obtained from the kinetic energy of large bodies of moving water.[47]

When river water flows into a sea or ocean, mixing fresh and marine water creates a spontaneous salinity gradient energy (SGE). It releases chemical energy (Gibbs free energy) associated with the solvation of salts. With an emerging reverse electrodialysis (RED) technology, the SGE can be harvested to generate electricity.[48] A RED electric cell comprises alternating cation- and anion-exchange membranes stacked between two electrodes. The compartments between the membranes are alternately fed with concentrated (i.e., sea or ocean water) and dilute (i.e., river water) saline solutions.[49] Migration of the respective counter-ions through the membranes leads to an ionic current between the electrodes, where an appropriate redox pair converts the chemical SGE into electrical energy.[49,50]

f. *Bioenergy*

Bioenergy encompasses all energy obtained by using biomass either directly via combustion to produce heat or indirectly after converting it to various forms of biofuel.[51-54] Biomass refers to biological material derived from living or dead organisms. Extracting energy by combusting fuelwood is human history's most prominent and longest biomass energy source. Biofuels include many fuels from biomass in solid, liquid, and gaseous forms. There are several methods of biomass conversion into biofuel, broadly classified into thermal, chemical, and biochemical methods. For instance, biofuels are often obtained from plants or plant-derived materials, specifically lignocellulosic biomass, starches, and sugars. Biogas is derived from rotting garbage and agricultural and animal waste, which releases methane gas. Crops, such as corn and sugarcane, can be fermented to produce the transportation fuel, ethanol. Biodiesel is made from vegetable oils, animal fats or recycled greases. Further, plant residuals can produce syngas and biodiesel through a pyrolysis process.

Bioenergy is unquestionably renewable energy, but its environmental benefits remain contentious. Biomass, biogas, and biofuels are burned to produce energy but harm the environment by releasing the combustion product, CO_2, into the atmosphere. Further, pollutants such as sulphurous oxides, nitrous oxides, and particulate matter are produced from biomass combustion. Similarly, the quest for biofuel crops has been responsible for converting some tropical forests to farming land.

(b) Climate adaptation techniques

The impacts of climate change are already evident. For example, many places are experiencing changes in rainfall patterns, resulting in more floods, droughts, heavy rain, and more frequent and severe heat waves. Similarly, wildfires have become very frequent. In addition, the planet's oceans are warming and becoming more acidic, melting ice caps and rising sea levels. As a result, technological development trends are focusing on both combating and adapting to climate change, emphasizing the following five areas of basic human and environmental needs:

i. ***Weather forecasting***
Rapidly changing weather conditions are pushing for much-needed innovation in the weather forecasting sector, requiring heavy dependence on information technology tools (i.e., satellites, software, computing, and sensors). Sensors, for instance, are needed to support the growing need for accurate environmental data, which is important for tracking changes and developing solutions to the problem.

ii. ***Innovations around infectious diseases***
Rising global temperatures have led to the increased spread of infectious diseases (e.g., malaria, dengue, tick-borne encephalitis, and Lyme diseases), an increase in the prevalence of non-communicable diseases (including cancer) and the emergence of new global pandemics. Further, higher temperatures will increase water- and food-borne diseases like Salmonella. Thus, innovations in drug development, delivery, and prevention are required.