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# GREEN CHEMISTRY

ADVANCES IN ALTERNATIVE ENERGY

*Edited by Mark Anthony Benvenuto,  
Heinz Plaumann*

GREEN CHEMICAL PROCESSING

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Mark Anthony Benvenuto, Heinz Plaumann (Eds.)

**Green Chemistry**

Green Chemical Processing

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Mark Anthony Benvenuto

**Volume 8**

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Advances in Alternative Energy

Edited by  
Mark Anthony Benvenuto  
and Heinz Plaumann

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**Editors**

Prof. Dr. Mark Anthony Benvenuto  
University of Detroit Mercy  
Department of Chemistry & Biochemistry  
4001 W. McNichols Rd.  
Detroit, MI 48221-3038  
USA  
[benvenma@udmercy.edu](mailto:benvenma@udmercy.edu)

Heinz Plaumann, Ph.D.  
QuantumQik Careers  
24374 Curtis Drive  
Brownstown, MI 48134  
USA  
[hmplaumann@gmail.com](mailto:hmplaumann@gmail.com)

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*Green Chemical Processing* is a continuing series of volumes composed of refereed chapters, with upcoming volumes having submission dates of 15 June and 15 December each year. All areas of green chemistry, pending as well as established, are considered and welcome.

If you are interested in contributing a chapter, please contact series editor Mark Benvenuto, of the University of Detroit Mercy, at: [benvenma@udmercy.edu](mailto:benvenma@udmercy.edu) concerning the appropriateness of your topic. We are interested in any and all new ideas that examine any of the twelve principles of green chemistry.

For more information on all previous and upcoming volumes of *Green Chemical Processing*, see

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## List of contributing authors

**Prof. Dr. Mark Anthony Benvenuto**

University of Detroit Mercy  
Department of Chemistry & Biochemistry  
4001 W. McNichols Rd.  
Detroit MI 48221-3038  
United States of America  
Email: benvenma@udmercy.edu

**Michael Bernard**

TFIE Strategy Inc. - Chief Strategist  
413-1088 Richards St Vancouver  
British Columbia V6B 0J8  
Canada  
Email: michael@tfie.io

**David Consiglio**

Southfield High School for the Arts and  
Technology - Chemistry  
24675 Lahser Rd Southfield Michigan 48033  
United States of America  
and  
Oakland Community College - Chemistry  
27055 Orchard Lake Rd Farmington Hills  
Michigan 48334  
United States of America  
Email: davecons@gmail.com

**Rhys Hakstol**

Lethbridge College - Environmental Sciences  
3000 College Drive S Lethbridge  
Alberta T1K 1L6  
Canada  
Email: rhys.hakstol@gmail.com

**Susan Krumdieck**

Heriot Watt University  
Edinburgh  
United Kingdom of Great Britain and Northern  
Ireland  
Email: S.Krumdieck@hw.ac.uk

**Simona Murph**

Savannah River National Laboratory  
Aiken, SC  
United States of America  
and  
Department of Physics and Astronomy  
University of Georgia  
Athens, GA  
United States of America  
Email: Simona.Murph@srnl.doe.gov

**Gholam-Abbas Nazri**

Wayne State University  
Physics Department  
Detroit Michigan  
United States of America  
and  
Wayne State University  
Department of Electrical and Computer  
Engineering  
Detroit Michigan  
United States of America  
Email: nazri@wayne.edu

**Dr. Heinz Plaumann**

University of Detroit Mercy  
Department of Chemistry & Biochemistry  
4001 W. McNichols Rd.  
Detroit MI 48221-3038  
United States of America  
Email: plaumahp@udmercy.edu

**Mosleh Uddin**

Iowa State University - Mechanical Engineering  
2611 Howe Hall Ames  
Iowa 50011-2140  
United States of America  
Email: muddin@iastate.edu

**XII** — List of contributing authors

**Joji Watanabe**

Kankyo Science

Email: [j.watanabe@kankyoscience.com](mailto:j.watanabe@kankyoscience.com)

**Mark Mba Wright**

Iowa State University - Mechanical Engineering

2611 Howe Hall Ames

Iowa 50011-2140

United States of America

Email: [markmw@iastate.edu](mailto:markmw@iastate.edu)

Mark Benvenuto\* and Heinz Plaumann

# 1 Introduction – we’ve come a long way ... and have a long way to go

**Keywords:** energy, green energy, power generation

The advent of the Industrial Revolution of the 18th and 19th centuries ushered in some of the greatest transitions in recorded human history. The invention of labor saving machines and devices such as the steam engine and electric light bulb required energy sources beyond the brute and brawn of the human. These energy requirements were in both mechanical and electrical forms [1].

Previously, much of this need was met by burning wood and animal dung, and occasionally placer coal as energy sources. Consequently, coal mining became an essential industry, since the new, emerging industries required more power than human or animal muscle power could give. Even the idea of water mills for such things as grist mills pre-dated the Industrial Revolution by centuries, but were unable to power the new machines that fueled the production of large amounts of new goods. One of the reasons the Industrial Revolution has its origins in Great Britain is that the entire nation sits atop one enormous bed of coal.

While the above might seem like nothing more than a glance at history, the need for energy and power, now mostly in the form of electricity, has continued to grow with the passage of time, and in the last two centuries grow extremely quickly. Today people take inexpensive energy for granted, often thinking seriously of it only during times of some upset, such as a power outage. But the coal that powered the Industrial Revolution still powers a great deal of our electrical grid and our industries today. Everything from the electrical power needed for an enormous commercial building to the small amount needed to re-charge a cell phone comes from only a few sources. The largest of these remains coal.

In this volume, it would be foolhardy to think that we have captured chapters on all the recent advances in the varying types of alternate energy. What is presented here is more of a survey across the broad spectrum of means by which energy is produced. Thus, we apologize for any areas in which we were not able to obtain a chapter.

For example, in parts of the world, the use of hydropower is well established as an alternative to coal (such as Scandinavia and Canada).

In addition to coal and moving water, nuclear power has become an established means of providing power to the existing electrical grids in many countries. Yet nuclear power remains a source of energy that evokes strong feelings, both pro and con, in the

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**\*Corresponding author: Mark Benvenuto**, Department of Chemistry, University of Detroit Mercy, Detroit, MI, USA, E-mail: [benvenma@udmercy.edu](mailto:benvenma@udmercy.edu)

**Heinz Plaumann**, Department of Chemistry, University of Detroit Mercy, Detroit, MI, USA

general public. Germany is shutting its remaining nuclear plants by end 2022 while France proudly claims their benefits [2, 3]. A chapter in this volume does examine the potential that could be brought into play if nuclear fusion, and not nuclear fission, were to become a major power source.

Beyond coal, water, and nuclear, wind power is in place and continues to expand, solar power is also an expanding source of electricity, and even geothermal power is significant in some areas of the world, and continues to grow. The growth of wind power has exposed another challenge – disposal of spent wind turbine blades by burying in “graveyards” [4].

We were not able to add a contribution to the volume from authors who wish to speak on all possible new and emerging power sources, unfortunately. For example, the subject of geothermal power and how green it is when compared to coal is one we must try to address in a future volume. While this absence can be frustrating, one might also consider it a mark of how carefully some segments of the power industry safeguard the steps in the techniques they use – such as geothermal power plant design. However, we do include chapters on more esoteric such as academic biodigester research [5].

On a positive note, Figure 1.1 gives an example of how completely alternate forms of power are creeping into the various aspects of our lives. This solar-powered kiosk is used to ensure parking fees in a municipal parking lot are paid. This example is



**Figure 1.1:** Solar-powered parking meter kiosk.

pertinent because the general public tends to think of solar power in terms of large fields of photovoltaic collectors all placed in open areas, as shown in Figure 1.2.



**Figure 1.2:** Field of solar-power cells.

The increasing demand for electricity means that a significant amount of coal and hydrocarbon fuel is still used in the world today. With the combustion of coal – as well as other hydrocarbon-based fuels – comes the release of carbon dioxide to the atmosphere. The scientific community is in broad agreement that the release of carbon dioxide over the past two centuries has contributed to climate change, even if the political leaders of the world continue to cast doubt on this. But whatever position a person takes on this issue, it has become obvious that energy generation cannot be separated entirely from economic and other factors. We are fortunate enough to have within this volume a chapter that discusses this in some detail.

The search for a wide variety of power sources continues and will most likely continue to expand in the near future. Coal, and its sibling fuel, oil, will probably continue to be important sources in the near future, but what are now considered alternate power sources are destined to become more widely accepted and seen. Not only will hydropower, wind, and solar remain important, but newer sources such as: tidal power, ocean thermocline, solar chimneys, and energy harvesting, will all begin to take their place in a widening array of power sources that will be needed to keep an energy-hungry world going.

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Susan Krumdieck\*

## 2 Survival is the driver for adaptation: safety engineering changed the future, security engineering prevented disasters and transition engineering navigates the pathway to the climate-safe future

**Abstract:** Consider a simple idea describing the time, space and relationship scales of survival. Engineering has been going along with the current paradigm that growth in wealth and material consumption can continue through innovation and technology development. The proposed survival continuum concept represents a new way to think about sustainability that has clear implications for influencing engineering projects in all fields. The argument for survival as the driver for adaptation is developed sequentially, building on theory, definition, examples and history. The key idea is that sustainability will be effectively addressed by a new engineering discipline furthering development of the field of safety engineering with longer time scale, broader space scale and more complex relationship scale. The implication is that the past 100-year development of safety engineering can be leveraged to fast-track the inclusion of sustainability risk management throughout the entire engineering profession. The conclusion is that a new, interdisciplinary field, Transition Engineering, is emerging as the way our society will achieve sustainability-safety through rapid reduction in fossil fuel use and reduction in detrimental social and environmental impacts of industrialization.

**Keywords:** energy transition; risk management; sustainability; transition engineering.

### 2.1 Introduction

It has been over 20 years since the Brundtland Commission [1] definition of sustainable development was put forward. In that time, this definition has not been challenged, but it has also not been practically applied in engineering practice. ‘Meeting our needs’ is rather subjective, and ‘considering the needs of future generations’ is not practically quantifiable, measurable or enforceable. One of the main problems is that neoliberal economics does not have a model for differentiation between essential, necessary and

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**\*Corresponding author:** Susan Krumdieck, School of Energy, Geoscience, Infrastructure and Society (EGIS), Energy Transition Engineering, Heriot-Watt University, Edinburgh, Scotland, UK, E-mail: S.Krumdieck@hw.ac.uk

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optional activities and uses of resources. The market and the price are the rationale for production and consumption of goods, not any kind of judgement about the essentiality for wellbeing. A range of authors and thinkers have proposed theories about the dynamics of sustainability. Anthropologist Joseph Tainter's explanation of collapse of complex societies is that socio-political complexity eventually fails to provide increased benefits compared to costs [2]. Jared Diamond proposes that societies either choose to collapse or they manage their resource and relationship situations through adapting shared cultural values in order to find some sustainable state [3].

Accounting approaches for sustainability have been proposed to include environment and society costs in the framework of conventional economics. Ecological economics is growing in popularity as a way to address the failings of growth-oriented classical economics by explaining how the world works and developing mechanisms and policies to make it work better [4]. Sustainable growth as envisioned by Hawken and the Lovins' involves recognizing the four types of capital and increasing wealth while reducing resource use via increased efficiency, productivity, new technology and profits [5]. In recent years, uptake of the United Nations Sustainable Development Goals (SDG's) amongst corporations has focused on Environment, Social and Governance (ESG) accounting and reporting, but has the practice changed the future, or is it greenwashing that perpetuates the business as usual (BAU) [6]? In 1987 when the UN Commission on Environment and Development [7] sought to outline the need for strong economic growth that is socially and environmentally sustainable, the appeal to action was aimed at citizens, organizations, educators and scientists. Although nearly all of the environmental threats identified were the result of engineered systems, the engineering profession was not mentioned. It is hard to set up requirements for engineering projects that involve the moral issues of our own needs weighed against needs of others who have no legal representation or economic participation. It is even harder for engineers to participate in socio-political decisions about collapse or complexity, let alone adopting new, non-standard economic accounting methods.

Limited evidence can be found that the philosophical, anthropological or economic arguments regarding sustainability have had a great impact on engineering education or the professional discipline. Commissioned reports and books on sustainability issues like peak oil [8] and global warming [9] hardly give mention to engineering as either a source of problems or solutions. Even in research, engineering academics incorporating sustainability into education and research are rare [10].

The Natural Step (TNS) has emerged as a project-based approach to sustainability. TNS focuses on education of people in organizations about the system conditions of sustainability. The first question in a TNS project is 'Does your organization have a definition of sustainability?' [11]. This points to the crux of the problem for engineering. The first rule of engineering is 'define the problem'. It is not a great surprise that the engineering professions have spent the past 20 years going about business as usual, including working on 'green' technologies that are perpetually 10 years away from technical and economic viability. In a few engineering fields, notably air pollution,

green chemistry and waste management, the goal to reduce environmental and health impacts of industrial pollution has seen great progress. On the whole, however, the engineering disciplines like petroleum engineering and mechanical engineering that are involved in fossil fuel production and conversion need some flash point or breakthrough ‘unified theory of sustainability’ that fits with the principles and practices already established. In engineering we apply the things we know to be true from science, for example the Laws of Thermodynamics, in order to design to meet requirements or analyze performance against objectives. If society could define sustainability for us, then we would include it in the requirements.

Consider that a simple idea can circumvent the predicament of waiting for a ‘definition of sustainability’ and disrupt BAU engineering of industrial systems and products in order to address the risks of un-sustainability. Consider the scenario where all engineering professions will take up transition engineering, in much the same way they have safety and hazards engineering over the past century. Transition engineering is emerging to achieve rapid adaptation of existing systems to reduce un-sustainability risks by combining existing change project engineering capabilities with the lessons learned from safety engineering. Transition engineering has discipline-specific practices but impact across all disciplines.

The key to achieving the breakthrough disruption of BAU is an insight: safety, security and sustainability are all part of the same type of engineering work, changing systems that fail. This work is done to satisfy the moral responsibility to society, not the politics or economics. Figure 2.1 illustrates the idea of continuity of safety, security and sustainability as different dimensions of survival. Safety engineering tracks accidents, near misses and hazards, and carries out change projects to avoid future failures. Through research and development, safety product design and operating standards workplaces, public spaces and products have become infinitely safer 100 years ago. The implications of this insight are that, just like safety, engineering in all disciplines will deliver the transitional research and adaptive changes that allow us, future generations and other species to survive our industrial success. An examination of the 100 years of Safety Engineering will demonstrate how survival depends on engineering first, then is enforced by policy and regulation, and finally economic benefits are understood. The

Dimensions	Continuum of Survival		
	Safety	Security	Sustainability
Time	Daily – Annual	Lifetimes – Generations	Continuous
Space	Immediate – Local	Territorial – Regional	Global
Relationships	Individuals - Families	Organizations - Populations	Civilizations - Species

**Figure 2.1:** The continuity of survival has dimensions across time, location and relationship scales. Survival requires successful management of risks of failures of safety, security and sustainability.

current debates around sustainability of energy systems, water and climate focus on policy and economics and have not delivered progress in reducing un-sustainability risks. The conclusion of the argument is that currently practicing engineers taking up the projects of *Transition* will be the key to survival through adaptation.

## 2.2 Insight: transition engineering is the work of sustainability safety

There is no doubt that engineered infrastructure, production and energy systems, chemicals and products are the primary source of risks to us and future generations. Policies, behavior and economics do not produce dangerous atmospheric levels of CO<sub>2</sub> – burning fossil fuel does. The insight presented in this paper came as a flash of inspiration to the author after a 30-year pursuit of sustainability via green technology R&D. The moment of inspiration is worth mention for the sheer frustration and impossibility of the situation. A round table meeting in 2007 of some 40 top academics had completed a hard day of work and had concluded that the one thing needed before progress could be made was a *definition of sustainability*. The insight from this moment was that ‘*No, you don’t!*’ You don’t have to define sustainability; it is a self-defining term like safety or security. *Statement of the Law of Survival*

Individual people, animals or plants, populations, social organizations, and species either survive or they do not.

### *Corollary to the Law of Survival*

Adaptation is the mechanism by which survival is achieved in response to change in habitat, circumstance or resource availability.

This ‘Law of Survival’ is presented as a starting point for the *Survival Spectrum* theory which puts sustainability into the engineering workflow in a similar manner to safety and security. We must start the theory development with an agreed point of truth. The theory expresses the non-negotiable nature of survival. Survival is another self-defining term. Indeed it is only achieved if its negative is not realized. Simply stated – you either survive or you do not. There is no conceivable debate about this law as there might be about the possible mechanisms of failure, such as climate change or peak oil. Survival is not a human construct like economics or politics. Survival does not have any particular means of success. Indeed, survival has as many manifestations as there have ever been individuals or species or organizations or civilizations or situations. The determination of survival depends on the identification of a particular individual, organization or civilization, their characteristics and an appropriate time scale. A system boundary must be set to define the individual, organization or civilization before applying the Law of Survival.

The Corollary might present a bit of controversy on *how* adaptations come about, whether through natural selection, divine will or conscious choice, but the fact that species and groups do adapt to fit their habitat should not be contentious. The next step in the argument is a full definition of what adaptation means. The following definition is adapted from a dictionary, so will be taken as given [12].

**Adaptation**

1. The process or state of changing to fit new circumstances or conditions, or the resulting change
2. Something that has been modified for a purpose
3. The development of physical and behavioral characteristics that allow organisms to survive and reproduce in their habitats
4. The diminishing response to a sustained stimulus

The first three definitions of adaptation are accurate descriptions of transition engineering if taken in the sense of purposeful changes in the built environment, infrastructure, technology, products, systems etc. The fourth definition is interesting because it is clearly also possible for humans to adapt to situations that are bad and getting worse. An example is the time spent in rush hour stop-and-go traffic by people in modern cities. It seems undesirable to sit in a car going nowhere, yet people adapt to doing it. In fact, technology also has adapted in this case, as one of the primary design objectives of a hybrid vehicle is to stop the engine while still operating the comfort and entertainment systems for occupied vehicles, thus reduce idling pollution during gridlock.

Change of behaviors or characteristics is how we survive when our systems are not sustainable. The classic Maya civilization of Mexico and Guatemala is often taken as an example of a civilization that was not sustainable, collapsed, and thus did not survive [13]. The classical Maya civilization (250 A.D.–900 A.D.) undertook a relatively short period of massive growth in building, agriculture and population. That particular civilization was not sustainable, it grew then collapsed. However, hundreds of thousands of individuals obviously survived throughout the whole period of decline. Indeed, Maya culture and Maya people are alive and well today, despite disease, warfare and slavery imposed by Spanish colonization from the fifteenth Century. The people of the Maya have adapted to everything from empire building and collapse to colonization to tourism.

## 2.3 Theory: survival means not failing at safety, security or sustainability

The law of survival must be applied to a specific dynamic entity, which was described as an individual, an organization or a civilization. This is because survival has three-dimensional scales of time, location and relationship as shown in Figure 2.1. Individuals

survive another day or another year if their immediate habitat and work places have a good degree of safety. Safe handling of water, food, refuse and fire has reduced the most immediate risks to health that have threatened survival for most of human history. The industrial revolution brought a vast array of new safety issues in the home, transport system and workplaces.

Human organizations and towns will survive if the supply of resources and trade goods is secure, and if they can recover from natural disasters or conflicts. Security is a longer-term survival issue, on the scale of lifetimes or generations. Security risks involve relationships with local resources and with trading partners. To some extent, international and interregional trade reduces exposure to risks of local crop failure or lack of local access to vital materials and nutrients. Infrastructure planning is a key to reducing risks of natural disasters. Diplomacy and communication reduce the risks of hostilities and war. The security scale is also appropriate for organizations like businesses and religions.

Civilizations and species survive for very long, even continuous time frames if they overcome the risks of collapse or extinction. One way this can happen is for the species to fit into their habitat successfully regardless of global changes. Sharks seem to be a good example of this in the natural world, and aboriginal Australians have had a continuous civilization for over 30,000 years. Part of the reason for the sustainability of the aborigines may have been luck of location, as Australia was not covered by ice during the past ice ages. Australia was also isolated from other humans, so the pressures for change were not present that have led to adaptation and change in other civilizations. Extermination is a sustainability risk to species and peoples that of course precludes the possibility for successful adaptation. Gradual changes in climate and global systems, both human and natural, will either drive adaptations or they will drive decline and collapse. Survival in the long term, known as sustainability, is either achieved through adaptation or it is not.

## 2.4 Definition of sustainability

In the introduction the argument was presented that sustainability is a self-defining term that is defined and measured by its negative. The reason people keep asking this question is because they do not like the answer. Sustainability is not a particular state or set of technologies or even policies. Sustainability is survival in the long term through adaptation. Resource use, energy use, agriculture, technology, values and behaviors adapt so that the civilization's activity systems fit with what is available, or they fail and are replaced by different activity systems or different civilizations. Rich countries have adopted a belief that they are not susceptible to failure because of their economic practice and their technology innovation. Transition engineering requires objective assessment of the risks being created by the politically and economically

successful engineered systems, and undertaking change projects to adapt these societies to live within the local and planetary limits.

Adaptive changes for survival represent a balance between benefit and risk. At any given time, individuals and populations have particular characteristics that are the result of cumulative historical adaptations. These characteristics include everything from language, knowledge, tradition, religion and shared cultural values to technology, infrastructure, skills, domesticated species and materials. There cannot be any adaptive change without taking some kind of risk. Industrial revolution changes created risk by changing environmental energy balance and ecosystems in unforeseen ways. Industrial history is full of these unintended consequences. The unintended consequences are usually on a different scale than the benefits. Benefits of a change or development are usually immediate and local, but the negative consequences may affect people in other regions, later generations, other species, or may accumulate over time on a global scale. Accurate modeling and communication by transition engineers who find ways to include complex systems connections in their risk-benefit analysis will be vital to the successful adaptation of our activity systems in this century. Using the different time scales in the continuum of safety, transition engineering proposes that engineering analysis, modeling and design can innovate adaptations to reduce the risks of un-sustainability by adapting man-made systems to downshift of energy and material consumption.

## 2.5 Role of engineering in survival

The role of engineering in survival has probably always been profound, particularly if you consider engineers to include anyone who applies scientific observation and testing to figure out how to do useful things. Think about the people who figured out how to preserve the food value of milk in the form of cheese, or the carbohydrates in grapes as wine. There have been countless technical and processing innovations that have increased capacity, reduced spoilage risk, increased efficiency and, it seems, inevitably increased human footprint. A large number of engineering developments of the past four hundred years have been adaptations to growth in resource extraction and use, and growth in a range of capabilities, i.e. communication, computing, medical treatment and warfare. The immediate benefits to particular businesses and consumers are obvious, but the longer-term and larger scale environmental risks and the pressures on different populations and ecosystems have led to a range of problems.

These problems of un-sustainability have been obvious for many years. The engineering professions have responded by pursuing innovation and development in clean energy and clean technologies. There have been many successful developments like emissions control on coal power plants that reduce particulates and replacement refrigerants that don't deplete stratospheric ozone. However, it is clear that even with all of the clean technology improvements conceivable, industrial society as we know it



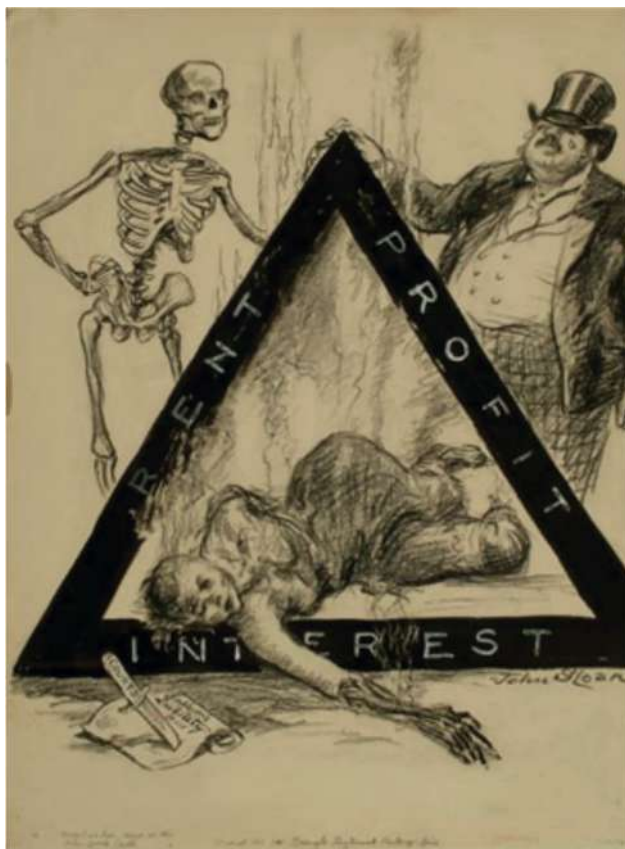
will have to change dramatically to adapt to reductions in fossil fuels consumption and depletion of material. According to the Law of Survival, the activity systems dependent on continuous growth of consumption will thus either adapt to decline of consumption or they will fail.

It seems obvious that the role of engineering in the future will involve the work of changing existing complex systems in order to adapt and survive by downshifting unsustainable energy and consumption practices. The problem definition in all fields will include *constraints* on energy and materials supply and constraints on environmental and social impacts. Engineering to constraints is not a problem when only technology considerations are involved. But because of the complex nature of the energy and material systems, behavior, politics, economics and social values are also involved. How can engineers from every discipline possibly take on projects that significantly change the way things are done when there are not direct political or market drivers? The answer is simple; it is the right thing to do and researchers will develop a methodology that works to achieve the objectives.

## 2.6 History of safety engineering

The growth of extractive and manufacturing industries by the turn of the twentieth century was generating immense profits, pollution and social problems. Safety, particularly workplace safety, was so poor that deaths and injuries were commonplace. For example, in the four years prior to 1911, worker deaths in American coalmines totaled 13,228. On March 12, 1911, the Triangle Shirtwaist Factory in New York City had a fire that cost 146 workers their lives [14]. Fires and accidents were common in factories at the time, but this tragedy became a focal point for public outrage over the state of workplace safety, and a trigger for change in the engineering profession. At the time of the fire, 27 buckets of water were the only safety measures provided to workers and there were no fire or workplace safety regulations in place. When the fire broke out, workers found most of the buckets empty. When the workers, most of whom were young women and girls, tried to escape the flames, they found the only un-locked doors opened inward, effectively being held shut by the press of people trying to escape. The ninth-floor fire escape led nowhere and collapsed when workers climbed onto it. The ladders of the municipal fire department were too short to reach the upper floors, and the water pumps could only get water to the sixth floor.

Over the course of several hours the people of New York looked on in horror as most of the young women jumped over 100 feet to the street below rather than burn to death, many of them in groups holding on to each other. Over the days following the tragedy, more than 100,000 people marched through the streets of New York City, mostly in protest, and more than twice that number lined the streets in support of the marchers. Later that year a group of mostly factory engineers founded the United Society of Casualty Inspectors with 62 members and declared that all of the deaths were



**Figure 2.2:** The Triangle Shirtwaist Factory tragedy was a catalyst for social and regulation change, but also the emergence of Safety Engineering.

preventable. In response to the public outrage over the Triangle Shirtwaist Factory Fire, the USCI set out some of the most basic fire safety regulations we now take for granted, and which were soon after adopted by New York State (Figure 2.2).

In 1914 the USCI became a national engineering organization, the present American Society of Safety Engineers (ASSE), as state after state passed the fire safety regulations. The practitioner's commitment to increasing workplace safety increased apace with public awareness and the worker's movement. In 1921 research led to the invention of eye protection goggles. In 1924 the first respirators replaced handkerchiefs in chemical factories. By 1933 safety manager training programs had grown in response to industry demand. In 1936 the first chemical exposure limit based on health hazards was set. In 1937 the industrial standards movement was underway and had moved into transportation and heavy machinery. 30 years after its founding in New York, the ASSE had well over 2000 members and was producing data sheets, training

materials, pamphlets, and posters, and many members were actually working in the insurance industry, helping companies to *avoid* workplace accidents [15].

After World War II the work of the ASSE accelerated greatly, with research into fall protection, foot protection, eye protection, hard hats, visibility, etc.; virtually all of the things that now make the total safety approach a normal part of the work environment. The ASSE has grown into an international organization, which provides specialist and general training and certification of practitioners. Even though the ASSE focuses on research and specialist training, it is also important to understand that safety is seen throughout all engineering professions as a responsibility inherent to good practice. In 2000 an OSH study found that every \$1 spent on safety saves \$4–\$6, but there is no suggestion that money is the reason for good safety practice. Rather, engineers put safety at the forefront of design and operating considerations because it is the right thing to do.

There are important lessons to be learned from the history of safety engineering.

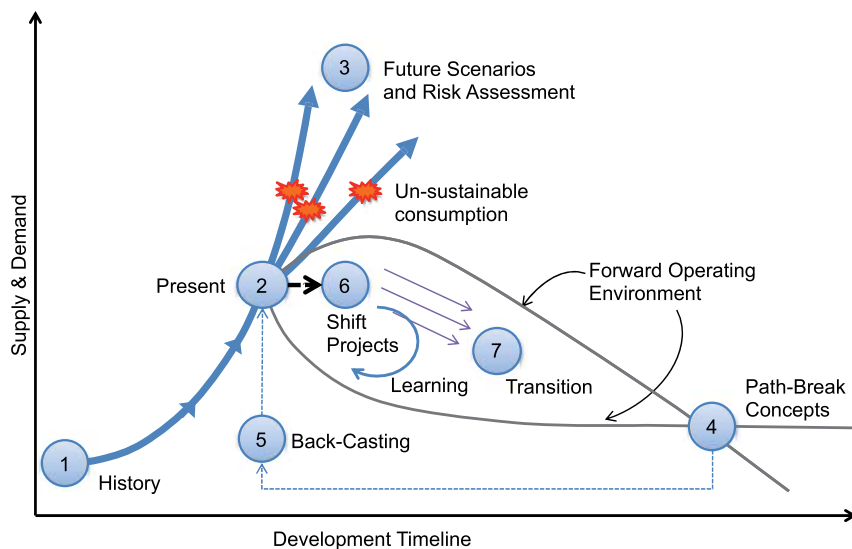
- 100 years ago there were no safety regulations and safety was appalling
- Safety engineering was born out of public outrage over a preventable tragedy
- A tenet of safety engineering is to be honest with businesses and the public about risks
- Safety changes and adaptations are not economic or market driven
- Safety innovations are developed through research and engineering
- Safety regulations came *after* safety engineering standards
- The public and businesses expect and trust engineers to address safety
- Behavior can be and is informed and managed for safety via training and signaling
- No one asks, “what do we mean by safety?”
- Engineers in all fields implement safety considerations by looking for *unsafe* elements

## 2.7 Transition engineering

Transition engineering is the research and application of state-of-the-art knowledge to bring about changes in existing engineered systems in order to improve the odds of survival [16]. These changes are largely adaptations to existing systems developed through research. Transition engineering projects are easily identified by risk analysis. Transition engineering projects focus on reducing the risks of unsustainable energy use, resource consumption, environmental impacts and social conditions.

Engineers are activated by the collective moral outrage of society when failures occur. Groups of engineering professionals and researchers respond to the un-acceptability of failure by organizing and getting to work on ways to change what is preventable. Market signals and policy directions follow transition engineering developments.

The theory of a continuum of engineering discipline to ensure survival has been set out. Safety engineering is a field of transition engineering that addresses the near-term,



**Figure 2.3:** The seven sub-projects in the Transition Engineering of Complex Systems (used with permission from Krumdieck, S., “Chapter 13. Transition Engineering”, In: *Principles of Sustainable Energy, 2nd Edition*, F. Kreith and S. Krumdieck (Eds.), CRC Press, Taylor & Francis Group, Boca Raton (2014), pp. 698–728).

immediate aspects of survival. Natural hazards engineering deals with prevention, response and resilience to rare, longer term disruptions. Environmental engineering develops ways to reduce emissions and waste, usually in response to scientific findings of the harm being caused. These engineering fields are sanctioned by public outrage when failures occur. They are also carried out and advanced continuously through research and practice because they are the right things to do. Policy and regulation then require best practice in fire safety standards, earthquake building codes or stack emissions *after* the engineering professions develop them. None of the existing fields of transition engineering are stalled waiting for the market or social signals about what safety or security mean. Indeed, part of the engineering job is using the existing scientific evidence to set limits, and then work on achieving them.

The difficulty experienced in the sustainability engineering area is that engineers, scientists, policymakers and stakeholders may be thinking about different parts of the transition engineering process, and thus often end up in communication impasse. Safety engineering is a good model again because the systems approach, working with the big picture as well as the internal processes, is effective at transitioning existing facilities and operations to better safety outcomes. Safety engineering has a straightforward methodology that has widely trained and followed in all businesses and industries [17]. Figure 2.3 illustrates the step methodology and engineering processes involved in transition engineering of complex systems. Firstly, the particular system to

be subject to transition must be defined according to the specific place and the essential needs that it meets. This problem definition places the work into the context of survival. Because the failures of unsustainable systems are on a long timescale, the first step is to study the place and the provision of the essential need through the lens of engineering, but also considering the complexity of social, economic and political context. Another novel aspect is the third step with uses engineering calculations to model the scenarios for technology solutions that are considered as options by the population in the particular location. There has recently been scholarly work done to examine some of the politically vetted scenarios and pathways for technology development to provide sustained growth, and they have highlighted the problems with ideas such as hydrogen and carbon capture and storage [18]. The other critical step is ‘time travel’ to the same place 100 years into the future where the society has not only survived but has thrived without exceeding environmental constraints and energy and material limits.

The diagram of the transition engineering processes in Figure 2.3 was first presented in conference discussions, and was the subject of more than 15 years of research into adapting transport systems to 80% lower oil use [19]. Each of the steps is clear in considering the history of safety engineering. The first steps involve auditing records, monitoring and scientific investigation to understand where safety problems arise. Scenario thinking is used to explore possible future trends identify unacceptable risks of continuing business as usual without remedial changes.

The fourth project of path-break concepts is mostly the work of research and innovation, but in the case of Safety Engineering may have also included expression of a key idea, the preventability of failures, e.g. deaths in factory fires. The trigger in the case of factory worker safety was the Triangle Shirtwaist Factory Fire tragedy. However, similar trigger events can be traced for other safety areas and security initiatives.

Back-casting points out what could have been done differently and what measures would most immediately reduce safety risks. Once on the path of preventing injury and death, the SE experience shows that progress toward a safe workplace involves many types of projects in all types of complex situations. However, we also see that the progress can be rapid and the transition remarkable when the engineering is done from a leadership position in response to social values. The final part of the transition is the enforcement of the new standards, training and equipment through policy and regulation.

## 2.8 Discussion

Transition engineering for long-term, global survival of people who live in a complex, democratic, industrial society has begun to emerge in response to realizations of environmental threats to survival as in the case of ozone depletion. A new trigger event for reducing oil consumption may have occurred on 20 April 2010 when an explosion on the

Deep Water Horizon oil platform initiated the worst environmental disaster in the history of fossil fuel production. There is no question that oil spills, flaring and groundwater pollution have been continuous and disastrous for over the past 70 years. Until this point, like factory worker deaths in 1911, these environmental disasters were the price of progress and were tolerated in the face of powerful business and political interests. Hopefully, the Deep Water Horizon oil spill is a big enough disaster, and a larger one, like a nuclear power plant melt-down, will not be required as the trigger for the initiation of transition engineering.

This paper presented several ideas and an argument. The first idea is that survival is an absolute condition defined by its failure not by any particular characteristics. Survival was explained to be accomplished by the mechanism of adaptation. This led to the description of the *Survival Spectrum* as having multiple dimensions; safety, security and sustainability, and scales; time, location and relationship. The argument was made that safety cannot be defined except by failures, and that this is true for the other dimensions of survival. A brief history of safety engineering was presented to illustrate how engineering to reduce the risks to survival due to preventable failures has developed. Importantly, it was shown how the initiation of safety engineering was in response to public outrage over a tragic factory fire in 1911, and how policy and regulation followed the engineering work. Finally, the safety history illustrates how economic or market signals are not effective or necessary signals for survival.

The conclusion of this paper is that no further time should be wasted trying to define sustainability because the *Survival Spectrum* shows how addressing un-sustainability, and in particular preventable failures, is the top-priority for transition engineering projects. The un-sustainable aspects of our current industrial civilization can be addressed by adaptation of the existing systems to reduce the un-sustainability risks through transition engineering. This argument leads to the conclusion that the critical transition engineering projects today are reducing energy and materials demands, not finding increasing supply. Further, this argument suggests that the engineering disciplines could begin working on these projects according to the same drivers as safety engineers – because it is the right thing to do. It was suggested that waiting for government leaders to find solutions or for the market to send the right signals would present a high risk of system failure, otherwise known as collapse.

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Md Mosleh Uddin and Mark Mba Wright\*

### 3 Anaerobic digestion fundamentals, challenges, and technological advances

**Abstract:** Anaerobic digestion (AD) is a natural biochemical process that converts organic materials into combustible biogas. AD has been long practiced for agricultural and urban waste management; however, this process is getting more attention as an alternative energy source nowadays. Additionally, various biogas-derived value-added chemicals and transportation fuels are turning AD into a profitable biorefinery business model. Despite its numerous potentials, AD technologies still face challenges in conversion efficiency, process stability, product quality, and economic feasibility. Researchers have been devising various mechanisms to tackle these challenges. However, a widespread adoption of commercial-scale AD is yet to be visible. The development of AD technology requires a concerted effort of scientists from different backgrounds to ensure rapid expansion.

**Keywords:** alternative energy; anaerobic digestion; biogas.

#### 3.1 Introduction


The use of biogas, the product of anaerobic digestion (AD), is known to humankind for hundreds of years. Historical evidence shows that biogas was used for bath water heating in Assyria and Persia during the 10th BC and sixteenth centuries. In the seventeenth century, Jan Baptita Van Helmont first discovered that organic matter decomposition in lakes produces combustible gas or biogas. Sir Humphry Davy first determined the presence of methane in the produced gas in 1808. In the eighteenth century, some anaerobic digestion plants were built in South Asia and slowly transferred to Europe as technology matured. However, the actual mechanism of biogas generation (from organic material decomposition) was unknown till 1930.

Like many other alternative energy technologies, World War II pushed the AD technology forward, and since then, many countries established AD plants, led mainly by European nations. For many years, AD has served as an alternative energy source. Nevertheless, its applications in agricultural and urban waste management often provide more benefits than merely energy production. Municipal wastewater treatment facilities use AD to control odor, reduce waste volume, and increase waste treatment capacity. AD turns the organic fraction of municipal solid waste (OFMSW)

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**\*Corresponding author: Mark Mba Wright**, Department of Mechanical Engineering, Iowa State University, 2611 Howe Hall, Ames, IA 50011-2140, USA, E-mail: [markmw@iastate.edu](mailto:markmw@iastate.edu)

**Md Mosleh Uddin**, Department of Mechanical Engineering, Iowa State University, Ames, IA, USA

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into biogas resulting in positive impacts on human health, the environment, and the economy. Many industries use AD digesters to manage industrial waste more efficiently with added energy incentives. Although current biogas applications focus on energy production, various biogas-derived value-added chemicals are expanding their economic and environmental potential. This chapter describes the fundamentals of AD and summarizes challenges and recent developments in AD technology and applications.

## 3.2 Anaerobic digestion

Anaerobic digestion (AD) consists of a series of biochemical reactions where bacteria break down the organic matters of any substrate into a gaseous mixture ( $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{H}_2$ ,  $\text{H}_2\text{S}$ , etc.) in the absence of free oxygen. Some groups of bacteria involved in the digestion process cannot survive in the presence of oxygen. Therefore, an anaerobic (oxygen-free) environment is necessary for the process. The AD process typically occurs in a closed vessel. Produced biogas flows out to temporary storage and later on to the end-use applications. The main commercial applications of biogas are heat and electricity generation. After AD, the vessel will contain residual solids and organic matter known as digestate. Digestate can be separated into liquid and solid streams. Both streams contain valuable plant nutrients and can substitute as fertilizer in agricultural applications.

## 3.3 Feedstock

AD can process a broad spectrum of feedstock from various sources. In principle, any biodegradable organic matter can be anaerobically digested to produce biogas. Examples of AD feedstocks from different sources are listed in Table 3.1. Feedstock for the AD should be readily biodegradable and free of any toxic components that would impact the bacteria. Some feedstock requires a pretreatment to enhance biodegradability. Multiple feedstocks can be mixed and codigested, but some feedstock combinations can degrade performance and even halt the AD process.

Livestock manure is one of the most common feedstocks employed in AD because it is readily available in agricultural farms. Despite containing many characteristics favorable for AD (neutral pH, different microbes, a wide variety of nutrients, etc.), they produce a lower amount of biogas than other feedstocks because they are already predigested by the animal intestine. However, manure is often added as a base substrate and codigested with other feedstock because of its desirable characteristics.

Feedstocks such as sewage sludge, slaughterhouse waste, OFMSW may contain harmful toxic components for the AD bacteria. These should be treated to avoid

**Table 3.1:** Common anaerobic digestion (AD) feedstocks grouped by waste category.

Category	Source
Agricultural waste	Livestock manure
	Energy crops
	Harvest remains
	Farm mortality
Industrial waste	Food/beverage processing
	Pharmaceutical industry
	Slaughterhouse waste
	Dairy product waste
Municipal waste	Agro-processing residues
	Organic fraction of MSW (OFMSW)
	Sewage sludge
	Yard trimmings
	Food waste from restaurants/cafeteria
	Supermarket waste

collapsing the AD bacteria. It is also essential to remove or minimize non-biodegradable components from the feed to use the digester volume effectively. Woody biomass or feedstock with higher lignin content are not easily digestible in the AD process and require specific pretreatments to break down the biomass structure. Codigestion of different feedstocks can improve the biogas production in AD, given that the resulting nutrients balance is optimum for the AD process. The biogas potential of various commonly used feedstocks is given in Table 3.2 [1]. The selection of proper feedstock depends on multiple factors such as availability, desired application of AD products, environmental conditions, digester technology, and economic benefits.

## 3.4 Anaerobic digestion chemistry

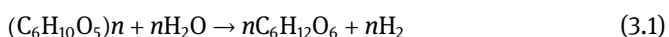
The AD process occurs through multiple steps with complex interactions between different types of microorganisms. Diverse microbial communities collaborate to break down the complex biomass polymers at different stages and turn them into a gaseous mixture. The biochemical AD reactions can be divided into four distinct stages: i) hydrolysis, ii) acidogenesis, iii) acetogenesis, and iv) methanogenesis, as shown in Figure 3.1. Specific groups of bacteria are more active than others at different stages. The products of one stage are used as the input for the later stages. Each stage is described in the following section.

**Hydrolysis:** This is essentially the first stage of the digestion process. Water and extracellular enzymes break down the complex polymeric structure of cellulose,

**Table 3.2:** Methane production potential and carbon to nitrogen ratio of different feedstocks [1].

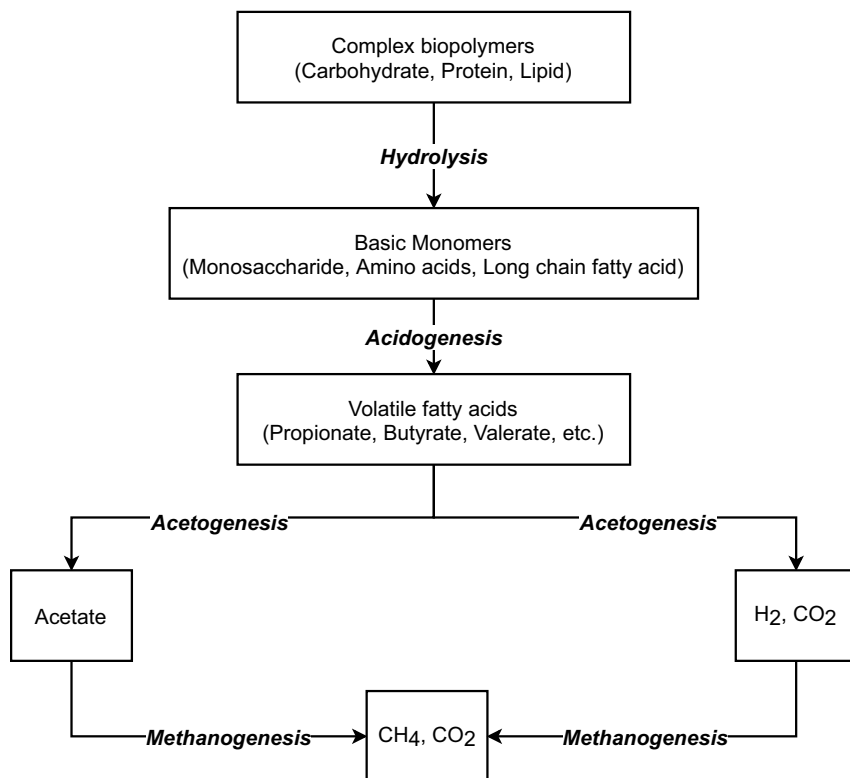
Substrate	Methane potential (mL/g VS)	C/N	Location
Food Waste	435	14.8	United States
Festulolium and Tall Fescue	393	N/A	Denmark
Dairy Manure	177	22.1	China
Chicken Manure	127	8.8	China
Wheat Straw	121	82	China
Winter Harvested Switchgrass	140	491	United States
Summer Harvested Switchgrass	205	92	United States
Chinese Maize Varieties	274	N/A	China
Cow Dung	133	24	Denmark
Sheep Manure	105	19	Denmark
Chicken Litter	105	10	Denmark
Leaves/Straw	45	56	Denmark
Food Wastes	199	14	Denmark
Pine Wood	492	N/A	Finland
Corn Leachate	107	N/A	United States
Dairy Manure	243	N/A	United States
Corn Silage	296	N/A	United States
Used Vegetable Oil	649	N/A	United States
Cheese Whey	424	N/A	United States
Plain Pasta	326	N/A	United States

starch, proteins and convert them into their respective simple units (monomers or oligomers) such as glucose, fatty acids, and amino acids. The generic hydrolysis reaction is shown in Equation (3.1),



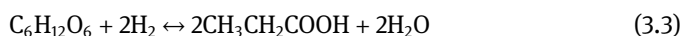
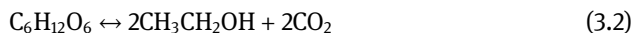
Hydrolytic enzymes generally include amylase, cellulase, lipase, protease, and pectinase. Typically, the growth rate of hydrolytic bacteria is very fast. However, for lignin-rich substrates, the breakdown of polymers turns into the rate-limiting stage. Some compounds in this stage are ready to be converted into biogas, but most compounds need further breakdown through other stages.

**Acidogenesis:** The products of hydrolysis are further broken down in the acidogenesis stage by acidogenic bacteria. Hydrolytic products are mainly transformed into short-chain volatile fatty acid (VFA) (acetic acid, propionic acid, formic acid, and lactic acid), alcohol (ethanol, methanol), and ketones (glycerol and acetone). CO<sub>2</sub>, H<sub>2</sub>, NH<sub>3</sub>, alcohols, and trace amounts of other products are also generated as byproducts. Some products, such as CO<sub>2</sub>, H<sub>2</sub>, acetate, and formats, are readily usable by the methanogens at the last stage. Other products need to be further decomposed for the methane production stage. Acidogenesis is generally a very fast process, and there is a



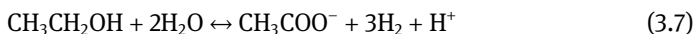
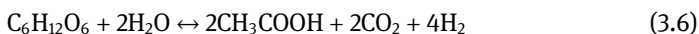
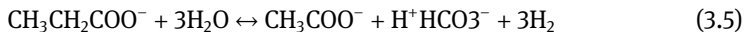
**Figure 3.1:** Anaerobic digestion (AD) biomass decomposition stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) and key compounds.

risk of VFA accumulation in the digester, resulting in digester toxicity if not properly controlled. Equations (3.2)–(3.4) illustrate the chemical reactions in the acidogenesis stage.



**Acetogenesis:** Acetogenic bacteria transforms the products of the acidogenesis stage and some of the long-chain fatty acids from the hydrolysis stage into acetate,  $\text{CO}_2$ , and  $\text{H}_2$ . Reactions in the acetogenesis stage are not thermodynamically spontaneous if the partial pressure of  $\text{H}_2$  is higher than  $10^{-4}$  atm. Nevertheless, methanogenic bacteria lower this partial pressure by consuming the produced  $\text{H}_2$ . This syntrophic relation, where some bacteria are fed from other bacteria's products, makes the acetogenesis stage thermodynamically feasible.

This interspecies  $H_2$  transfer is synonymous with electron transfer as  $H_2$  is essentially a proton ( $H^+$ ) with an additional electron. The rate of this electron transfer can significantly influence the overall digestion rate. Equations (3.5)–(3.7) illustrate the chemical reactions in the acetogenesis stage.



**Methanogenesis:** This is the final stage where methane is produced from all intermediate products of the previous stages. This stage is strictly anaerobic as the methanogenic bacteria cannot survive in the presence of oxygen.  $CH_3COOH$  (acetate) and  $H_2$  are converted into  $CO_2$  and  $CH_4$  by two different groups of bacteria, such as acetophilic and hydrogenophilic. Acetophilic bacteria convert acetate into  $CH_4$  and  $CO_2$ , while hydrogenophilic bacteria convert  $H_2$  and  $CO_2$  into  $CH_4$ . The reactions in this stage are illustrated in Equations (3.8)–(3.10).



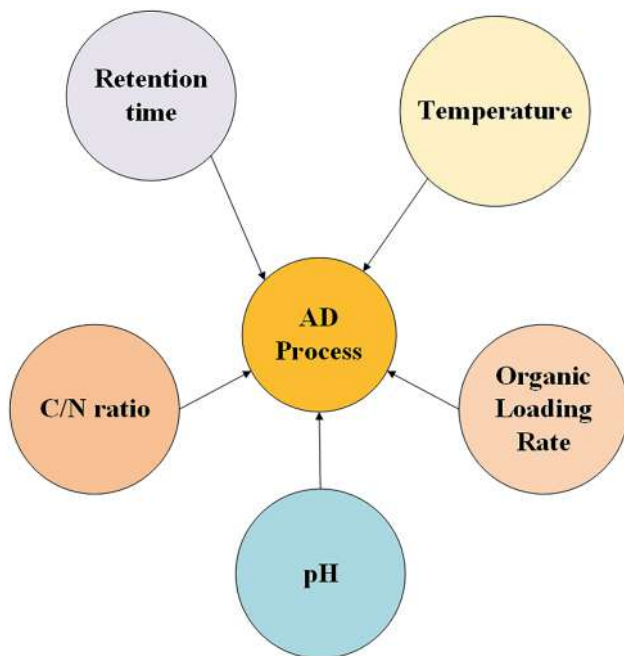
## 3.5 AD process parameters

AD bacteria are sensitive to several process conditions. Some critical process parameters are temperature, pH, organic loading rate (OLR), hydraulic retention time (HRT), C/N ratio, etc., as shown in Figure 3.2. Based on the feedstock properties and surrounding environment, optimization of these parameters controls the efficiency, and speed of the digestion process.

### 3.5.1 Temperature

Two temperature ranges are widely accepted as the most favorable temperature for the maximum performance of anaerobic bacteria. A digestion temperature ranging from 55–60 °C is defined as *thermophilic digestion*. Thermophilic digestion requires additional energy (heat) input but provides a higher biogas production rate. However, the process is often unstable. A thermophilic temperature increases the feed degradation rate leading to a shorter hydraulic retention time (HRT). It also generates a high-quality digestate with fewer pathogens.

*Mesophilic digestion* occurs within the 35–40 °C temperature range. Most of the commercial digesters operate at the mesophilic range. Mesophilic digestion produces



**Figure 3.2:** Important anaerobic digestion process parameters.

less biogas than thermophilic digestion. However, it provides a more stable operation with lower operating costs.

**Organic Loading Rate (OLR):** The OLR describes the input rate of organic material per unit volume of the digester. The OLR can be defined as,

$$\text{OLR} = \frac{Q \times \text{COD}}{V} \quad (3.11)$$

where  $Q$  is the feed flow rate in  $\text{m}^3/\text{day}$ , COD is chemical oxygen demand in ( $\text{kg COD}/\text{m}^3$ ) (a measure of organic material content in any substrate), and  $V$  is the reactor volume in  $\text{m}^3$ . The OLR depends on the substrate organic matter concentration, and the optimal rate is determined experimentally. Higher than optimal OLR can cause toxicity to the digester leading to a decrease in methanogenic activity, as discussed later. On the other hand, a lower than optimal OLR reduces biogas production.

### 3.5.2 Hydraulic Retention Time (HRT)

HRT defines the average duration that the substrate resides in the digester. Substrates should be allowed to stay in the digester for a sufficient time to ensure maximum

conversion of organic materials into biogas. However, a longer HRT requires a larger digester size, as shown in Eq. (3.12), which increases the digester's capital cost.

$$\text{Digester volume (m}^3\text{)} = \text{HRT (day)} \times \text{substrate input flow rate} \left( \frac{\text{m}^3}{\text{day}} \right) \quad (3.12)$$

### 3.5.3 Carbon/nitrogen (C/N) ratio

The substrate C/N ratio is another crucial factor for a balanced AD process. C (carbon) is the energy source for microorganisms, whereas they require a certain amount of N (nitrogen) for their growth or metabolism. The optimal C/N ratio ranges from 20 to 30 for most AD, depending on the substrate characteristics [2]. A low C/N ratio represents a higher N concentration, which will eventually turn into excess ammonia. Excess ammonia produces higher digester alkalinity and inhibits the digestion process resulting in lower biogas yield.

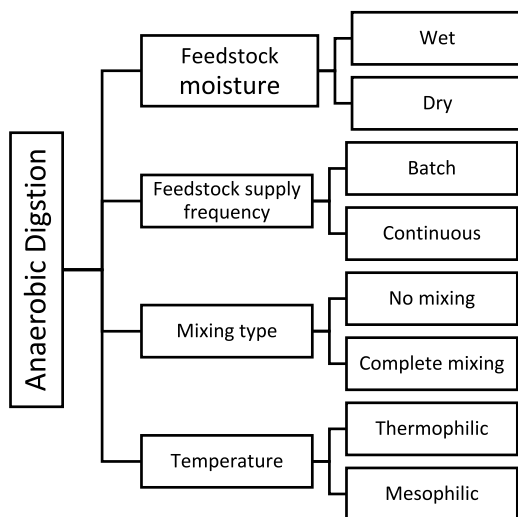
On the other hand, a high C/N ratio means a deficiency of N in the substrate. Microorganisms will readily consume the N, and not enough N will be available for their metabolism. Adding C or N-rich organic material to the substrate to achieve an optimum C/N ratio is common in the AD process.

### 3.5.4 pH

The pH defines the concentration of H (Hydrogen) in any solution. Most microorganisms prefer a neutral pH range. Methanogens are very sensitive to pH and prefer around seven for their highest performance. Hydrolytic and acidogenic bacteria perform better between pH values of 5.5 and 6.5. On the other hand, acidogenic bacteria are more tolerant to a larger pH range [3]. Maintaining an optimum pH for all microorganisms in the same digester is challenging, especially for substrates with varying compositions like sewage sludge.

## 3.6 Anaerobic digestion technologies

Anaerobic digestion occurs in a closed tank or vessel, often called a digester, to provide an oxygen-free environment. A wide varieties of AD technologies exist based on the feedstock moisture content, feeding frequency, mixing type, temperature, and other considerations. The main design parameters of AD technologies are shown in Figure 3.3.



**Figure 3.3:** Anaerobic digestion (AD) key technology design parameters.

### 3.6.1 Wet versus dry

The *wet digester* is the most common type of digester, where the feedstock moisture content is more than 85%. Feeds are mechanically stirred to prevent solid precipitation. Generally, substrates are continuously fed to the digester and removed after a specific HRT. Feedstocks with high moisture content such as sewage sludge and animal manure employ a wet digestion process due to the high energy demand required to reduce their moisture content.

*Dry digesters* are suitable for feedstock with a higher solid content (>15%). Typically, the feedstocks are stacked in a sealed tank, and hot water or slurry is spread over them to provide a specific digestion temperature. Substrates like solid animal manure, biosolids from municipal solid waste (MSW), food waste, yard trimmings, and energy crops are suitable for the dry digestion process.

### 3.6.2 Batch versus continuous

In a *batch digester*, feedstocks are added at the beginning of the process and kept covered for a specific period. The digester is emptied before adding the next batch of feedstocks. Operation and maintenance of a batch digester are simple, but the biogas production is periodic. In a *continuous digester*, feedstocks are continuously added, and biogas and digestates are removed at a similar rate. Continuous digesters constantly produce biogas with minimum digester downtime. In practice, most digesters operate as semibatch, or semicontinuous, in that they allow continuous operation but require periodic maintenance.



### 3.6.3 No-mixing versus complete mixing

Mixing of AD feedstock is vital to provide a uniform environment and avoid composition and thermal dead-spots. These are pockets where the substrate is no longer being digested and occupies unnecessary volume or even concentrates toxic compounds. Feedstocks with high moisture contents often do not require mixing. An example of a nonmixing digester is a covered lagoon. Feedstock mixing can be done in different ways, such as mechanical agitation, biogas recirculation, recirculation of digester content using a pump or nozzle. Mixing requires a complex digester design, and operating costs are higher compared to their nonmixing counterpart. However, higher biogas production can offset the increased production costs.

## 3.7 Common digester designs

There are several standard digester designs for AD. The optimal choice of digester design depends on multiple considerations, including feedstock composition, environmental temperature, and microbial requirements. Table 3.3 summarizes the key characteristics of digester designs and their advantages or disadvantages. Following is a detailed discussion of the standard digester designs.

**Table 3.3:** Properties (feedstock solid content, hydraulic retention time, and temperature) and comparison of different types of digester design.

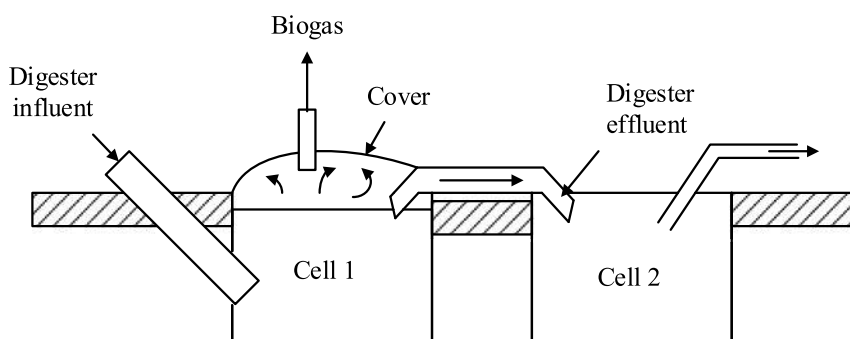
Digester type	Total solid (%)	HRT (days)	Temperature range	Advantages	Disadvantages
Covered lagoon	0.5–2	30–40	Psychrophilic	Operating cost is very low	Not suitable for colder region
Complete mix	3–10	10–25	Mesophilic/thermophilic	Suitable for different ambient conditions Can tolerate feedstock variations	Higher energy demand for mixing
Plug flow	10–15	10–25	Mesophilic/thermophilic	Operating cost is low Can digest high solid feedstock	Solids can be settled on the bottom
Fixed film	1–5	>5	Mesophilic/thermophilic	HRT is very low Digester size is smaller	Digester media can be plugged with solid content

### 3.7.1 Covered lagoon

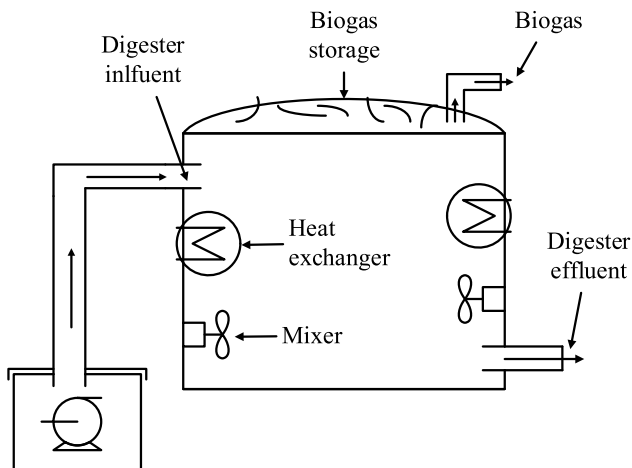
Covered lagoons are the most straightforward anaerobic digester technology where feedstocks are stored in an underground lagoon, covered with a gas-tight flexible cover, as shown in Figure 3.4. Lagoons serve simultaneously as storage and reactor. A covered lagoon sometimes consists of two connected lagoons in series. The first one (cell 1) acts as the digester for biogas production. The second one (cell 2) contains the digester effluent for further processing. These digesters are best suited for warmer regions where the ambient temperature is sufficient to provide the required digestion temperature. Feedstocks with low solid content (0.5–2%) are optimal for this type of digester due to the easy and inexpensive handling of larger volumes. The typical HRT is 30–45 days. Often, screening larger solid particles from the feedstock is necessary to prevent a crust from forming on the lagoon surface to lower the biogas production efficiency.

### 3.7.2 Complete mix

A complete mix digester is an above-ground tank made of insulated concrete or steel, as shown in Figure 3.5. A rigid or flexible cover is used to hold the produced biogas and later collect via gas collecting pipes. Heat exchangers maintain the digestion temperature, and generally, a mechanical mixing system is attached to ensure complete mixing of the feedstock. Complete mix digesters can handle non-homogeneous feedstock with higher solid content (3–10%) feedstock and are suitable for any ambient conditions. The HRT is lower than for a covered lagoon, and it typically ranges from 10 to 25 days.



**Figure 3.4:** Schematic diagram of a covered lagoon digester.



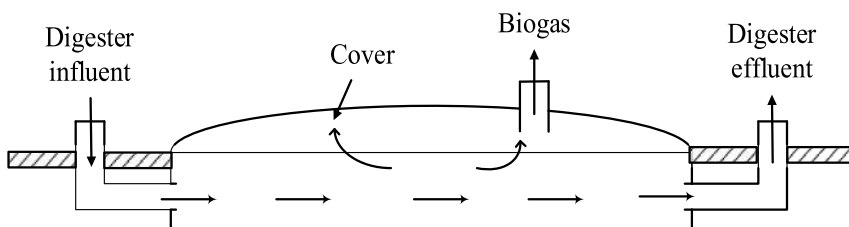
**Figure 3.5:** Schematic diagram of a completely mixed anaerobic digester.

### 3.7.3 Plug flow

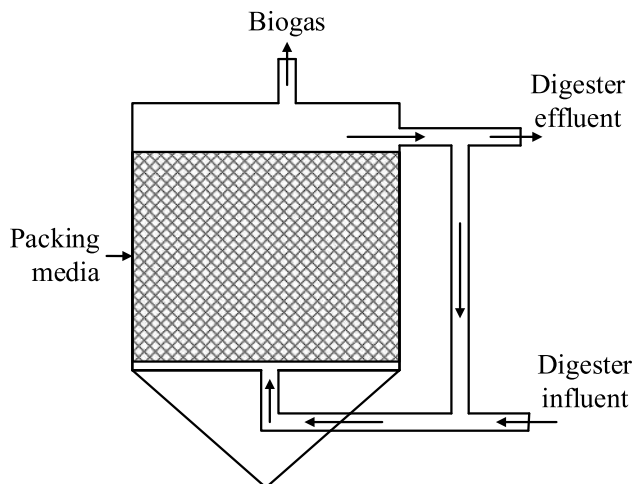
Plug flow digesters function similarly to the complete mix digester, except for the feedstock having no mechanical mixing. The plug flow digester is a horizontal, cylindrical shape reactor where feedstock enters from one end and the digestate exits from the other end, as shown in Figure 3.6. The incoming feedstock pushes out an equal amount of substrate while digestion occurs along the way. Plug flow digesters are typically in-ground and covered with a flexible cover. The feedstock solid content needs to be high (>10–15%) to ensure fluid movement through the reactor.

### 3.7.4 Fixed film digesters

This digester design supports microbial growth as a thin film on the surface, often called a biofilm. A column packed with supporting media such as a small plastic ring or wood chips is placed inside the digester, as shown in Figure 3.7. Not all substrates can be



**Figure 3.6:** Schematic diagram of plug flow anaerobic digester.



**Figure 3.7:** Schematic diagram of a fixed film anaerobic digester.

used for this type of digester as the packed column has a very narrow space for the substrate flow. The acceptable solid content for this type of digester is 1–2%; higher solids can clog the substrate flow through the digester media. A shorter HRT, typically 2–6 days, is the main characteristic of this digester type, resulting in a smaller digester volume.

### 3.8 Challenges with the AD process

Despite being a mature technology, AD still suffers from various challenges limiting its widespread application. Some of the significant challenges include feedstock variability, low process efficiency, and low product quality.

**Feedstock variability:** Ideally, any biodegradable organic material can be digested for energy production. However, the wide variability in feedstocks' physical and chemical properties is challenging for proper technology selection. Physical characteristics such as feedstock size and moisture content need to be compatible with the digester technology. Too much or too low moisture content creates difficulties in digester feeding and affects bacterial growth in the system. Cellulose, hemicellulose, and lignin-based materials such as animal manure, agricultural residues are the primary candidate feedstock. However, high lignin content reduces the biodegradability of the substrate due to its recalcitrant nature resulting in a slower hydrolysis stage.

Attaining optimal C/N ratio for the anaerobic digestion, as described before, is often challenging with many available feedstock types. Inhomogeneity within the same feedstock, such as wastewater sludge or food waste, is often responsible for

process performance fluctuation. Therefore, maintaining optimum process conditions is a major challenge to process performance.

**Low process efficiency:** As discussed previously, four different types of bacteria break down the organic materials in four stages. Each type of bacteria requires specific process conditions (such as temperature, pH, and C/N ratio) to function properly. Due to the syntrophic relations among bacteria at different stages, disruption in one stage produces cascading effects on other stages.

Higher accumulation of several intermediate products ( $\text{NH}_3$ , VFA, LCFA, etc.) during digestion is detrimental for the microbes, resulting in process inhibition.  $\text{NH}_3$  is usually produced during the digestion of nitrogen-rich substrates such as food waste, slaughterhouse waste, etc. Some amount of  $\text{NH}_3$  is necessary as nutrients of the microorganisms. However, beyond a threshold level,  $\text{NH}_3$  damages VFA consuming methanogens lowering methane production. This further creates VFA accumulation and reduced digester pH. VFA accumulation can also be caused by higher OLR. Accumulation of long-chain fatty acids (LCFA) is also inhibitory for the methanogens. LCFA can accumulate from the lipid-rich substrates during the hydrolysis stage. Higher accumulation of molecular hydrogen in the acetogenesis stage reduces the conversion of LCFA into  $\text{CH}_4$ . The combined effect of  $\text{NH}_3$ , VFA, LCFA accumulation, and pH fluctuations reduce biogas production and sometimes lead to digester failure.

**Lower product quality:** Biogas is the main product of the AD process, and it has a lower calorific value than its natural gas counterpart. The presence of more than 40%  $\text{CO}_2$  reduces the biogas-specific energy content, flame speed, and increases transportation costs. The electricity production efficiency from biogas combustion ranges from 35 to 42%. The rest is converted into heat and used for the digester heat supply. The combined heat and power (CHP) engine increase the conversion efficiency up to 80%. Nevertheless, most of the time, the produced heat dissipates to the environment without gaining any economic value.

Another AD coproduct is the unconverted substrate as digestate. Digestate is mostly used for soil application as a replacement for chemical fertilizer due to its nutrients value. The high moisture content of digestate often requires solid–liquid separation for easy transportation and storage. Nevertheless, the separation process reduces the digestate nutrient value. Managing a high volume of digestate is also challenging. Energy and cost-intensive posttreatment processes may require producing value-added products from digestate.

### 3.9 Conventional processes for overcoming challenges

A broad spectrum of techniques is available for overcoming the challenges mentioned above. Not all types of techniques are applicable for every digestion technology. The

suitable method depends on the feedstock type, digestion technology, and targeted outcomes.

Various thermal, chemical, and mechanical pretreatment methods are available to improve the hydrolysis or solubility of the digester's organic materials. Conventional heating of the substrate increases their solubility in water. It also provides a pathogen-free feed to avoid process inhibition. This is specifically useful for industrial-scale wastewater treatment. Recently, microwave irradiation is being considered as a low-energy alternative. This technique uses focused direct heat to improve the degradability of complex polymers. For lignin-rich substrate, the addition of acids or bases can improve solubility and enhance biogas production. Although energy and cost-intensive, the addition of oxidants is useful when the waste substrate mainly consists of the recalcitrant component such as lignin. Mechanical pretreatment methods such as grinding, shredding, milling, or screening are commonly used for improving digestion efficiency. This method mainly increases the molecule surface area and enhances bacterial activity during the digestion process. High-pressure homogenization (HPH) is another pretreatment technique to homogenize the substrate. Substrate cell membranes are disrupted using high pressure (30–150 MPa) induced shear.

Process inhibitions due to accumulation of harmful intermediate products and nutrients imbalance are minimized via different techniques. Optimizing OLR is a common approach to reduce VFA accumulation. Mono-digestion of any substrate is inefficient because of nutrients imbalance and lack of microorganism diversity [3]. Codigestion or adding other organic materials helps to maintain nutrient balance and avoid process inhibition. Codigestion is also applicable for ensuring optimum C/N ratio. Typically, the carbohydrate-rich substrate is added to the nitrogen-rich substrate, such as animal manure.

Additives are used in the digester for improving material conversion and biogas production. The primary role of additives is to support microbial growth, adsorption of inhibitory products, nutrient supplementation, and enhancing buffering capacity [4]. Various conductive materials such as sand, molecular sieve, zeolite, charcoal, etc., are used to improve syntrophic activity while providing habitat for microbial growth [5]. They can also adsorb inhibitory products like  $\text{NH}_3$ ,  $\text{H}_2\text{S}$  resulting in more efficient conversion. If any substrate lacks specific nutrients necessary for the digestion process, micro- and macro-nutrient supplements are added to the digester. It stimulates biogas production while maintaining process stability [6].

### 3.10 Applications of anaerobic digestion

Anaerobic digestion has attracted attention due to its diverse applications to support environmental protection and potential to create economic benefits. AD has been

considered an effective waste treatment strategy that provides a means of waste volume reduction, odor minimization, and creates multiple revenue streams.

As a waste treatment method, AD has been long used for wastewater treatment. AD helps divert a massive amount of agricultural residues and food waste from landfills or other disposal methods that are environmentally harmful. Many industries are using AD to treat wastewater, minimize the waste treatment costs, and create additional revenue sources when produced biogas is used as an energy source. Confining odor-emitting manure in the digesters is helping livestock farms to solve a critical problem. AD process destroys many environmentally harmful pathogens in the manure.

AD is considered one of the potential renewable energy sources and is in many aspects' superior to others. Turning the waste that would be anyhow generated into energy is environmentally benign and economically profitable with incentives. Biogas produced from AD can be directly used as a replacement for natural gas, although some upgrading may be necessary depending on the end-application. Various tailor-made internal combustion engines are available that are used for electricity production using raw biogas. Combined heat and power (CHP) generators are widely employed technology in many AD plants to produce heat and electricity simultaneously. In many countries, biogas-produced electricity is directly supplied to the main grid. The heat produced by CHP is mainly used within the facility; but in some places, excess heat is provided to the district heating network.

Approximately 80% of the substrate remains in the digester after the digestion process as digestate and retains most of the original nutrient values. This digestate contains nitrogen and phosphorous, which are essential nutrients for plant growth. Therefore, the most beneficial use of digestate is in direct land application as a conventional fertilizer substitute. Digestate nutrients can be separated and applied for a specific purpose. The solid portion of the digestate can be turned into fibers for animal bedding.

Another emerging application of AD is the recovery of intermediate chemicals such as volatile fatty acids (VFA). VFA is a useful substrate for biodegradable plastic production and bio-energy [7]. Upgraded biogas can be turned into many platform chemicals and fuels, valorizing the waste feedstock even more [8].

## 3.11 Advanced anaerobic digestion technologies

Most of the advancements in AD technologies are for feedstock pretreatment. Feedstock pretreatment enhances substrate digestion as well as biogas production. It reduces the retention time and allows to build small-scale digesters. Examples of advanced pretreatment methods include ultrasound, use of microbial enzymes, use of pulsating electrical fields, thermal wet oxidation process, use of vacuum, etc. [9]. Although not every method is applicable for all digester applications, combinations of more than one method have already proven effective in enhancing performance.

A critical concern for the AD process is the organic loading rate (OLR). Improper OLR leads to process inhibition and sometimes causes digester failure. Modern reactor designs focus on achieving a high and sustainable loading rate with minimum retention time. The main principle is to trap the methane-forming bacteria in the digester, unlike conventional designs, where bacteria flow with the substrate. Anaerobic sequencing batch reactor (ASBR), anaerobic filter, anaerobic fluidized bed, up-flow anaerobic sludge blanket (UASB) reactor, anaerobic baffled reactor (ABR) are some of the advanced high rate digester design concepts.

Two-staged or two-phased anaerobic digesters are becoming common design practice for better performance. As discussed before, acidogenic bacteria require different process conditions (pH, temperature) than methanogenic bacteria. In a two-staged digester, two digesters are connected in series. The first digester is designed for the acid-producing stages (hydrolysis and acidogenesis). The second digester is for the methane-producing stages (acetogenesis and methanogenesis). Each digester is separately controlled to provide the best process conditions for the respective bacterial group.

Digester disruption can occur due to poor substrate composition, accidental inclusion of toxic substrates, improper loading rate, or various other process parameters. Advanced digester technology uses a complex process monitoring system to give real-time information about the digester conditions [10]. Digester VFA concentration is an important control parameter to signal the process condition and needs to be monitored. The use of multivariate sensors and several analytical methods have made monitoring and controlling more effective.

Process instability leads to reduced biogas production and sometimes total process failure. This is a significant challenge for any commercial-scale AD plant. Lack of balanced nutrients in the substrate is often responsible for this instability due to pH fluctuations, especially in the monodigestion process [6]. Using nutrients supplements helps maintain nutrients balance in the digester. With the expanding knowledge on the biochemical reaction kinetics of AD, the list of new additives is growing.

Biochar (a carbonaceous material produced by thermal decomposition of biomass in the absence of oxygen) is an emerging additive that can increase AD performance by simultaneously counteracting multiple challenges [11]. Biochar adsorbs inhibitory elements ( $\text{NH}_3$ ,  $\text{H}_2\text{S}$ , etc.) produced during the digestion process and improves the digester buffering capacity by supplying alkaline earth metals. It also accelerates syntrophic metabolism among different groups of bacteria by acting as a Hydrogen transfer medium. Although the exact kinetics of biochar in the AD process are not fully understood, its positive influence on increasing AD performance is well documented in the literature [12]. The use of charcoal and zeolite also have similar effects on the AD system. However, more than optimum dosage is inhibitory for the AD process.



## 3.12 Conclusions

AD is an established waste management strategy with a long history. It provides a sustainable solution to conventional waste management problems such as odor minimization and greenhouse gas (GHG) reduction. Recent interest in AD is mainly due to its significant potential to turn waste into various energy products. Biogas and biogas-derived chemical products are becoming more competitive with other renewable energy sources as the technology improves. Moreover, industrial and urban waste are also becoming sources of energy and revenue due to increasing concerns around their environmental and human impacts. Public incentives to reduce waste are helping make biogas an economic natural gas substitute for transportation fuel.

Several challenges remain for the digestion of potential feedstocks. Low biodegradability, process inhibitions, and digester toxicity are still limiting the adaptation of many potential feedstocks. Although various techniques are being investigated to mitigate these challenges, economic viability is a major roadblock for their implementation. The development of AD technology requires a concerted effort of multidisciplinary research communities to continue its business scale adoption and implementation.

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Simona E. Hunyadi Murph\* and Melissa A. Murph

## 4 Nuclear fusion: the promise of endless energy

**Abstract:** This chapter introduces the reader to the fundamentals and reasoning for exploring fusion energy. Fusion, the reaction of two hydrogen atoms colliding, is the process that powers the Sun and stars. Fusion works by turning small amounts of matter into vast amounts of energy. If realized on Earth, nuclear fusion could solve global energy demands for generations to come.

**Keywords:** energy; fusion; nuclear.

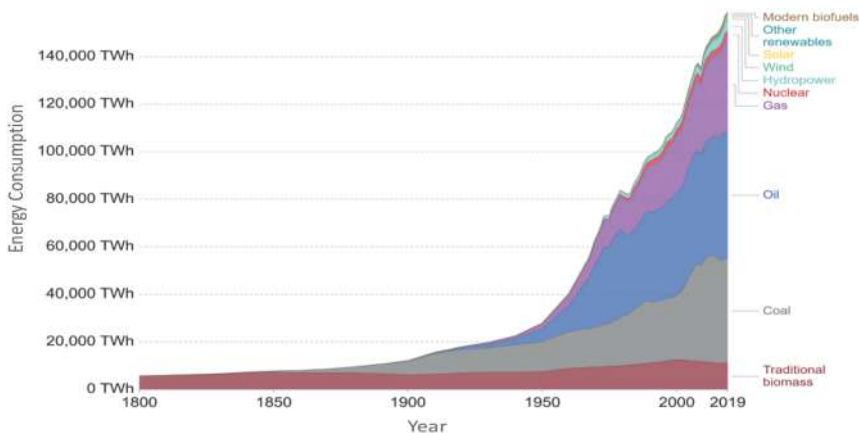
### 4.1 Introduction

Energy is essential to everyday life. It is everywhere. It is the basis of life. Energy can be found in many forms such as heat, light, motion, electrical, chemical and gravitational field. Everyday activities revolve around production and use of energy. This includes heating or cooling of buildings, driving or moving merchandise, running machines, communicating, and manufacturing of products. Every economic system of our society from the residential, transportation, commercial to industrial sectors rely on the routine consumption of energy [1]. But what is energy? Energy is the ability of a physical system to do work. According to the International Energy Agency, currently, the world's energy consumption is around 157 PW h ( $1.575 \times 10^{17}$  W h). This corresponds to an energy consumption of  $5.67 \times 10^{20}$  J or 13.54 billion tons of oil equivalent [2–4]. Global energy consumption, however, has increased steadily for decades. Yet, even though the global population has tripled in the last 100 years, the energy consumption has increased almost six times (Figure 4.1) [2–4]. A steady-state population growth coupled with an increased standard of living are attributed to the enormous amounts of energy needed to sustain society's daily activities. Moreover, with the global population projected to grow from 7.7 billion in 2019 to over 9 billion in 2040, energy demands will continue to increase at a very rapid pace. For example, it is expected that, by 2040, the global energy demand and consumption will continue to escalate in the future with projections of 20–30% increase. As economic development continues to rise, future energy supplies will be inadequate and potentially depleted. Therefore, energy security is one of the most stringent concerns of our society. For a

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\*Corresponding author: **Simona E. Hunyadi Murph**, Savannah River National Laboratory, Aiken, SC, USA; and Department of Physics and Astronomy, University of Georgia, Athens, GA, USA, E-mail: [Simona.Murph@srnl.doe.gov](mailto:Simona.Murph@srnl.doe.gov)

**Melissa A. Murph**, The University of Alabama, Tuscaloosa, AL, USA, E-mail: [mamurph@crimson.ua.edu](mailto:mamurph@crimson.ua.edu)



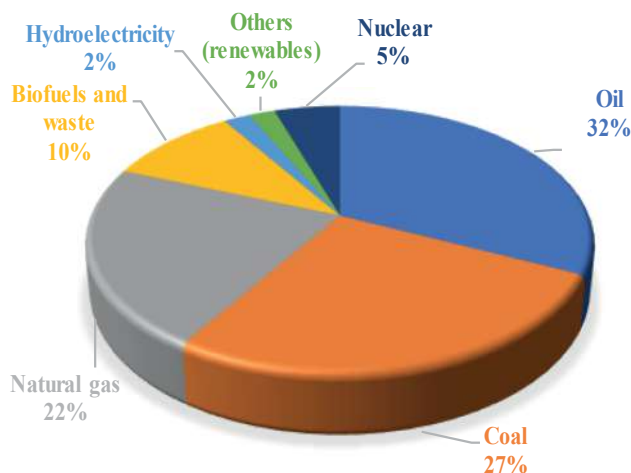
**Figure 4.1:** Global direct primary energy consumption from 1800 to 2019 by fuel type [2, 3].

sustainable and prosperous future, we must ensure continued economic prosperity and population growth. The energy security challenge relies on society's ability to continue to push the boundaries and (a) identify new energy resources, (b) efficiently harness renewable energy resources such as wind, solar, nuclear, biomass and geothermal energy, (c) enhance the efficiency and performance of current energy systems by developing energy efficient vehicles, buildings, etc., and (d) establish appropriate policies and regulations that support and promote a balanced sustainable energy future [1].

## 4.2 Current and future energy resources

Current energy resources fueling our world rely on several primary assets: fossil fuels, nuclear energy, or renewable resources. These major forms of energy have each been discussed through political debate and public policy over the past few centuries since their discovery. Arguments consider the ease of human life, the carbon footprints they leave on the Earth as well as the sustainability of our planet as a whole. Currently, fossil fuels such as oil, natural gas or coal, supply approximatively 80% of the world energy stream (Figure 4.2).

- (a) *Coal.* The fuel that launched the industrial revolution, coal, is the most abundant fossil fuel. It is one of the largest sources of electrical generation. Major coal reserves are currently found in North America, Europe and the Asia-Pacific regions, with estimates of one trillion tons of proven coal resources worldwide [5]. With the (usually) inverse relationship of cost/temporary human benefit and positive environmental effect, coal leans most heavily on the side of the former. It is one of the longest and most commonly used forms of energy, but also “the



**Figure 4.2:** Total primary energy supply.

dirtyest of all fossil fuels” and a harmful means to fulfilling the same goal. When burned, it adds carbon dioxide and gases to the atmosphere that contribute to climate change and the warming of the Earth. Scientists also consider coal-fired power plants to be “the greatest contributor to mercury pollution” with over 50% of human-caused mercury emissions [6]. Another disadvantage is the process of extraction that can be unsafe, or even deadly, for those lacking the necessary machinery and safety equipment. Its positives are its cheaper cost and abundance that continue its frequent use to this day [7]. Clean coal technologies that are less polluting have been developed over the years. The most notable clean coal technologies include coal washing, wet scrubbers, ion  $\text{NO}_x$  burners, gasification,  $\text{CO}_2$  capture and storage, among others. For example, coal washing relies on a pre-washing step that is achieved before burning. However, many complete and tedious washing steps are needed to remove dangerous minerals before they seep into the air. Other common techniques are using wet scrubbers to limit sulfur dioxide release in the atmosphere, low- $\text{NO}_x$  burners to limit nitrogen oxides emission, and electrostatic precipitators to limit particulates release. Coal Gasification technology is converting coal to other gases before it is burned [8]. Although these are all beneficial methods to reducing some of the related environmental negatives, harmful pollutants must still be released, despite the enhanced technology that exists. Carbon dioxide and coal’s burning by-product gases remain fateful enemies to nature and continue their globe-warming quest with a high carbon footprint. Most notable, however, carbon-based energy assets are limited and cannot provide the energy needed in the future. It is projected that, if the current rate of burning fossil fuel is maintained, fossil fuels will be exhausted in the next several decades [9].

- (b) *Natural gas.* Similar to coal, natural gas may emit carbon dioxide and other greenhouse gases, particularly methane, which makes up its greatest concentration (80–95%). And if you have been watching the news lately, you may have heard of the debate over fracking, the often-harmful process through which oil companies extract shale gas from the Earth. This can be one of the most dangerous and environmentally impacting techniques but employs thousands of laborers each year (1.2 million in the entire industry) and supports the economic success of our country as a whole. We see the same push-and-pull of cost versus the environment, and just as with coal's burning process, fracking is similarly harmful to our world. Aside from this, and from the harmful pollutants released, natural gas is the cleanest form of energy coming from fossil fuels and emits significantly less carbon dioxide than coal and oil [10]. With many countries continuing to use natural gas as their main form of energy, technological improvements have been made to the industry to lessen the negative effects of its extraction. These include dimensional seismic imaging through computational models and CO<sub>2</sub>-Sand fracturing that eases the Earth's recovery. Coiled tubing, as well, is a relatively simple improvement that reduces drilling space and therefore leaves a much smaller footprint on the environment. Even more recent innovations include liquefied natural gas and natural gas fuel cells, each which is growing in popularity and improving both the financial and global aspects of generating energy. Liquefied natural gas, however, only makes up "about 1% of natural gas used in the USA," so it has a significant way to go in terms of consumption and environmental impact, yet natural gas is still relatively beneficial compared with coal ("Natural Gas and Technology"). Natural gas supplies may only last an estimated 100–250 years. The largest oil reserves from Venezuela (20% of global reserves), Saudi Arabia (18% of global reserves), Canada (13% of global reserves), and Iran (9%) could soon be depleted [11].

As society and the political climate move toward a zero-net carbon economy, adoption of alternative and renewable energy resource is highly encouraged and promoted. A few favorable alternatives on the rise that promise a cleaner and greener future include solar energy, nuclear energy, and energy from wind and biofuels.

- (c) *Biofuels.* Biofuels, a mature technology that generates lower carbon emissions than fossil fuels, presently provides around 10% of the total primary energy supplies. However, it is constrained by inadequate land and water available for the crop's stewardship. Further hurdles, such as the increased costs of labor, transportation, and storage pose additional barriers toward a profitable worldwide implementation.
- (d) *Solar Energy.* In contrast to the aforementioned energy sources, coal, natural gas, and biofuels, solar power is not a fossil fuel; rather, it is clean and renewable, not directly emitting pollutants "into the atmosphere and water supply." It is one of the most environmentally friendly forms of energy, and it has no carbon footprint,

meaning it is incredibly beneficial to the Earth. Solar energy is a renewable energy resource. Despite this, consumer drawbacks exist, such as that it is costly to install solar panels and they cannot be easily moved or installed, so some choose not to have them while others' houses are not suitable for their installment [12]. These hindrances significantly limit the role of solar energy in today's world, yet solar technology continues to improve due to the work of scientists and engineers. For example, photovoltaic cells contain internal electrical fields to take in sunlight and concentrating solar-thermal power systems reflect sunlight so it can be converted into heat and stored [13]. Each is a fantastic stride toward sustainability, but solar power has yet to be as widespread – and therefore effective – on a global scale. Solar energy resources rely on the use of solar power and could play a vital role in meeting future energy demands. Nevertheless, solar energy cannot be generated throughout the entire day, as it does not produce power at night. Large scale implementation requires significant breakthroughs in increasing solar energy conversion's efficiency and storage.

- (e) *Wind and tidal.* The wind and tidal supplies are green energy resources that have zero-carbon emissions. While they could provide predictable energy outputs, unfortunately, just as solar energy resources, these are temporary solutions that are hindered by the intermittent availability. The limited land availability, however, obstructs their widespread adoption.
- (f) *Nuclear energy.* Nuclear energy promises to unravel society's energy needs dilemma. It is often considered as clean energy and provides a good alternative to the environmental challenges that exist in other energy sources. Whereas others either benefit consumers or the environment, nuclear power benefits both through its lack of emissions, creation of jobs, and ease of use for everyday people. We should mention that because nuclear energy releases zero emissions, both humans and the atmosphere benefit as “acid rain, smog, lung cancer and cardiovascular disease” lessen. It also produces much less waste than most other sources, and takes up only a small amount of land, giving it small land and carbon footprints.

Nuclear *fission* power plants generate energy, in the form of heat and power, by splitting heavy and unstable atoms. Unfortunately, the nuclear fission reactions generate unstable nuclei that are radioactive for millions of years. The chain reactions generated by splitting off heavy nuclei are also often difficult to control and stopped. The process requires the use of highly radioactive materials. It also generates substantial radioactive waste. The radioactive materials pose a risk to the environment and all living organisms for decades [14]. Efficient capture and disposal of the radioactive wastes it is not a trivial task as significant controls must be in place when handling radioactive materials [14–17]. The long half-life, toxicity, and high energy emitted from radioactive waste makes this a very challenging and complex process [14–17]. The nuclear fission energy is often received with significant public criticism due to numerous safety and

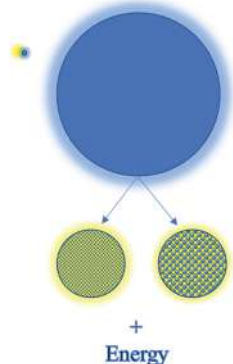
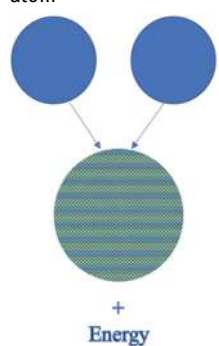


proliferation concerns. Even though the fission reactions are the most efficient sources of energy compared to the fossil fuel and/or renewable energy resources, the recent nuclear disasters, such as Chernobyl (1986) and Fukushima (2011), make it difficult for widespread implementation and support from all stakeholders such as public, government, regulators, industry, etc.

*Fusion*, however, is an environmentally friendly nuclear energy resource, however, that generates 3–4 times more energy than fission. Fusion reaction is the opposite reaction of fission. While both, fusion and fission, are nuclear reactions that generate energy from nuclei, there are however fundamental differences between these two energy-generating resources (Table 4.1). For example, in a fusion reaction, atoms fuse together while in a fission reaction, the atoms split into smaller atoms. Fusion reaction byproducts are environmentally safe, while fission reactions generate hazardous radioactive materials. Moreover, fusion reactions can be stopped immediately while the fission chain reactions, once initiated, are more difficult to terminate.

Fusion reactions power the Sun and stars. Through a *nuclear fusion reaction*, every second 600 million tons of hydrogen fuse together in the Sun, generating helium while converting matter into energy [18]. The resulting energy in the form of light and heat

**Table 4.1:** General similarities and differences between fusion and fission reactions.

Characteristics	Fission	Fusion
Reaction	Splits a large heavy atom into 2 or more smaller atoms	Fuse 2 or more light atoms into a larger atom
Reaction schematic		
Fuel	Heavy radioactive atoms such as uranium or plutonium	Light atoms such as hydrogen's isotopes (protium, deuterium and tritium)
By-products	Used nuclear fuel and other radioactive atoms	Helium
Uses	Energy	Energy – if realized on Earth
Efficiency	One million times more energy than any other energy resources, except fusion	3–4 times greater efficiency than fission

makes life possible on Earth. The Sun was born almost five billion years ago, nevertheless, it is an endless source of energy each day.

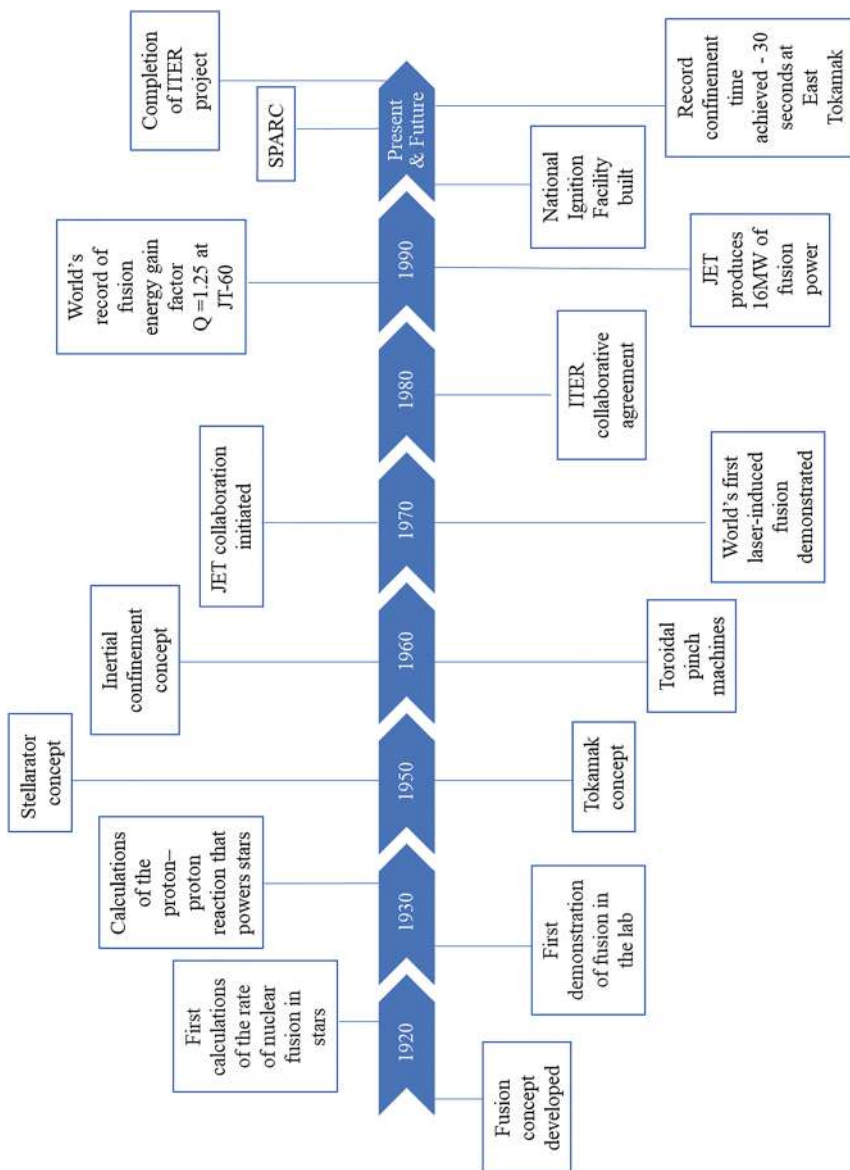
For decades the scientific community has focused on exploring ways of replicating and harnessing the energy generated by the Sun on Earth. High temperatures in excess of 100 million degrees must be achieved on Earth for fusion reactions to occur. Unfortunately, no materials on Earth can withstand these extraordinary temperatures. At this high temperature, fuel is turned into plasma. High pressures are also needed to force hydrogen atoms to fuse together. Innovative and clever solutions are needed to meet these challenges to create fusion on Earth. It is believed that fusion energy could embody the quintessential “Holy Grail” paradigm for providing a clean, environmentally friendly and abundant energy resource. If efficiently initiated, harnessed, and sustained, fusion energy could provide us with endless energy for life on Earth.

## 4.3 The history of fusion

Fusion energy could solve global energy demands for millions of years. It has been reported that the amount of energy released in nuclear fusion reactions is 10 million times greater than that of burning fossil fuels [19]. The amount of fuel needed to generate a fusion reaction is significantly smaller compared to any other energy sources, such as fossil fuels, renewable energy, or nuclear fission [20]. This is why a significant smaller amount of fuel is needed to initiate a fusion reaction. Ultimately, the energy produced from nuclear fusion reactions is capable of powering the whole humanity at a relatively low cost.

The concept of fusion was first introduced in the late 1920s (Figure 4.3), by British astrophysicist Arthur Eddington in *Internal Constitution of the Stars* [21]. With a keen interest in trying to understand how energy radiates from stars like the Sun, he suggested that energy from stars is due to the fusion of hydrogen atoms. Eddington presumed that four hydrogen atoms with an atomic mass of 1.00794 amu (atomic mass units) combine in the Sun to create helium with an atomic mass of 4.0026 amu. The difference in mass would be converted into energy, according to Einstein’s famous relation:  $E = mc^2$ , where  $E$  is energy,  $m$  is mass, and  $c$  is speed of light. This suggests that the fusion reaction from 1 kg of hydrogen would generate  $7.5 \times 10^{14}$  J of energy. This could sustain life on Earth for 10,000 years.

Not long after, Robert d’Escourt Atkinson and Fritz Houtermans provided the first mathematical calculations for the rate of nuclear fusion in stars [22]. In the late 1930s, building on Ernest Rutherford’s early nuclear transmutations discoveries, Mark Oliphant (Rutherford’s student) experimentally demonstrated a fusion reaction by producing helium-3 and tritium from heavy deuterium nuclei. This was the first time that a fusion reaction was demonstrated experimentally in the lab. Subsequently, Hans Bethe provided calculations showing a star’s energy is released through proton–proton



**Figure 4.3:** A chronologically timeline of major development in fusion. The timeline is not exhaustive as numerous other advances were made throughout the years.

reactions. In 1967, Bethe received the Nobel Prize in Physics for extraordinary contributions to the theory of nuclear reactions [23].

These advances in the foundations of theoretical and experimental concepts inspired scientists and engineers to embark on an ambitious mission to build a fusion device on Earth. Historic advances were made in this field throughout the 1950s–1960s by Soviet scientists Andrei Sakharov and Igor Tamm. They pioneered a unique magnetic confinement configuration in the shape of a hollow donut design that could confine particles at high temperatures. This novel design harnesses the energy of fusion reaction. They coined this toroidal concept – *Tokamak*. Tokamak is an acronym in Russian language for toroidal magnetic confinement. Tokamak design was a monumental achievement that still dominates fusion research efforts today. The first working Tokamak was credited to Natan Yavlinski in 1958. These early successes subsequently launched a series of prolific activities and advancements.

As scientists and engineers embarked on their most enticing journey's yet for creating the endless source of energy for the future, a series of outstanding discoveries were achieved over the next few decades. These include the developments of the (a) Sterallator which is a plasma device that uses intricate external magnets to confine plasma, (b) inertial confinement fusion which attempts to initiate the fusion reaction by heating and compressing a fuel pellet target, (c) z-pinch machines that use electrical currents in plasma to generate magnetic fields that compress it, (d) magnetic mirrors in which electromagnets are used to increase the density of magnetic field lines at the ends of confinement areas, or (e) divertors that remove heat and ash produced in fusion reactions while protecting surrounding vessels from thermal and neutronic loads, and minimizing plasma contamination.

Significant developments were subsequently made by key scientists from the United States, Russia, and multiple European countries. In the 1970s, the Joint European Torus (JET) partnership was created in which more than 40 European laboratories started working collaboratively toward achieving fusion energy.

In 1985 at the Geneva Superpower Summit, Soviet Union's leader Mikhail Gorbachev made a historic proposal to then USA. President Ronald Reagan to create an international collaborative project to develop fusion energy for peaceful purposes. This would be the largest international venture of working toward the developing of fusion energy of its kind. Engagement of the global scientific community would play a pivotal role in this success. A year later an agreement was reached, and the USA, Soviet Union, European Union, and Japan embarked on one of the most magnificent and inspiring projects in human history: designing and building the world's largest international mega-fusion facility. It was named the International Thermonuclear Experimental Reactor (ITER). There are currently 35 countries from around the world working collaboratively to build the first ITER in France.

For fusion process to be considered efficient and self-sustainable the thermal energy output must exceed input energy. The ultimate goal is to achieve fusion energy with a gain factor ( $Q$ ) of 10.  $Q$  of 1 is considered breakeven. For fusion energy to be

feasible in terms of input/output energy,  $Q$  must be greater than 1. The ITER is projected to produce 500 MW of fusion power,  $Q \geq 10$ , from 50 MW of heating input power produced from deuterium-tritium plasma. The integration of numerous parts, components, and operational technologies needed to operate a fusion power device must be demonstrated before these parameters are met. A tritium breeding module must also be established. By using a 50–50 mix of tritium and deuterium fuel, JET demonstrated a world record of  $Q = 0.67$ . A fusion energy output of 16 MW was generated from an input of 24 MW of heating [24]. This success was first demonstrated in 1997. A fusion energy gain factor of  $Q = 1.25$  was demonstrated by Japan's Torus-60 for extrapolated breakeven [25]. The extrapolated breakeven value was obtained from a mixture of protium and deuterium, not tritium. These mixtures are typically more difficult to ignite.

The National Ignition Facility (NIF), the largest laser-based inertial confinement fusion ever built, became operational in 2009. It contains powerful lasers that confine, amplify and focus hundreds of beams into a target fuel (the size of a pencil eraser) in a few billionths of a second. Two million joules of ultraviolet energy and 500 trillion watts of peak power generate high temperature and pressure (180,000,000 F and 100 atm) needed to fuse hydrogen to release energy in a controlled reaction [26]. In 2018, NIF reported 54 kJ of fusion energy power and a total fusion neutron yield of  $1.9 \times 10^{16}$ , which double the previous record [27].

Fusion research is currently at the verge of creating a “burning plasma” in which sufficient heat from a fusion reaction is retained within the plasma and able to sustain the reaction for a long duration [28]. In 2017, the Experimental Advanced Superconducting Tokamak (EAST) reported a record time of 100 s steady-state high confinement performance plasma [29]. In 2018, SPARC was formed. It was a collaborative venture between the Massachusetts Institute of Technology and a private fusion company named Commonwealth Fusion Systems. SPARC embarked on a mission to produce 50–100 MW of fusion power to achieve a  $Q$  of 2. This is based on a smaller deuterium–tritium burning tokamak device that is compact and uses a stronger superconducting magnet. If successful, SPARC will be the first experimental device to demonstrate a “burning plasma.” Completion of ITER is expected to be finalized by 2025 and generate its first plasma. Deuterium and tritium operations are anticipated to start in 2035.

## 4.4 A deep dive into the fusion energy

### 4.4.1 Why fusion?

The Sun generates energy through nuclear fusion reactions by joining together two small atoms, such as hydrogen, to form a larger nucleus. It is the simplest natural

fusion reactor. The process is driven by the Sun's mass, gravitational force, and extremely high temperatures [30]. The benefits of this nuclear reaction include:

- Fusion works by turning small amounts of matter into vast amounts of energy. The nuclear fusion reaction is a clean technology, as no harmful waste is produced.
- Its major by-product is helium gas which is inert and non-toxic.
- Fusion reactions can be controlled and stopped within seconds as high temperature plasma and the external magnetic field confinement needed for a sustainable fusion reaction can be terminated at any point. As a result fusion energy production is inherently safe.
- Its non-polluting as no greenhouse gases or carbon dioxide are being produced in the process. It is a carbon-free energy source.
- An extremely small amount of fuel, a few grams, could produce megawatts of electricity per 1000 s. For example, fusion reactions require about six orders of magnitude ( $\sim 10^6$ ) less fuel compared with chemical energy sources (coal, oil, etc.) [31].
- Enormous energy output may be generated from fusion processes, making this an extraordinary and highly sought-after energy producing solution.
- The fusion reaction is continuous, and no energy storage strategies are needed.
- With minimal proliferation risks, nominal land, and water use, fusion could be easily implemented and accepted by public environmental advocates. Fusion power plants would have a limited negative environmental impact when compared with other renewable energy resources.

#### 4.4.2 The fuel – hydrogen

Hydrogen (H), the fuel needed for a fusion reaction, is the most common and abundant element in the universe. Hydrogen is the lightest element of the periodic table. Its atomic number is 1 and the atomic mass is 1.008 amu.

Hydrogen has three (3) naturally occurring isotopes: protium, deuterium, and tritium (Figure 4.4. **Hydrogen isotopes**). All three isotopes have the same number of

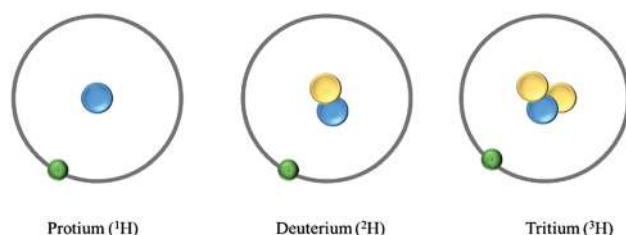


Figure 4.4: Hydrogen isotopes.

protons and electrons, but different numbers of neutrons. Protium has no neutrons, deuterium has one neutron and tritium has two neutrons. Protium (P) and deuterium (D) are both stable isotopes while tritium is not. Tritium (T), the radioactive isotope of hydrogen, has a half-life of 12.3 years, with a loss of approximately 5.5% per year. Tritium radioactively decays to helium-3. Hydrogen isotopes have been used in the medical field, nuclear energy, and defense missions [33, 34]. Deuterium can be used in fission reactors, neutron scattering, or as an isotope tracking marker in numerous chemical reactions [34]. Tritium is a critical component of nuclear weapons, fusion reactors, and self-illuminating light sources [32–35].

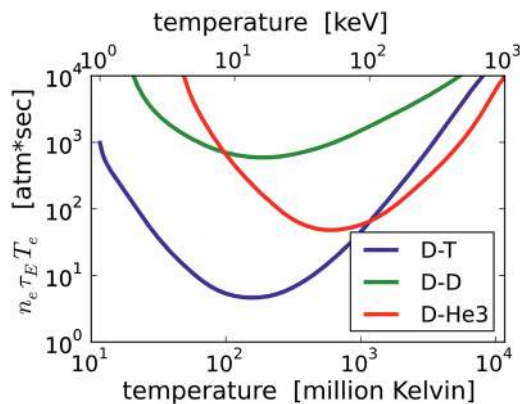
For fusion processes to be viable, an optimum energy balance must be achieved. The energy balance in these processes, such as output/input energy, determine which nuclei are the best candidates for the fusion reactions. Typically, the highest energy balance is obtained when lighter elements fuse together. Heavier elements can also be used, however. Output energy decreases as the mass of the nuclei increases. If elements heavier than iron are used, the energy balance is negative. This means the input energy is higher than the output energy.

When hydrogen nuclei fuse together during fusion reactions, a large amount of energy is released, along with byproducts such as helium and neutrons. These reactions typically produce weights that are less than the parent nuclei. The difference between the sum mass of the parent nuclei and the sum mass of the products is called the mass defect. The loss of mass in a fusion nuclear reaction is converted into energy, based on Albert Einstein's relation between energy and mass:  $E = mc^2$ . The most favorable fusion reactions include [36]:



While there are a number of potential fusion reactions, the most energetically feasible fusion reaction is between deuterium (D) and tritium (T) as the cross sections for their occurrence are high [37]. This particular fuel mixture could reach fusion conditions at lower temperatures and generate the maximum amount of energy than any other system (Figure 4.5) [38]. Moreover, the amount of energy generated per nucleon (neutron or proton) for the same mass of fuel, is significantly greater in a fusion reaction than in a fission reaction.

The deuterium fuel used in this fusion reaction is unlimited. Deuterium is abundant in nature and can be supplied from ocean waters. Approximately 33 g of deuterium could be collected from cubic meter of water. The estimated availability in Earth's ocean is  $5 \times 10^{16}$  kg which makes it accessible for billions of years.



**Figure 4.5:** The fusion triple product condition for three fusion reactions [38].

Tritium, the other fuel needed in fusion reactions, does not occur naturally and is very limited in nature. As a result, it needs to be produced or bred internally within the fusion reactor. Tritium can be easily produced from lithium. Lithium is a highly abundant metal on Earth. Tritium can be produced when lithium is being bombarded with neutrons as follows:



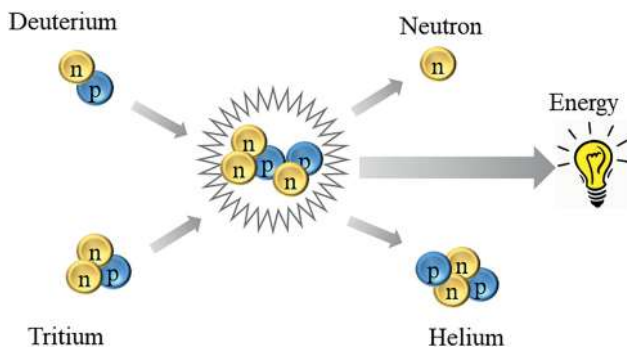
Tritium is produced in what is called a blanket region. The major functions of the blanket region are to (a) efficiently capture the neutrons and energy produced by fusion reactions, (b) transfer heat to a coolant for electricity generation, and (c) create and extract fresh tritium fuel (by utilizing nuclear transmutation reactions with lithium-containing liquid or solid materials) to enable continuous operation of the fusion energy system [39]. The process does not pose any safety or health risks, and can be used to produce necessary fuel within the containment vessel. It is important to note that the amount of tritium needed in a fusion reaction is extremely low. Current lithium reserves could supply the world's energy demands for thousands of years.

Another potentially feasible fusion reaction is based on the reactions between deuterium and helium-3 (reaction 4.6):



In this case, the output energy is highly advantageous, generating 18.3 MeV of energy. No neutrons are initially being produced in this reaction. Nevertheless, the subsequent  $\text{D} + \text{D}$  reaction does generate neutrons. Moreover, the input energy needed for the reaction to take place is higher than  $\text{D} + \text{T}$  reaction. This results in an energy balance that is less effective. The helium-3 fuel used in this reaction is also extremely rare on Earth however. Helium-3 is 100 million times more abundant on the Moon. If efficient mining strategies of helium-3 from the Moon are developed, one could see their use in fusion reactions in the future.





**Figure 4.6:** Fusion reaction between deuterium and tritium.

Ultimately the fusion reactions between D and T producing helium and a neutron are universally accepted as the ideal fusion reaction (Figure 4.6, Reaction 4.1). As expected, this still is not a trivial process as high temperatures that are 10 times higher than the temperature at the core of the Sun must be achieved for the fusion reaction to take place.

#### 4.4.3 Plasma

Fusion reactions take place at temperatures in excess of 100,000,000 K = 10 keV. Typically, at temperatures higher than 5000 K, matter becomes plasma. Once these enormous temperatures are reached, electrons are stripped from hydrogen atoms producing plasma, which is a collection of negatively charged electrons, positively charged nuclei (protons) and neutral atoms. Plasma is electrically conductive and can be manipulated, controlled and confined by electric and magnetic fields.

Ionized particles carry a charge. Electrically charged particles repel each other. For a fusion reaction to occur, these charged particles must be close enough to overcome inherent repulsive electrostatic forces. Given that both nuclei are positively charged and most likely repel each other, enormous energy and pressure are required to overcome these repulsive forces. The fusion process will depend on scientists' ability to create perfect conditions for (a) temperatures and (b) confinement for efficient collision of these charged particles. These nuclei must be confined and have a temperature over 100 million degrees for a fusion reaction to take place. The highest probability of a D-T fusion reaction can be achieved when the nuclei have kinetic energies of approximately 100 keV [40]. Once distance and temperature conditions are met, the strong nuclear force that binds quarks (protons and neutrons) together takes over, bringing the charged particles together. The particles' velocities and probability of collision increases with the temperature. The conditions needed for self-sustaining plasma are: a sufficient plasma density of  $10^{20}$  nuclei/m<sup>3</sup>, be sustained at high enough temperature

of 15–20 keV, maintaining its heat for a sufficient time (2 s), and sustained fusion plasma that follows Lawson Criterion – output energy is higher than input energy and loss [37–42].

#### 4.4.3.1 Achieving high temperatures of plasma for fusion

Fusion must occur at very high temperatures to generate plasma. The fusion reaction must be continuous and, like stars, must heat itself to millions of degrees Kelvin. Plasma heating is typically achieved when an electric current pass through a conductive plasma. The origin of this heating is due to the Joule effect, or resistive or ohmic heating. Temperatures of up to 10 million degrees can only be achieved through the Joule effect. As temperatures increase, plasma resistance decreases, limiting the efficiency of the process. Achieving and sustaining the high temperatures necessary for a steady state fusion reaction require the use of external heating processes. Two different heating strategies have been developed: high-frequency electromagnetic wave heating and neutral-beam injection heating.

High-frequency electromagnetic wave heating relies on using the unique characteristics of radiofrequency (RF) energy or microwave energy to heat plasma. This antenna-type heating approach relies on the transferring of heat to plasma via electromagnetic waves at appropriate frequencies. This is because ionized particles can sustain and support the propagation of RF energy. At resonance, when the frequency of the electromagnetic wave matches the frequency at which a nucleus rotates around a magnetic field line, energy is transferred to the nucleus. The substantial heating of plasma with RF waves was demonstrated for the first time in 1960 by Stix and collaborators in the B-65 Stellarator [41]. In 1985, the heating of a fusion reactor to relevant temperatures was first demonstrated on the Princeton Large Torus [42]. RF heating of plasma has since drawn considerable interest. Heat can be applied to specific targeted areas without affecting other nearby areas [32, 34, 43]. The use of RF energy to heat plasma is also non-intrusive, making it a preferable method.

Heating can also be achieved by the injection of a neutral beam into the plasma. The collision between these particles and plasma leads to temperature rises. Two different technologies have emerged: ion cyclotron resonance heating and electron cyclotron resonance heating. Charged particles are neutralized before introduction into the plasma. A high-intensity beam of electromagnetic radiation with a frequency of 40–55 MHz is used in the ion cyclotron resonance heating. The electron cyclotron resonance heating requires very high frequencies, tens to hundreds of gigahertz, which are generated by free-electron lasers and gyrotron tubes [44]. The electron cyclotron resonance heating system is often preferred over the ion cyclotron resonance heating as (a) it can be incorporated to generate heat at specific locations in the plasma, eliminating the instability issues that cool the plasma and (b) could be transmitted through air, simplifying the design and allowing the source to be far from the plasma simplifying maintenance.

#### 4.4.3.2 Achieving confinement of plasma for fusion energy

Temperatures in the millions of degrees are required to generate fusion energy on Earth. Unfortunately, no material can withstand these temperatures. In order to circumvent these limitations, the unique properties of plasma must be interrogated and exploited. Turbulent mixtures of ions and free electrons, plasma, must be stabilized and in a state of equilibrium. Plasma must also be confined as if its drifting to the reactor walls it cools instantly.

Plasma conducts electricity as its constituents are charged particles. Movement of ionized particles generates localized magnetic fields that can be controlled and manipulated by external magnetic fields. Two different strategies have emerged to confine and control the movement of the charged particles at extraneous temperatures: magnetic confinement (or Tokamak) and inertial laser confinement. Confinement refers to all of the conditions necessary to keep a plasma dense and hot enough to undergo fusion.

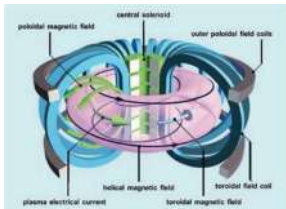
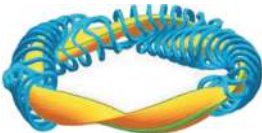
##### 4.4.3.2.1 Magnetic confinement

Magnetic confinement refers to the process in which ionized particles are confined by magnetic fields. Magnetic fields generated by induced currents can be used to confine the plasma [37]. Charged particles, when exposed to a magnetic field, are deflected by the Lorentz. These forces oblige charged particles to move into circular orbits. The gyroscopic motion of the charged particles, electrons, and ions, in the direction of the magnetic line of force, confines the particles away from the wall vessel. Speeds of approximately 1000 km/s were reported [45]. These speeds were obtained at the temperatures necessary to achieve fusion. Heat and energy are also transported along these fields. If a simple straight configuration is used, end losses are inevitable. Plasma end losses are typically eliminated by using a donut or torus design. This configuration was first introduced by Russian scientists in the 1960s. The donut shape or torus was coined the “Tokamak” configuration. This is an acronym from Russian language for “toroidal chamber with axial magnetic field.” Three different magnetic field coils efficiently confine the path of travel of charged plasma particles: the toroidal field coil, the central solenoid field coil, and the poloidal field coils. All magnetic field components are needed to confine, shape, and contain the plasma in a steady state at equilibrium [46].

Tokamak was a major achievement in the field of nuclear fusion. It has led to additional advances such as the Stellarator. Stellarator operates on the same principle as Tokamak. It is based on the use of external magnets to confine plasma [21]. This design is based on a cumbersome spiraling ribbon that is more difficult to produce (Table 4.2). Nevertheless, once operational, a steady state plasma with limited magnetic disruptions is achieved.

Magnetically confined plasmas have achieved temperatures today that are 10 times hotter than the core of our Sun at various facilities across the world. The DIII-D

**Table 4.2:** Tokamak versus Stellarator [47].

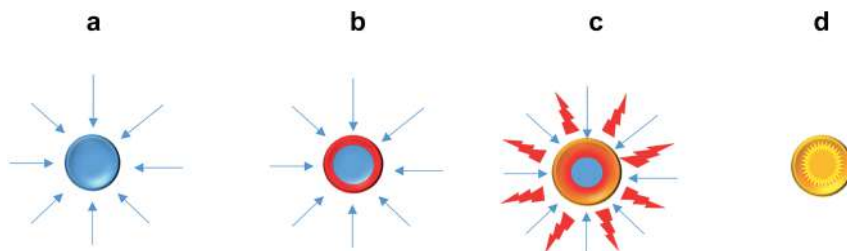
Tokamak	Stellarator
	
<ul style="list-style-type: none"> <li>– Powerful electromagnetic fields confine and heat plasma inside a tokamak;</li> <li>– A strong toroidal current is induced by a central solenoid;</li> <li>– Excellent plasma confinement;</li> <li>– Requires the continuous flow of an electric current in a donut-shaped plasma; steady-state operation require strong current drive;</li> <li>– Most advanced confinement configuration</li> </ul>	<ul style="list-style-type: none"> <li>– Complex spiraling ribbon shape design produces high-density plasma that's symmetrical and more stable than a tokamak's, allowing the reactor to run for long periods of time;</li> <li>– Weak, self-generated toroidal current;</li> <li>– Challenging geometry makes it complicated to build and extremely sensitive to imperfect conditions;</li> <li>– Requires careful optimization to ensure sufficiently good confinement properties;</li> <li>– It is inherently in steady state, and the likelihood of exciting major disruptions is much lower</li> <li>– Excellent plasma confinement to be proven</li> </ul>

National Fusion Facility, operated by General Atomics for the US Department of Energy, is one of the few facilities that uses a toroidal (donut-shaped) chamber surrounded by powerful electromagnets to confine high-temperature plasmas [48]. The National Spherical Torus Experiment Upgrade (NSTX-U) is a fusion facility built by Princeton Plasma Physics Laboratory (PPPL). It uses a tokamak design that was recently upgraded, making it the most powerful in the world.

#### 4.4.3.2.2 Inertial laser confinement

Since 1970, a radically different confinement approach was proposed – inertial laser confinement. This new strategy does not involve the use of a magnetic confinement, but extremely powerful lasers to generate fusion. It is based on the inertia generated in imploding matter. The inertial laser confinement approach uses lasers to compress and heat fuel pellets containing hydrogen and tritium at high rates to generate fusion. This process is based on four steps (Figure 4.7):

- Deliver laser energy:** Energy is delivered to the external fuel pellet's shell by high-energy laser beams;



**Figure 4.7:** Schematic of the inertial laser confinement [47].

- (b) **Plasma generation:** The outer layer of fuel is getting hot generating a plasma outer layer;
- (c) **Blow-off and fuel compression:** The heated outside shell shatters outward generating inward forces (shock-waves) that compress the fuel pellet. This process is based on Newton's third law of motion. Newton's third law states that for every action force, there is an equal and opposite reaction force.
- (d) **Ignition and fusion reaction:** If shock waves are powerful enough, the fuel pellet is compressed and heated to sufficient temperature to accomplish fusion reactions.

The amount of fuel needed to achieve fusion is extremely small. The size of a 10 mg of fuel is around the size of a pinhead, making this a highly feasible approach. The laser-plasma instabilities often hinder the required heat and densities needed for the fusion reaction. The high cost and complexity of laser drivers limits the large-scale implementation of this strategy.

The National Ignition Facility (NIF) is the most advanced facility of its kind in USA. It specifically focuses on achieving inertial confinement fusion. It has been reported that two MJ of light energy (the energy consumed by 20,000 100-W light bulbs in 1 s) can be delivered in 16 ns [49].

#### 4.4.4 Materials and fusion

*Nature* provides us with an extraordinary assortment of materials that can meet many of our demands regarding performance, cost and availability. Material scientists have also designed and created new materials with improved properties and performance. This has resulted in outstanding technological achievements and successes. Surprisingly, however, materials are still the limiting factor in many industries. Stronger and more robust materials that are virtually unaffected by stringent thermal, radioactive and chemical environments are still needed in the foreseeable future.

Development of materials for fusion energy poses new challenges as nearly all components and materials must withstand aggressive operational and experimental parameters such as radiation, high temperatures, stress, and pressures. Resilience

against high heat fluxes under steady state conditions, plasma particle fluxes, and fluxes of high-energy neutrons must be taken into consideration when designing and developing new materials. Materials must be thermally conductive, resilient regarding corrosion and fatigue damage caused by neutron resistance, or oxidation resistant during accidental air ingress. Neutron-induced effects, e.g., transmutation adding to embrittlement, hydrogen isotope retention, and changes to thermomechanical properties, are also crucial to material performance. High thermal stress and high strength or high-fracture toughness at elevated temperatures are critical parameters and challenges that require material innovation breakthroughs. The field is rich with opportunities toward developing innovative complex hierarchical composites, complex alloys, adaptive-and self-healing materials, and hybrid liquid/solid systems to incorporate in fusion reactors [50].

The most attractive materials for fusion energy applications are typically high  $z$  materials, as low  $z$  materials have low melting points and high erosion rates. Refractory metals, such as tungsten (W), tantalum (Ta), niobium (Nb), rhenium (Re), molybdenum (Mo), are explored as plasma facing materials as they have favorable properties. Tungsten and tungsten-based alloys for example have high melting points above 2000 °C. Additionally, they have high strength, high thermal conductivity, low tritium inventory, low thermal expansion, low activation, low erosion rate, and high-temperature yield strength [51]. Their recrystallization and brittle-to-ductile transition must be overcoming before successful incorporation and implementation.

There are several candidates for investigation including ferritic martensitic steel, and vanadium-based alloys. High entropy alloys such as V-Nb-Mo-Ta-W, Fe-Ni-Mn-Cr, and Ni-Co-Fe-Cr systems, and castable nanostructured alloys such as MAX-phase materials ( $\text{Ti}_3\text{SiC}_2$ ) are potential candidates [50, 52] Vanadium alloys are superior to ferritic/martensitic steels as they display greater high-temperature performance [53]. There are also reports that vanadium alloys have low activation materials that are also compatible with liquid lithium. However, production of vanadium alloys is still in its infancy.

Low  $z$  materials, such as beryllium or carbon, are also attractive due to their low sputtering yield. SiC/SiC fiber-reinforced SiC composites have been investigated as a viable first wall material due to their excellent high-temperature strength [54]. Beryllium was also explored as a candidate for the first wall. However, its low melting temperature, swelling during transient loads, and toxicity must be taken into consideration.

Carbon-based materials have been also shown promising results. Graphite, a crystalline form of carbon with a hexagonal structure, was found to increase plasma temperature dramatically due to its efficient radiation properties [55]. High-quality diamond films have been produced that have low loss and high thermal conductivity [56]. Diamond has also been suggested as an alternative to graphitic carbon as a possible divertor material [57]. Its exceptional thermal conductivity is favorable for high thermal loads and its strong bonding should decrease its susceptibility to

chemical erosion by hydrogen. Protective nano- and micro-scale coatings of diamond materials on Mo, Si, and graphite have shown successes [58].

Liquid metals have been explored as a plasma-facing interface material due to their self-healing/renewable ability to adapt to conditions in a fusion energy reactor. They can transfer heat from the system while maintaining the structural integrity of the walls and minimizing the tritium retention [59]. Lithium, gallium, and tin are the most promising plasma facing components liquid metals as this extensive research has been focused on using liquid lithium (Li) or lithium-based systems (Li-Mo, Li-Sn), in confinement devices by Russia, USA and China [60–62]. The Lithium Tokamak Experiment, for example, the only device with a full liquid Li wall, has extremely encouraging results on confinement [63]. Li pellets and Li spray in DIII-D demonstrate enhanced confinement correlated with recycling [64]. The biggest concern when handling Li is its flammability. Liquid gallium was employed for power removal as it possesses excellent heat transfer properties. While promising advances have been made in these areas, additional studies regarding tritium handling and recovery, temperature control, chemical compatibilities between systems, and materials instabilities, reliability, successful integration of systems in a safe manner must be addressed when using liquid metals technologies in the fusion power plants.

The widespread adoption of fusion energy technologies relies on scientist' ability to accelerate materials discoveries. Materials-By-Design or Materials Genome Initiative are just a few multi-agency initiatives designed to support and fund US institution in their quest to “discover, manufacture, and deploy advanced materials twice as fast, at a fraction of the cost” [65]. Scientists currently exploring production of materials-by-design for fusion energy through additive manufacturing technologies. Additive Manufacturing (AM), or 3D printing, is a unique technology in which structurally complex objects can be easily manufactured. AM methods have several advantages over traditional manufacturing techniques. AM offers “design freedom” that allows the creation of structurally complex objects that were once unbuildable. With AM, it is possible to create functional parts without the need for assembly. AM reduces the amount of generated waste and often requires a minimal use of harmful chemicals. It also eliminates the need for additional etching and cleaning steps.

## 4.5 Conclusions and outlook

If realized on Earth, nuclear fusion could solve global energy demands for generations to come. Fusion is an environmentally friendly clean energy resource that produces no greenhouse gases. Limitless amounts of fuel are available for fusion reactions. Deuterium can be extracted from oceans, while tritium can be easily bred from abundant lithium resources. Fusion reactions are fundamentally safe and can be stopped on command, eliminating the risk of uncontrollable processes.

For decades, scientists have been exploring multifaceted and comprehensive strategies for the production and development of a controlled nuclear fusion reaction in the laboratory. Achieving fusion in a laboratory setting, however, is not trivial. Fusion can only occur at extremely high temperatures (10–15 million K) making it difficult to achieve and contain. It is a very complex process that requires the use of numerous devices, technologies, materials, and interfaces. These include magnetic field coils, transformers, cooling equipment, blanket modules, divertors, vessels, beam injectors, etc. The integration of these components and an integrated operation of all technologies promises to generate 500 MW of fusion power from 50 MW of input heating power. This is to be demonstrated in the most advanced prototype – ITER – in 2035. A typical fusion power plant will need to satisfy Lawson criterion (energy output > energy input), breed tritium and collect heat to drive turbines to actually make electricity and put it on the grid. While extraordinary advances have been made in these fields to date, the energy required to make fusion work is greater than the output energy. Broad implementation of innovative technological advances is still required to realize fusion on Earth meet Lawson criterion.

The entire fusion energy and plasma science community has recently come together and developed a long-range plan for the USA to accelerate the delivery of fusion energy, and advance plasma science. This consensus vision has culminated in the creation of the Powering the Future Fusion & Plasmas Report [66]. This report was recently approved by the Fusion Energy Science Advisory Committee (FESAC) [67]. The year-long study identified new opportunities and developed guidance for prioritization including [66]:

- (a) The Fusion Science and Technology (FST) scientific community should establish the scientific and technical basis for a fusion pilot plant by 2040s. This fusion plant, if realized, will sustain a burning plasma, integrate and operate materials and technologies in extreme conditions and harness fusion power.
- (b) The Plasma Science and Technology (PST) area should advance fundamental understanding of plasma and translate those advances into applications that benefit society. These advancements would expand our understanding the Plasma Universe, strengthening of the matter/new regime foundations, and the creation of create transformative technologies.

Government and private industry from around the world have made substantial capital investments in their quests to bring fusion to fruition. These efforts must continue to accelerate progress. Public–private partnerships like ITER at the national and international level are highly encouraged as they may lead to the rapid development of a commercially viable fusion energy. Although much research is still needed in this area, once the fusion process can be efficiently replicated on Earth, it could provide limitless, clean and sustainable energy to power the world.



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Parisa Bashiri\* and Gholamabbas Nazri

## 5 Solid state lithium ion conductors for lithium batteries

**Abstract:** Lithium ion batteries will play a significant role in the future of energy generation. The need for polymer electrolytes will be critical as such batteries are developed and implemented. The use of inorganic solid electrolytes likewise will be critical in the development of this emerging technology.

**Keywords:** lithium battery; lithium ion; solid electrolytes.

### 5.1 Introduction

Solid state ion conductors have enabled emerging number of technologies including solid oxide fuel cells [1], smart windows [2], sensors [3], and solid state batteries for electric vehicles [4]. Ionic conduction in solids takes place by ion transport through solid framework. Solid state ion conductors can be in forms of crystalline, amorphous or polymeric structures. Each category includes different families which are briefly discussed later in this chapter. The ion motion mechanism and hence ionic conductivity and diffusivity are dependent on material structure and composition. Despite of the rigid skeleton of solid conductors, some has ionic conductivity as high as liquid electrolytes. Various attempts have been conducted to tune the structure-composition and charge carrier's density to optimize the ionic conductivity of solid electrolytes. In this chapter, we have briefly reviewed the ion conduction mechanism in solid electrolytes.

### 5.2 Polymer electrolytes

In 1973, Fenton and coworkers showed that polymer-Li salt complexation shows ionic conductivity properties [5]. This study and many others have become the initial realization to use polymer salt complexes as solid electrolytes. There are several advantages of using polymer electrolytes over liquid electrolytes such as: excellent flexibility, resistance against electrodes volume changes during charge/discharge, ease of processing, improved safety, etc. [2]. Yet there are some key requirements for polymer-Li salt complex to be used as electrolyte in Li ion batteries, which are listed as:

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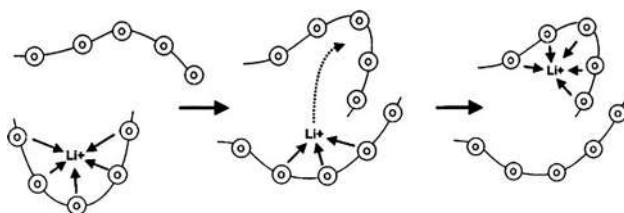
**\*Corresponding author: Parisa Bashiri**, Physics Department, Wayne State University, Detroit, MI, USA, E-mail: [nazri@wayne.edu](mailto:nazri@wayne.edu)

**Gholamabbas Nazri**, Physics Department, Wayne State University, Detroit, MI, USA; and Department of Electrical and Computer Engineering, Wayne State University, Detroit, MI, USA

- High ionic conductivity
- High  $\text{Li}^+$  transference number
- Mechanical integrity
- Wide electrochemical stability window
- Improved chemical and thermal stability.

The ability of the polymers to dissolve alkali metal salts is the crucial factor to choose the right category of polymers for this specific application. Polymers with polar groups, such as  $-\text{O}-$ ,  $-\text{S}-$ ,  $-\text{N}-$ ,  $-\text{P}-$ ,  $=\text{O}$ ,  $\text{C}=\text{O}$ ,  $\text{C}=\text{N}$ , are able to dissolve salts [6, 7]. Dissociation of inorganic salts in polymer matrix is easier in polymers with high dielectric constant and when salts have low lattice energy such as  $\text{LiClO}_4$ ,  $\text{LiPF}_6$ ,  $\text{LiBF}_6$ ,  $\text{LiCF}_3\text{SO}_3$ , etc. [8–10]. In solid polymer electrolytes, the  $\text{Li}$  ions are located at coordination sites near polar group of the polymer chains (e.g.  $-\text{O}-$  in polyethylene oxide, PEO). When the polymer chain undergoes segmental motions ( $T > T_g$ ), free volume will be created.  $\text{Li}$  ions then migrate from one site to another along the polymer chain (intrachain) or hop between chains through free volume (interchain). Thus, the amorphous regions of the polymer which contains less ordered structure and more flexible to accommodate ion transfer are responsible for ion conduction [20] (Figure 5.1).

PEO is the most propitious solid solvent for  $\text{Li}$  salts due to its strong ethylene oxygen donor group which makes PEO a special solvate for  $\text{Li}$  metal salts. However, The ionic conductivity of PEO – based membranes vary from  $10^{-8}$  to  $10^{-6} \text{ S cm}^{-1}$  at room temperature; below its melting point ( $\sim 60^\circ \text{C}$ ) due to the coexistence of crystalline domains and amorphous regions which prevent the use of PEO as practical polymer electrolyte [11, 12]. Several approaches have been attempted in order to improve the ionic conductivity of polymer-salt complexes, for example; adding lower molecular weight polymers (plasticizers) such as dimethyl carbonate (DMC), ethylene carbonate (EC), poly-ethylene glycol (PEG) which improve mobility of polymer chains and provide free volume for ion transfer inside the polymeric structure which results in enhanced ionic conductivity [13, 14]. Another method which has been used to polymer-salt complex is the inclusion of small amount of oxide nanoparticles as fillers such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SnO}_2$ ,  $\text{ZnO}$  etc. [15–18].  $\text{Al}_2\text{O}_3$  nanoparticles as fillers have also been shown to suppress dendrite growth in composite polymer electrolyte films [19]. Although the



**Figure 5.1:** Li ion conduction mechanism in polymer–salt matrix [20]

addition of plasticizers and nanoparticles can improve ionic conductivity by enhancing the amorphous regions of polymer, the main drawback of these electrolytes is their low mechanical and thermal integrity. This has led to the development of a new category of inorganic solid electrolytes containing Li-ions.

## 5.2.1 Ionic conduction mechanism in polymer electrolytes

Polymer electrolytes are formed by dissolving low lattice energy alkali salts in polymer matrix. Polymers with highly electron donor polar head group can dissolve alkali salts by attracting cations through electrostatic force. The cations can transfer from one site to another when subjected to the electric field. The transport of cations through polymer matrix takes place when the cations move between nearby coordinating sites. It is reported that, cations that are connected to the functional group move by recoordination through polymer backbone [20]. There are also reports that polymer chains form cylindrical channel which provides pathways for cation to coordinate with polar groups [21]. Polymeric electrolyte structure contains both crystalline and amorphous regions. The crystalline structure is mainly responsible for the low ionic conductivity in polymeric systems which delays the application of polymer electrolytes in current energy storage technology. There are two models that are proposed to understand the crystalline and amorphous nature of polymer electrolytes which are based on the behavior of conductivity versus  $1000/T$ : the Arrhenius model and the Vogel–Tamman–Fulcher (VTF model). More promising polymeric electrolytes are based on polymers with flexible backbone and side chains with polar anionic end group. This class of polymers can be designed for facile side chain movement and low coulombic interactions of the polar end groups with lithium ions. Among these polymers the poly[(oxyethylene)8methacrylate]diamine and derivatives of polyphosphazene with various side chains provide high ionic conductivity and low glass transition [22, 23].

### 5.2.1.1 Arrhenius behavior

The well-known Arrhenius model describes the fact that the motion of cations is independent of the motion of polymer chain. Therefore, the transport of cations can be associated with that motion of cations in crystals where the ion jumps from one site to another.

This behavior can be described by:

$$\sigma_{dc}(T) = \sigma_0 \exp\left(\frac{-E_a}{RT}\right)$$

where  $\sigma_0$ ,  $E_a$  and  $k_B$  are preexponential factor, activation energy and Boltzmann constant.

### 5.2.1.2 Voget–Tammann–Fulcher (VTF) behavior

Another model which is used to describe ionic conduction in polymeric systems is Voget–Tammann–Fulcher (VTF) which presents the strong interrelation between conductivity and polymer segmental motion. The nonlinear behavior of ionic conductivity versus invers temperatures comes from the fact that the ion transport is assisted by the polymer chain motion. VTF behavior can is described by:

$$\sigma(T) = AT^{-1/2} \exp\left(\frac{-B}{k_B(T - T_0)}\right)$$

where,  $A$  is the preexponential factor,  $k_B$  is the Boltzmann constant,  $B$  is the pseudo-activation energy and  $T_0$  ( $T_0 = T_g - 50\text{K}$ ) is the temperature corresponding to zero configurational entropy.

## 5.3 Inorganic solid electrolytes

Inorganic solid electrolytes have the advantages of simple design, wide potential stability window and resistance to shock, vibrations, temperature, and pressure variations. Different classes of inorganic solid electrolytes have been studied in detail such as perovskite, LISICON (lithium super ionic conductor), LIPON (lithium phosphorous oxynitride), garnet type, and many more. A brief review on some of these inorganic compounds is presented below.

### 5.3.1 Perovskite

The first perovskite structure solid electrolyte was introduced by Inaguma as  $\text{Li}_{3-x}\text{La}_2/3\text{-xTiO}_3$  (LLTO) with bulk ionic conductivity as high as  $1 \times 10^{-3} \text{ S cm}^{-1}$  [24]. The main problem with LLTO is instability against potentials bellow 1.8 V versus  $\text{Li}/\text{Li}^+$  due to  $\text{Ti}^{4+}$  reduction at low voltages [25]. This issue has been resolved in different studies such as partial substitution of  $\text{Ti}^{4+}$  by  $\text{Zr}^{4+}$ ,  $\text{Sn}^{4+}$ , and  $\text{Zn}^{4+}$  [26–28]. However, the doped perovskites show lower ionic conductivity, e.g. in  $\text{Li Sr}_{1.65}\text{Zr}_{1.3}\text{Ta}_{1.7}\text{O}_9$  (LSZT) the ionic conductivity is  $1.3 \times 10^{-5} \text{ S cm}^{-1}$  at  $30^\circ\text{C}$  [29].

### 5.3.2 LISICON

LISICON is an acronym for lithium super ionic conductor.  $\text{Li}_{14}\text{Zn}(\text{GeO}_4)_4$  as the first LISICON structure solid electrolyte with high ionic conductivity of  $1.25 \times 10^{-1} \text{ S cm}^{-1}$  at  $300^\circ\text{C}$  [30]. More studies have reported conductivity of  $2 \times 10^{-6} \text{ S cm}^{-1}$  at  $50^\circ\text{C}$  and  $1.3 \times 10^{-6} \text{ S cm}^{-1}$  at  $33^\circ\text{C}$  [31, 32]. Other examples of LISICON – type solid electrolytes such

as  $\text{Li}_{3.5}\text{Ge}_{0.5}\text{VO}_4$  and  $\text{Li}_{3.6}\text{Ge}_{0.6}\text{V}_{0.4}\text{O}_4$  have been prepared and showed ionic conductivity of  $4 \times 10^{-5} \text{ S cm}^{-1}$  and  $\sim 10^{-5} \text{ S cm}^{-1}$  at  $18^\circ\text{C}$  [33]. The ionic conductivity of LISICON-type solid electrolytes is very low to be practically used in solid state lithium ion batteries.

### 5.3.3 LIPON

LIPON type electrolytes are lithium phosphorous oxynitride compounds. The first LIPON was synthesized by radio frequency magneto sputtering using  $\text{Li}_3\text{PO}_4$  as target in  $\text{N}_2$  atmosphere which showed ionic conductivity of  $2 \times 10^{-6} \text{ S cm}^{-1}$  at  $25^\circ\text{C}$  [34, 35]. LIPONs' low ionic conductivity hinders practical use in bulk all solid-state batteries.

### 5.3.4 Garnet

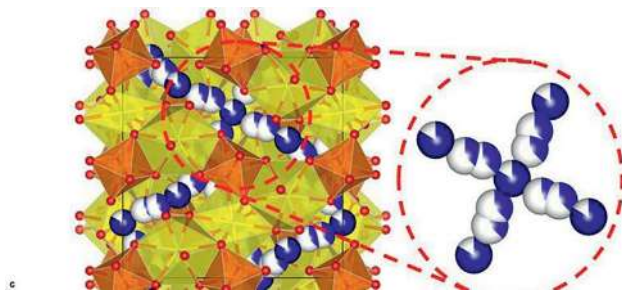
Different classes of solid-state compounds and their examples have been briefly introduced above. However, they are far from being applicable in lithium ion batteries due to their low ionic conductivity at room temperature which is affected by high grain boundary resistance. Garnet structure compounds exhibit general formula of  $\text{A}_3\text{B}_2\text{C}_3\text{O}_{12}$  where (A = Ca, Mg, Y, La or rare earth elements; B = Al, Fe, Ge, Ga, Mn, Ni and C = Si, Ge, Al) and are arranged in fcc centered cubic [36]. The first garnet like structure Li ion conductor was investigated in 2003 by Weppner et al. [37] as  $\text{Li}_5\text{La}_3\text{M}_2\text{O}_{12}$  (M = Nb, Ta) and its bulk ionic conductivity was reported as  $\sim 10^{-6} \text{ S cm}^{-1}$  at  $25^\circ\text{C}$ . Among all the garnet like materials which are Li – rich and potential as solid electrolytes,  $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$  (LLZO) has exhibited the highest total ionic conductivity at room temperature ( $2.2 \times 10^{-4} \text{ S cm}^{-1}$  at  $25^\circ\text{C}$ ) [38].

### 5.3.5 Li-rich garnet like structure: $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ (LLZO)

Weppner et al. [39, 40] synthesized Li-rich compound garnet structure LLZO in cubic structure using solid state reaction for the first time in 2007. LLZO has been characterized in two different structures as tetragonal ( $a = 13.077 \text{ \AA}$  and  $c = 12.715 \text{ \AA}$ ) and cubic ( $a = 13.002 \text{ \AA}$ ) with  $I4_1/acd$  and  $Ia_3D$  space groups, respectively [42–44]. In LLZO, isotropic edge sharing  $\text{ZrO}_6$  octahedra and  $\text{LaO}_8$  dodecahedra create framework in which the tetrahedral ( $24d$ ) and distorted octahedral sites ( $48g$  or  $96h$ ) of Li ions and Li ion vacancies percolate as shown in [43, 44] (Figure 5.2).

Several parameters can have crucial effects on structure of LLZO such as sintering temperature and time, Li content, and contaminants. The LLZO in cubic structure usually forms at high temperatures and it seems that it is stabilized by small amount of Al due to using alumina crucible at temperatures  $>1200^\circ\text{C}$  [45, 46]. According to Sakamoto et al. [51], the optimized amount of Al and excess Li in order to stabilize cubic phase is 0.24 and 6.24 mol, respectively which are hot pressed under Ar flow at  $1000^\circ\text{C}$  for 1 h. It has been





**Figure 5.2:** Crystal structure of cubic LLZO [52].

reported that tetragonal structure exhibits lower ionic conductivity compared to cubic structure mainly due to different crystal structure, Li content, atomic displacement and Li diffusion pathway [42]. As the total ionic conductivity is the contribution of both bulk and grain boundary hence the density of the LLZO pellets plays a crucial role as tetragonal LLZO with 60% relative density (with respect to theoretical density) exhibits  $\sigma_b = 1.63 \times 10^{-6} \text{ S cm}^{-1}$  and  $\sigma_{gb} = 5.59 \times 10^{-7} \text{ S cm}^{-1}$  at 300 K, while

$\sigma_{\text{tot}} = 2.23 \times 10^{-5} \text{ S cm}^{-1}$  and  $3\text{--}4 \times 10^{-5} \text{ S cm}^{-1}$  for 98 and 100% relative density, respectively, which indicates that the total ionic conductivity in tetragonal structure is hindered by grain boundary resistance [41, 47]. However, the total ionic conductivity of cubic structure stabilized by Al or Ta is reported to be  $1 \times 10^{-4} \text{ S cm}^{-1}$  and  $1 \times 10^{-3} \text{ S cm}^{-1}$  when the relative density is 93 and 98%, respectively [48–56]. It is also reported that, the activation energy in tetragonal LLZO is 0.4 eV while it is 0.26–0.35 eV in cubic structure [41]. Although the shear modulus of LLZO is about 12 times higher than Li metal (~60 GPa), dark features due to formation of Li filament have been observed in LLZO pellet for high current density ( $0.1 \text{ mA cm}^{-2}$  at room temperature). It has been shown that the propagation of Li dendrite through LLZO pellet is through grain boundary (intergranular) rather than grains [57].

### 5.3.6 Ionic conduction in solids

Solid ionic conductor materials allow macroscopic movement of ions through their rigid structure which results in high ionic conductivity. This ionic behavior is promoted at elevated temperatures and is characterized by one of the constituent species' diffusion. Some of these materials also show electronic conductivity which are called mixed conductors. However, super ionic conductors or fast ionic conductors are referred to the materials that show high ionic conductivity and negligible electronic conductivity.

The ionic conduction through crystals is mainly governed by thermally created vacancies in lattice. Ions move from one vacancy to another either by diffusion or applied

external electric field. The physical vacancies in crystal structure are also called lattice defects which are known as two main defects: Schottky and Frenkel defects:

### 5.3.6.1 Schottky defect

Schottky defect is the point defect created by a vacancy named after German physicist Walter H. Schottky in 1936. This defect forms when an ion leaves the lattice site which leads to formation of a vacancy. In order to keep the lattice charge neutrality, the Schottky defect includes both anion and cation vacancies. Schottky defects exhibits in ionic crystals when there is a small difference in size of the anion and cation. This type of defect takes place in highly ionic or coordinated compounds such as NaCl, KCl, KBr, CsCl, and AgBr.

### 5.3.6.2 Frenkel defect

Frenkel defect which is also known as dislocation defect was discovered by Yakov Frenkel, a Russian physicist. In this defect, the ion leaves the original lattice site and moves to an interstitial position leaving a vacancy and an interstitial defect. Frenkel defect takes place when the size of the cation is smaller than the size of the anion. Frenkel defects are exhibited in ionic solids such as: AgBr, ZnS, AgCl, and AgI.

The total electrical conductivity of a solid is the sum of the both ionic and electronic conductivity.

$$\sigma_{\text{tot}} = \sigma_{\text{ionic}} + \sigma_{\text{electronic}}$$

$$\sigma = \sum q_i \mu_i c_i$$

where  $c_i$  is the carrier density,  $q_i$  is the charge and  $\mu_i$  is the mobility of the charge carriers. It is clear that the ionic conductivity can be improved by increasing charge density and mobility. However, Armstrong et al. has studied that the number of lattice sites, low energy difference between ordered and disordered mobile ions over these sites and low thermal activation energy can improve the ionic conductivity of solids.

## 5.3.7 Ionic conduction in glasses

Ionic conduction in glassy materials was originated in 1884 when Warburg observed electrolytic  $\text{Na}^+$  transport by applying DC electric field on glass. Ionic glasses have attracted attention due to their application as solid electrolyte in electrochemical energy storage devices. There are several advantages of glassy ionic conductors over crystalline ones including the absence of grain boundaries, isotropic conductivity, compositional flexibility, and ease of fabrication.

Several glassy compositions (mostly silver and alkali-ion) conductors have been studied with maximum ionic conductivity of  $\sim 10^{-2}$  to  $10^{-3}$  at 25 °C [58–60]. Despite different models which are proposed to explain the ionic conductivity mechanism in glassy materials, there are two main models which are referred as two extreme behaviors: Anderson–Stuart model and weak-electrolyte model.

### 5.3.7.1 Anderson–Stuart model

The Anderson–Stuart model is first proposed in 1954 for; the activation energy in ion conducting glasses. As it is mentioned before in this chapter, the total conductivity of a system is the contribution of all charge carriers and it can be shown as:

$$\sigma(T) = n(T) \cdot Z \cdot e \cdot \mu(T) = \frac{\sigma_0}{T} \exp\left(\frac{-\Delta E_{\text{act}}}{RT}\right)$$

$$n(T) = n_0 \exp\left(\frac{-\Delta E_b}{RT}\right)$$

$$\mu(T) = \frac{\mu_0}{T} \exp\left(\frac{-\Delta E_s}{RT}\right)$$

$$\sigma(T) = \frac{n_0 \mu_0 Z e}{T} \exp\left(\frac{-(\Delta E_b + \Delta E_s)}{RT}\right)$$

where  $n(T)$  is the  $T$  dependent number density of charge carriers,  $Z$  in the valance of the mobile ion,  $e$  is the charge of the electron and  $\mu(T)$  is the  $T$  dependent mobility of carrier,  $\sigma_0$ ,  $\mu_0$  and  $n_0$  are preexponential factors.  $\Delta E_{\text{act}}$  is the total activation energy which is the sum of  $\Delta E_b$  (binding or Coulomb energy) and  $\Delta E_s$  (strain or migration energy). The charge carrier in glass faces two processes: dissociation from other ions and migration to the next position. In this model, the activation energy is assumed to be the energy required for the ion to move.

Similar to the close-packed liquid, the strain energy for glasses can be written as:

$$\Delta E_s = 4\pi G r_D (r - r_D)^2$$

where  $r$  is the cation radius,  $r_D$  is (doorway) radius in glass to accommodate the cation, and  $G$  is the shear modulus of the glass. This is the energy which is required to dilate the structure to accommodate the cation.

The bonding energy which is modified form from ionic crystal theory can be written as:

$$\Delta E_b = \frac{\beta z z_0 e^2}{\gamma (r + r_0)^2}$$

Here  $z_0$  and  $r_0$  are the charge and radius of the anion,  $\beta$  is a lattice parameter,  $z$  is the charge of anion and  $\gamma$  is covalent parameter.

According to Anderson–Stuart model, the activation energy can be written as:

$$\Delta E_{\text{act}} = \Delta E_b + \Delta E_s = \frac{\beta_{\text{ZZ}_0} e^2}{\gamma(r + r_0)^2} + 4\pi G r_D (r - r_D)^2$$

### 5.3.7.2 The weak-electrolyte model

The weak electrolyte theory was proposed by Ravaine and Souquet. According to this model, there are two types of charge carriers: associated and dissociated. Where the energy required dissociating the cation can be considered as activation energy and the dissociated ion have sufficient energy to overcome the Coulombic force and move through the framework.

Although Anderson–Stuart and weak electrolyte models are based on different concepts, both models reach similar predictions.

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Rhys Hakstol\*

## 6 A holistic environmental investigation of complementary energy in Alberta

**Abstract:** As Canada progresses toward its pledge of net-zero carbon emissions by the year 2050, it is worthwhile to thoughtfully examine the current energy landscape and how one might hope to achieve decarbonization within this timeframe. This examination is of particular importance in a fossil fuel producing region such as Alberta. Through an analysis of renewable energy strategies as well as the potential difficulties in this transition, an appropriate strategy may be devised. A combinatorial approach of wind, solar, and geothermal energy sources in the residential, commercial, and industrial spheres may serve as a transition measure, and eventually supplant fossil fuels as the dominant source of energy produced in Alberta with appropriate incentivization. Decarbonization is a pressing need given the imminent climate crisis the world is encountering, and these technologies are capable of serving as a step toward lower carbon emissions and ultimately curbing human-accelerated climate change.

**Keywords:** climate change; environmental impacts; fossil fuels; remediation; solar energy; wind energy.

### 6.1 Introduction

On February 13, 2021, a winter storm descended onto the southern United States. The massive winter storm placed enormous strain on the energy grid system of several states, most notably, Texas. Due to Texas' isolation from national power grids to avoid national oversight, they were unable to leverage power from outside their borders. The reliance of Texas on predominantly one energy source and lack of diversification has been identified as a potential cause of the disastrous outcome and the loss of power to millions of homes and businesses for several days.

A portion of the issue stems from a lack of understanding and acceptance of a comprehensive approach to energy supply that not only utilizes hydrocarbons as such but also allows for development of complementary energy sources such as nuclear, hydrogen, wind, solar, and geothermal. Throughout this chapter, the term "complementary energy" will be used to emphasize the fact that they are able to coexist

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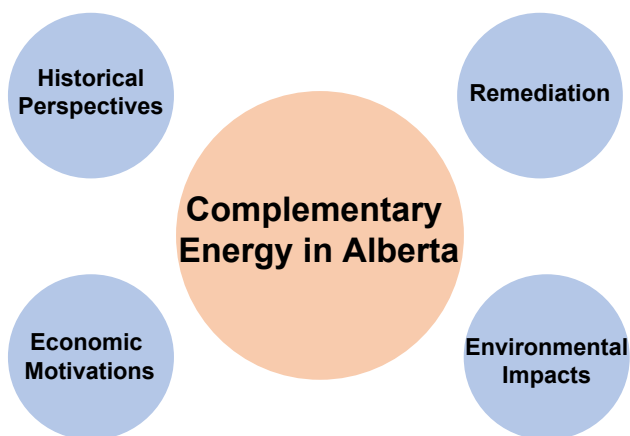
**\*Corresponding author: Rhys Hakstol**, Lethbridge College School of Environmental Sciences, 3000 College Dr S, Lethbridge T1K 1L6, AB, Canada, E-mail: [rhys.hakstol@gmail.com](mailto:rhys.hakstol@gmail.com).  
<https://orcid.org/0000-0001-7720-3170>



alongside traditional fossil fuel energy sources as decarbonization programs are fully established. The future of complementary energy in Alberta and more broadly around the globe relies on consideration of factors related to the historical methods of energy production, the socioeconomic drivers of this production, as well as the remediation outlook and environmental impacts of each complementary energy outlook (Figure 6.1). In the future, the information in this chapter will be assembled into a freely available microcredential course.

Complementary energy is an approach that recognizes the importance of providing energy to citizens while also acknowledging that fossil fuel consumption is not only contributing to accelerated climate change but is also unsustainable in nature. For a complementary energy approach to be successful long-term it should be economically viable, have minimal environmental impacts, be easy to remediate land and water after its lifetime, and meet the needs of citizens and be renewable in nature. For this reason, much of the discussion in this chapter will focus on the technology and implications surrounding wind, solar, and geothermal energies. Nuclear energy, while promising, is not strictly-speaking renewable, but it is capable of producing large amounts of energy for residents, and has been used in other Canadian provinces such as Ontario for decades [1].

While this chapter and future course development is targeted toward a somewhat older audience, there is no reason to prohibit this type of information from being distributed to younger primary school children in an age-appropriate context. Certainly, when one can appreciate and understand the immense physical and chemical potential of the planet, there is clarity and respect that is brought to a discussion of the world's energy future. Additionally, while this chapter will be focused on the oil-rich Canadian province of Alberta, it is certainly extensible to other regions



**Figure 6.1:** An overview of the considerations a complementary energy approach must address to establish itself.

interested in long-term gradual decarbonization. This gradual approach is likely to be more palatable to the broader population as a starting point, and can hopefully spur on necessary and meaningful, rapid climate change action.

## 6.2 The history of complementary energy in Alberta

Before discussing complementary energy through a strictly Alberta lens, it is important to define each of the sources of energy that will be discussed. To begin with, non-renewable fossil fuel combustion refers to the burning of coal, natural gas, crude oil, gasoline for the production of energy. Extraction and refining of these fossil fuels is a laborious process requiring skilled work and expertise. The bonds of these hydrocarbons contain a large amount of energy that is liberated by their combustion and subsequent release of carbon dioxide as a product. The heat energy released may be used to heat water to steam in order to power electrical generation via turbines, or to directly heat homes and businesses among other examples. Released carbon dioxide contributes to accelerated climate change [2, 3] which motivates the transition to complementary energy sources. Solar energy, utilizes the electromagnetic radiation from the sun to produce electricity predominantly through the photovoltaic effect. A solar cell containing silicon absorbs solar radiation, causing electron excitation and creation of an electric current which can then be utilized by consumers [4]. This conversion of light energy into electrical energy is often aided by batteries or storage cells for use at a later time. Wind energy utilizes the physical power of wind to generate electricity. As wind hits the blades of a large turbine, the blades spin, resulting in kinetic energy being passed to a generator which converts that kinetic energy to electrical energy [5]. Lastly, geothermal energy is an approach that uses the natural heat deep within the Earth to equilibrate the temperature of homes, businesses, and other consumers. Geothermal may also refer to the harnessing of heated water underground to be used as a reservoir of warm water for heat exchange. In either case, the strategy is to drill into the Earth and either use the warmer air or water present to equilibrate the temperature of a building. The heat may also be used to power electrical generators to produce electricity [6].

While Alberta is a province that is perhaps best known for its expertise in petrochemicals and nonrenewable methods of providing energy to its citizens and those around the globe, there is a history of renewable, complementary sources of energy in Alberta. In fact, Calgary power was established in 1909 and at its height, its hydroelectric production provided nearly half of the power used by the entire province [7]. While other provinces in Canada currently have much larger hydroelectric capacities than Alberta, around 7% of energy production in the province comes from hydroelectric sources [8]. Alberta's hydroelectric energy development represents around 10–15% of the province's water use, while the majority is used for coal and gas power plants [9]. In contrast to the long history of hydroelectric generation in Alberta,

the history of wind power is somewhat more recent. The first commercial wind farm in Canada was established in Southwest Alberta in 1993, and since that date the capacity of wind farms in the province has increased to nearly 1100 MW [10]. Lastly, solar power and solar technology has a lengthy history in both thermal and photovoltaic, adopted by early Western Canadian European settlers [11]. Moreover, as the cost of materials for solar panels has become more inexpensive, the barrier to uptake will be lowered [12, 13]. While there are historical examples of complementary energy sources in Alberta, the adoption has not been as widespread or as incentivized as it would need to be for the benefits to be fully realized.

## 6.3 Socioeconomic drivers

When considering incentives to move to renewable complementary sources of energy, it is important to remember that oil and gas is still Alberta's largest economic sector, accounting for 16% of provincial GDP [14]. Because this industry represents such a large portion of the provincial energy interest, there is understandable inertia toward diversification. Global oil price fluctuations in the previous decades [15, 16] have created economic instability and uncertainty for a large portion of the workforce. It is for this reason that there is increasing interest in complementary energy sources and a move toward decarbonization.

Given its latitude and abundance of sunlight during summer in the Northern Hemisphere, Alberta is uniquely positioned to be a leader in solar power generation. Much of the province experiences between 1500 and 1800 kW h/m<sup>2</sup>/y of solar irradiation [17] which is sufficient for power provision to most individuals below the 58th parallel. However, solar power, whether thermal or photovoltaic does have inherent seasonality and unpredictability throughout the year, when energy production may be lower or higher, and therefore other sources of renewable energy may be used as a supplement in times of low solar irradiation. Another concern individuals have with respect to adoption of solar energy is cost of setup and maintenance. In recent decades, the cost of solar energy has come down several thousand dollars per kW generated [18] and projections for this cost reduction indicate that solar power will be less expensive than fossil fuel energy production in a high solar radiation area as soon as 2028 [19]. With this in mind, the tipping point for solar power to be economical in consumer and commercial settings is coming. Lastly, people have raised concerns about the aesthetics of solar panels with individuals feeling that panels are an eyesore or just not as visually appealing as other home and business accessories. With that in mind, designers and solar technology companies are in the process of designing and bringing to market solar panels which are indistinguishable from normal roofing, or more appealing in their appearance [20, 21].

Alberta was quick to recognize that wind is a natural phenomenon worth harvesting in the early 1990s. In Southern Alberta in particular, air is moved east off the slopes of the Rocky Mountains producing high-speed warming winds known as chinooks. The amount of wind that occurs in Southwest Alberta makes it an ideal position for wind farms to be established. However, the concerns surrounding wind power are numerous. The large windmills that are often placed in agricultural lands are sometimes seen as a disruption. Despite this, in 2010, when asked about the issue, a majority of people were in favor of wind power generation [22]. Because most wind power generation takes place in areas far removed from urban areas (i.e. where there is sufficient space for large windmills to exist) there is a disconnect between the consumption of wind power and the production of wind power, and consumers may be agnostic to the concerns producers have. An advantage that wind generation has is that it is nonseasonal and can occur throughout the entire 24 h of a day while solar photovoltaic cells are somewhat limited to daylight hours in this regard. Wind energy has been used for over 100 years [23] and has grown in Canada to be a widely accepted alternative [24].

Each of the previous resources mentioned are seasonal in nature, or weather dependent. A source of energy should be predictable and available when needed. For this reason, an often-overlooked source of energy should be considered: geothermal. By harnessing the heat inherent deep within the Earth, we may be able to heat homes and businesses as well using the heat of the Earth [25]. This approach would limit natural gas consumption in the province and provide a true alternative to gas-powered home and water heating. However, the current state of geothermal energy generation is still relatively expensive and not widely adopted in urban areas [26]. It is important to remember that geothermal energy is not limited to homes and businesses but may be applied industrially as well [26]. The promise of geothermal energy production is high, but due to a lack of public discourse and high costs of drilling and surveying for a residence, the uptake remains relatively low in most of North America [27, 28]. As the cost of geothermal systems is reduced through greater availability of technical workers, or the cost of natural gas increases to an unpalatable level, geothermal will become a viable complement, if not a desirable alternative in the future [29].

Overall, there is an appetite in society to reduce pollution in the form of greenhouse gasses to curb the impact of climate change. While this will not be an immediate transition, a gradual decarbonization strategy aided by the use of solar, wind, and geothermal energy will assist in ensuring future generations are able to enjoy the same comforts we do. Indeed, our global capacity to produce this energy has increased alongside our demand [30], the implication is that the present day is an appropriate one to pursue this decarbonization agenda.

## 6.4 Environmental impacts

While the strategies outlined above are designed to be used alongside and eventually replace traditional fossil fuels in some capacity, they are not without environmental impacts and drawbacks.

### 6.4.1 Impacts of solar energy

One of the predominant concerns regarding the generation of solar energy in a commercial or residential context is the generation of the panels themselves. Most photovoltaic solar cells rely on crystalline silicon, which is not trivial to obtain, or produce panels from, as large amounts of water and electricity are required in this process [31]. In addition to the raw materials required, adhesives and installation materials must be used in order for the solar panels to be functional. Moreover, a 2016 study found the upkeep and maintenance cost of photovoltaic solar panels to be between \$20–\$40USD/kW of energy produced annually with the average installation cost of a photovoltaic system being around \$3USD/W [32]. This cost, while high, is often offset by the implementation of government subsidies to promote renewable energy sources [33]. These subsidies are often used to offset carbon emissions in the interests of curbing climate change.

### 6.4.2 Impacts of wind energy

The power of wind can be damaging in itself should a high velocity be achieved. However, the methods of harnessing the wind power should endeavor to be as environmentally friendly as possible overall. Predominantly, wind power in Alberta is produced in massive wind farms situated near the Rocky Mountains which have the capacity to produce over 1600 MW across nearly 1000 wind turbines [34]. Wind in Alberta is plentiful, which leads to the lowest weighted average cost per megawatt hour across the Canadian provinces of \$37CAD [35]. However, these large wind turbines are responsible for the deaths of several birds and bats annually [36–39]. Perhaps even more detrimental to the ecosystem is the impact on habitat and migration patterns of both aerial and terrestrial organisms as a result of turbine locations [38].

Another major concern associated with wind power is the noise of the turbines used to produce energy. Of course, noise is inherent in the system as it is not 100% efficient. The noise has been cited in multiple countries as a potential annoyance [40–42] and even tenuously correlated with increased with impaired heart function, though more persuasively as a sleep disturbance [43]. The noise generated by turbines is certainly disruptive to humans and wildlife, but as the efficiency and reliability

of wind generation improves it is likely that this noise will become less problematic. A 2020 study from the University of Alberta [44] identified the major drawbacks of large scale wind farms being the occupation of space and associated habitat loss. Certainly, Alberta has vast tracts of unoccupied land which can be used for wind power, but these concerns should inform further development of this sector.

### 6.4.3 Impacts of geothermal power

While it is a reliable source of power even in the absence of wind and sunshine, geothermal power production is not without its own issues. Primary among these is the efficiency of geothermal production on a large scale. The amount of energy released from natural gas or other fossil fuel combustion on a large scale is significantly more scalable than the amount yielded by geothermal, however this difference is less pronounced in a smaller residential situation [45]. While most of the drilling for access of geothermal energy does not disturb terrestrial macroorganisms, it may still impact the habitats of those that live underground which should be considered. Moreover, there is a risk that in drilling up to 3000 m deep into the Earth (as is sometimes done for large-scale production) that the geological disturbances will create instability. This seismicity is certainly a large environmental impact, and can be seen as a caution against deep drilling of any kind, as instability is created [46]. Seismic instability can be particularly damaging and difficult to repair, with the long-term impacts being concerning for many generations [46]. Certainly, the increase in temperature is roughly 30 °C for every kilometer drilled [47], but the risks of drilling this deep must be weighed against the potential seismic costs.

## 6.5 Remediation

As outlined above, there are environmental and ecological concerns associated with acquisition of any type of energy. The major issue becomes how best to manage the concerns as well as how best to remedy the damage that is done after the energy is obtained. For example, in the case of the Alberta tar sands, tailings ponds exist in which residual bitumen is left to sit in ponds after oil is separated from the sand and clay it is suspended in. Even if precautions are taken, this is a sizable contamination load for the ecosystem at large to contend with. Fortunately, remediation strategies for this type of contamination are present; however, it is ultimately the responsibility of the company obtaining the petrochemicals to remediate the ecosystem which requires significant oversight and supervision in some cases. This section will focus on the remediation strategies that may be adopted to assist in remedying damage done in production of complementary energy.

### 6.5.1 Remediating solar energy

Much of the concern surrounding solar energy and its environmental impacts comes from the compounds used in the production of solar panels. The silicon wafers in the photovoltaic panels can be recycled to recover the active portion of the panels once their use is concluded [48]. The reclaimed wafers can be used in new panels with similar efficacy to the initial manufactured photovoltaic panels [48]. Additionally, utility-scale solar energy often occupies large stretches of land, which cannot be as effectively occupied by biota, and may alter the natural nutrient dynamics of a parcel of land [49]. However, after the lifetime of a solar array has elapsed (often 25 years), gene flow and biodiversity are free to return to the land. Moreover, in well-planned utility-scale solar applications, the land may be used for multiple purposes. For example, part of the land may be used for solar capture while a portion is still available for grazing, or the solar array may be angled/elevated to provide shade for shade-tolerant crops to grow [49, 50]. Certainly, the prospect of both allowing a parcel of land to renaturalize and also be productive in the form of solar energy should be an intriguing prospect for agricultural producers. The remediation techniques for solar energy arrays are akin to natural attenuation, as once solar panels are removed, the land is allowed to return to its natural state. In terms of water usage, large solar array systems must be washed with water periodically, but this water demand is certainly minimal compared to other energy generation systems [51, 52]. Photovoltaic systems, by their nature are put in nonshaded areas with little tree cover. This means that there is an increased chance of erosion and dust deposition on the surface of the solar panel which reduces efficiency, so washing must be done to maximize efficiency. This is not necessarily a concern from a remediation standpoint, as the water used for cleaning the panels will be used by surrounding vegetation.

### 6.5.2 Remediating wind energy

Certainly, wind energy production suffers from similar concerns as solar energy in its occupation of space that could be otherwise used. This land must be reclaimed after the lifetime of the wind turbine [44]. While these concerns are indeed important, the use of land for a wind turbine does not preclude it from being used for agricultural production. One of the major issues for wind energy is the harvesting of raw materials and recycling of those raw materials. For example, balsa wood is often used in the core of turbine blades for its light weight and durability. However, the reclamation of this wood once a turbine is decommissioned is sometimes difficult due to the assembly process. Outside of its obvious (albeit minimal when compared to other energy approaches) negative impact on biodiversity in causing death of several birds and bats annually, a wind turbine also contributes a sizable amount of noise pollution, impacting communication of the natural aerial biodiversity. The remediation

from this type of event is straightforward as once the turbine is removed or relocated, the noise is no longer an issue for that ecosystem. Certainly, the noise generated by wind turbines is of concern to human residents as well, which is why appropriate measures to situate turbines appropriately far from homes must be taken.

### 6.5.3 Remediating geothermal energy

Geothermal remediation relies on long-term monitoring and is not as straightforward as remediation methods associated with wind or solar energy harvesting. Because harnessing geothermal energy requires drilling into the Earth, it is entirely possible that groundwater and surrounding soil microecosystems may be disturbed in the process [36, 53, 54]. These must be monitored over the lifetime of the geothermal system to ensure that contaminants have not been introduced inadvertently, at which point a remediation strategy would have to be investigated and adopted. Contaminants would be removed via excavation which would be costly for the landowner. Moreover, the concern of increased seismicity in the areas surrounding geothermal drilling also bears long-term investigation. Any structural weaknesses or small earthquakes in the area surrounding a geothermal drill site should be identified as a potential concern for future development.




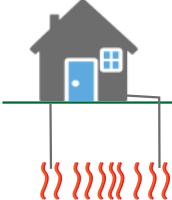
## 6.6 Recommendations and best practices

Canada as a whole has pledged to reach net-zero emissions by the year 2050 [55]. As Canada's fourth-most populous province, Alberta has a role to play in this net-zero goal and framework. Alberta has a proud history of innovation in the resource sector and with proper training and opportunities available to all, the transition to a net-zero emissions energy landscape can be a smooth one. However, it is unlikely to be a matter of an immediate transition; certainly such an abrupt pivot would be unpalatable to governments and corporations in the province alike. It is for this reason that a gradual decarbonization approach utilizing the complementary energy sources outlined above is the more likely solution moving toward 2050. Without question, an inflection point will be reached at which point fossil fuels are no longer the dominant energy producer in Alberta that is the nature of a nonrenewable resource. The recognition that fossil fuel combustion is contributing to the largest current threat to humanity should serve as motivation for a transition within the reasonable 30-year timeframe outlined by the federal government. As global energy needs are increasingly met by renewable sources, the technology and access to it will become less expensive and more widespread, with little or no recurring cost once infrastructure is purchased and maintained [6, 49, 56].



While we currently operate in a carbon-heavy nonrenewable landscape, that may not always be the case, and in the spirit of reclamation and recycling, much of the infrastructure currently used for fossil fuels can eventually be repurposed to serve the needs of citizens with renewable sources of energy. Throughout this chapter, the advantages and disadvantages of each approach to energy production have been laid out and should be considered carefully moving forward (Figure 6.2). Alberta and fossil fuel producing regions around the world have the highly skilled workforce that can make such a transition relatively easily if it is incentivized. There are routes which Alberta and other jurisdictions can pursue that are more environmentally friendly during decarbonization. Chief among these is blue hydrogen, or production of hydrogen from natural gas. If natural gas generation plants are near to sites where the power is to be used, blue hydrogen is a logical extension of this technology, and the associated emissions are nongreenhouse gases which is a large advantage.

In the pursuit of decarbonization and net-zero emissions by 2050, it is important to remember that the technologies above cannot be used indiscriminately and careful pre-planning and remediation planning should be in place before the approach is installed. For example, proper planning of wind and solar farms will allow for wildlife corridors so as to not fragment habitats for migratory species too extensively. Additionally, mitigating factors such as lights and subsonic whistles on windmill blades will assist birds and bats in circumventing them to preserve native biodiversity. Care must be taken to ensure that soil is returned to its natural state after the residence of a solar or wind farm has elapsed to once again preserve native biodiversity [44].

				
	Fossil Fuels	Wind	Solar	Geothermal
Advantages	<ul style="list-style-type: none"> <li>-Existing infrastructure</li> <li>-Large capacity</li> </ul>	<ul style="list-style-type: none"> <li>-Operates 24hr/day</li> </ul>	<ul style="list-style-type: none"> <li>-Efficient use of infinite resource</li> </ul>	<ul style="list-style-type: none"> <li>-Efficient heating/cooling especially in arid areas</li> </ul>
Disadvantages	<ul style="list-style-type: none"> <li>-Non-renewable</li> <li>-Creation of greenhouse gases</li> <li>-Prices fluctuate</li> </ul>	<ul style="list-style-type: none"> <li>-Large, with expensive up-front cost</li> </ul>	<ul style="list-style-type: none"> <li>-Infrastructure must be intentionally installed</li> </ul>	<ul style="list-style-type: none"> <li>-Expensive startup cost</li> <li>-Potential surface instability</li> <li>-Suited to specific geologic areas</li> </ul>

**Figure 6.2:** Highlighted advantages and disadvantages to different energy production outlooks. Importantly, these advantages and disadvantages are from the perspective of a traditional fossil fuel producing jurisdiction.

In investigating complementary energy sources, it is important to compare the potential drawbacks to the current state of the art. Certainly, while birds and bats are lost to wind farms, and small seismic activities may occur due to geothermal drilling, the risk of these is miniscule when compared to current fossil fuel extraction activities [36, 39, 53, 57]. Once the overall cost of these methods of generating electricity and heat are lowered through innovation and improved technology, adoption should follow. Certainly, with the wealth of renewable natural resources available, whether they be sun, wind, or the heat of the Earth, it would be prudent to utilize them to the benefit of humanity as a whole.

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David Consiglio\*

## 7 The story of nitrogen

**Abstract:** For centuries, farmers have needed fertilizers rich in nitrogen to increase crop yields. This need led to one of the most unusual wars in history: a war over fossilized bird droppings. Twentieth century chemists solved the problem of mass-producing nitrogen fertilizer, but their solution required enormous amounts of energy. Twenty-first century chemists now face the challenge of producing nitrogen fertilizer without the need for energy provided by fossil fuels.

**Keywords:** catalyst; fertilizer; green chemistry; nitrogen; nitrogen fixation; nitrogenase.

The date is February 7, 1866. A combined Peruvian and Chilean fleet is undergoing repairs at the port city of Abtao. They are caught unaware by Spanish ironclads. The harbor is shallow, and the Spanish worry about running their ships aground. The fleets exchange cannon fire from afar – a Spanish frigate is damaged. The Spaniards withdraw, but the war rages on.

What drew these nations to take up arms and fight one another? Was it independence, or political disagreement? No. These nations fought over a resource so valuable that the Spanish were willing to sail halfway around the world to secure it. It was not gold or silver, not a precious metal at all.

It was guano. Bird droppings. Fossilized poop.

The story of the Chincha Island War is a small footnote in a struggle that has plagued humanity for thousands and thousands of years. Ever since we first put seeds into the ground and purposely grew crops, we have had a problem. Plants, like all living things, need nitrogen to grow. For anyone who has studied the chemistry of our atmosphere, this may seem surprising—our atmosphere is nearly 80% nitrogen! However, the nitrogen in the air is all but unusable by plants. The bond that holds the  $N_2$  molecule together is too strong for them to break on their own. So, they must turn to the soil for their nitrogen. Most soils, however, are not rich in nitrogen that plants can use.

And thus, our quest to enrich the soil with usable nitrogen began. For our ancient ancestors, this problem was easily solved. Animal manure, which was present in abundance, was rich in *fixed nitrogen*, the term used by farmers to this day to describe nitrogen that plants can easily access. Indeed, until the 1800s, manure provided the

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\*Corresponding author: David Consiglio, Jr., Department of Chemistry, Southfield High School for the Arts and Technology, Southfield, MI, USA, E-mail: [davecons@gmail.com](mailto:davecons@gmail.com)

majority of the nitrogen needed for crops to feed the people of the world. But, with modernity came population explosion, and soon the soils were not fertile enough to provide food for this burgeoning population.

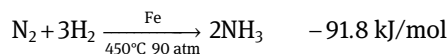
Enter guano.

Guano is extremely rich in nitrogen, and it exists in large deposits on islands that have served for millennia as colonies for seabirds. Some of these islands, including the Chincha Islands off the coast of Peru, contain millions of tons of fossilized guano. Guano was easy to use, as well. Simply powder it and plow it into the soil. Immediately, crop yields will increase.

Guano, however, is a finite resource, and the population of the world nearly doubled from 1700 to 1800, and then nearly doubled again from 1800 to 1900. By the turn of the 20th century there were nearly two billion human beings, and the guano supply was rapidly being depleted. If a solution was not developed, humanity would face a starvation crisis the likes of which had never been seen before.

It was this potential crisis that spurred 20th century chemists to crack the most important problem in the modern world: how to fix atmospheric nitrogen.

The chemist who solved the problem was Fritz Haber. He discovered that nitrogen gas from the air could be reacted with hydrogen gas at high pressure and temperature to form ammonia, provided a suitable catalyst was used. Haber used osmium metal, but osmium is rare and expensive. Later, Carl Bosch and his team developed an inexpensive iron catalyst; a catalyst is still used today.



The product of the Haber process is pure liquid ammonia, a substance which can be sprayed directly onto the ground to fertilize crops. Today, the world produces nearly 200 million tons of ammonia annually, a process that consumes nearly 2% of the world's energy production. This may seem surprising, considering the reaction that produces ammonia is exothermic. However, the high temperature and pressure required involves a considerable amount of energy input—today, ammonia production requires roughly 600–800 kJ/mol.<sup>1,2</sup> Therein lies the primary problem with ammonia production—we can easily make enough to fertilize the world's crops, but the energy required to make ammonia contributes more greenhouse gases to the atmosphere than the production of any other single chemical on the planet. The high temperatures and pressures required to produce ammonia via the Haber process are created by burning enormous amounts of fossil fuels.

What if there was another way? As is so often the case in these situations, solutions can be found by turning to nature. For centuries, farmers knew that rotating crops

1 [https://www.energy.gov/sites/prod/files/2015/01/f19/fcto\\_nh3\\_h2\\_storage\\_white\\_paper\\_2006.pdf](https://www.energy.gov/sites/prod/files/2015/01/f19/fcto_nh3_h2_storage_white_paper_2006.pdf).

2 <https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.0c00455>.

increased yields, though they did not know why. Later, it was found that planting beans in off years increased yields even more, though again the reasons were unclear.

Today, we know the answer: bean plants can fix atmospheric nitrogen, with a little help from some amazing bacteria, called diazotrophs, that live in their roots. The same reaction that requires enormous pressures and scorching temperatures for humans to perform can be accomplished by a simple microorganism, at room temperature and atmospheric pressure.

Not surprisingly, the bacteria require an amazing catalyst to perform this reaction. This type of enzyme, collectively known as *nitrogenases*, are used by microbes to synthesize ammonia. The reaction performed using nitrogenase uses only slightly less energy, roughly 450 kJ/mol<sup>2</sup>, as compared to modern industrial processes. But, the manner in which this enzyme operates offers a glimpse at a future where ammonia could be produced in a far safer and less polluting manner.

The most well-studied nitrogenases have, at their hearts, a pair of molybdenum atoms, along with 24–32 atoms of iron and 24–32 atoms of sulfur, surrounded by a complex protein structure.<sup>3</sup> Nitrogen fixing bacteria were first thought to exist only in structures within the roots of certain plants. However, some ocean bacteria can fix nitrogen as well. Recently, such an organism was found in Antarctic waters, proving that nitrogenases can operate at near-freezing temperatures.

While we are unable to directly replicate nitrogenase's extraordinary ability, the past few years have yielded significant advances. Electrolytic processes powered by solar energy have recently produced ammonia at just 560 kJ/mol, slightly better than the average for ammonia produced by the Haber process.<sup>4</sup> This production takes place at 20 °C, but still requires higher pressures (about 8 atm), and yields are quite low.

Plasma-driven processes have been successful at producing ammonia at atmospheric pressure, but at a cost of elevated temperatures and with an energy requirement of 4610 kJ/mol, more than six times that of the Haber process.<sup>5,6</sup> However, this technique has the advantage of not requiring the nitrogen to be separated from air. Instead, nitrogen is combined with oxygen to form nitrogen dioxide which is, in turn, reacted with hydrogen gas to produce ammonia.

And, in 2020, researchers produced ammonia using a one-pot synthetic approach at room temperature and just 5 atm of gaseous nitrogen pressure.<sup>7,8</sup> This synthesis involves several precursor steps that must be performed at –50 °C, so it is likely that this procedure still requires more energy than the Haber process. However, the possibility of synthesizing “green” ammonia is closer than ever.

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3 <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4012840/>.

4 <https://www.sciencedirect.com/topics/engineering/nitrogenase>.

5 <https://onlinelibrary.wiley.com/doi/10.1002/ange.202011676>.

6 <https://www.greencarcongress.com/2020/10/20201028-pnocra.html>.

7 <https://www.nature.com/articles/s41557-020-0520-6>.

8 [https://www.researchgate.net/figure/A-one-pot-borylene-mediated-synthesis-of-ammonium-chloride-from-N2-and-elucidation-of\\_fig1\\_344246874](https://www.researchgate.net/figure/A-one-pot-borylene-mediated-synthesis-of-ammonium-chloride-from-N2-and-elucidation-of_fig1_344246874).





Michael Barnard\*

## 8 Small modular nuclear reactors are mostly bad policy

**Abstract:** People asserting that SMRs are the primary or only answer to energy generation either don't know what they are talking about, are actively dissembling or are intentionally delaying climate action.

**keywords:** climate action; climate change; economics; nuclear generation; policy; small modular reactors.

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Like hydrogen, small modular nuclear reactors have been seeing a resurgence of interest lately. Much of that is driven by governmental policies and investments focusing on the technology. Much of it comes from the nuclear industry. And inevitably, some comes from entrepreneurs attempting to build a technology that they hope will take off in a major way, making them and their investors a lot of money.

Small modular reactors won't achieve economies of manufacturing scale, won't be faster to construct, forego efficiency of vertical scaling, won't be cheaper, are not suitable for remote or brownfield coal sites, still face very large security costs, will still be costly and slow to decommission, and still require liability insurance caps. They don't solve any of the problems that they purport to while intentionally choosing to be less efficient than they could be. They've existed since the 1950s and they are not any better now than they were then.

### 8.1 Most of the attention and funding is misguided at best, and actively hostile to climate action at worst

First, let's explore briefly the world of small modular nuclear reactors (SMNR) or small and medium reactors (SMR). The most common acronym is SMR, but you'll see both.

As it says on the box, they are nuclear generation devices, specifically fission nuclear. That means they use radioactively decaying fissile materials, fuels, to heat a liquid which creates steam which drives steam turbines to generate electricity. Technically, they are like a coal generation plant, but with the heat provided by the decay of uranium instead of the burning of long-buried plant matter.

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\*Corresponding author: Michael Barnard, TFIE Strategy Inc., 413-1088 Richards St, Vancouver, BC, V6B 0J8, Canada, E-mail: [michael@tfie.io](mailto:michael@tfie.io)

There are a handful of differences between them and traditional nuclear generation reactors. The biggest one is that they are smaller, hence the ‘small’ and ‘medium’ in the names. They range from 0.068 to 500 MW in capacity, with the International Atomic Energy Association using small for up to 300 MW and medium for up to 700 MW.

Despite the buzz, this is not new technology. The first nuclear generation plant was a Russian 5 MW device that went live in 1954. Hundreds of small reactors have been built for nuclear powered vessels and as neutron sources. This is well trodden ground. Most of the innovations being touted were considered initially decades ago.

Status	#in Status	Median capacity (MW)
Concept or abandoned	22	208
Construction	2	119
In design phase	28	60
Operating	5	50
Grand total	57	100

Table of SMNR’s types by status by author with data from World Nuclear Association.

In the seven decades since the first SMR was commissioned, 57 different designs and concepts have been designed, developed and, rarely, built. Most of the ones which are built are doing what nuclear reactors do, getting older without new ones being built to replace them.

Name	Capacity range	Type	Developer	Status
EGP-6	1–100	LWGR	At Bilibino, Siberia (cogen, soon to retire)	Operating
KLT-40S	1–100	PWR	OKBM, Russia	Operating
RITM-200	1–100	Integral PWR, civil marine	OKBM, Russia	Operating
PHWR-220	201–300	PHWR	NPCIL, India	Operating
CNP-300	201–300	PWR	SNERDI/CNNC, Pakistan and China	Operating
CAREM25	1–100	Integral PWR	CNEA and INVAP, Argentina	Construction
HTR-PM	201–300	Twin HTR	INET, CNEC and Huaneng, Chin	Construction

Table of operating and in construction SMRs by author with data from the World Nuclear Association.

The Russian models are far-north icebreaker power plants being considered for land-based deployment in remote northern towns, with the Siberian one at end of life. The Indian ones are 14 small CANDU variants in operation, most decades old now. The Chinese one is coming up to end of its 40-year life span as well.

Type	#of Type	Median capacity (MW)
BWR	2	300
Heatpipe	1	10
Heatpipe FNR	2	3.25
HTR	9	20
HTR, FNR	2	145
Integral PWR	9	125
Integral PWR, civil marine	1	50
Lead FNR	3	300
Lead-bismuth FNR	2	67.5
Lead-cooled	1	36
LWGR	1	11
MSR	6	125
MSR-Triso	1	50
MSR/FNR	2	675
PHWR	2	260
PWR	9	220
Sodium FNR	3	311
Twin HTR	1	210
Grand total	57	100

The Argentinean model has been in construction on and off for over a decade with work stoppages, political grandstanding, and monetary problems. It may never see the light of day.

The Chinese HTR-PM, under construction for the past decade, is the only one with remotely new technology. If commissioned, it is expected to be the first Gen IV reactor in operation.

SMNR technology types, table by author with data from World Nuclear Association.

And to be clear, this is not a technology, it's many technologies. Across the decades, 57 variants of 18 types have been put forward. None of the types can be considered to be dominant.

## 8.2 Claims About SMRs Don't Withstand Scrutiny

Advocates for SMRs typically make some subset of the following claims:

- They are safer
- They can be manufactured in scaled, centralized manufacturing facilities so they will be cheaper
- They can provide clean power for remote facilities or communities
- They can be deployed onto decommissioned coal generation brownfield sites
- They can be built faster

None of these are actually good arguments.

First, *traditional nuclear is safe already*, dominantly due to passive safety features in the majority of operational reactors and lots of attention to management and operations. Chernobyl was a bad design. Fukushima was deeply bad siting and operational decisions. Those siting and operational decisions have resulted into a cost which is likely to be around a trillion US Dollars to the overall Japanese economy when all the bills are counted. SMRs are not immune to bad siting and bad operational decisions, but there have been some lessons learned by the industry.

Safety concerns are not why nuclear is failing in the marketplace, economics are why nuclear is failing in the marketplace.

Second, *in order for economies of scale to kick in, a manufacturing facility has to build hundreds or thousand or millions of the same thing* and have a projected future market for hundreds or thousands more. The field is littered with 18 different types of technologies and many competing designs within those types. There is no coherent single technology which will dominate the field. Each country engaged in SMR research has its own preferred technologies and its own companies to support.

In order for any of these designs to see economies of scale, several major countries would have to get together, decide on a single specific technology, form a joint venture with the manufacturer, and commit to building and deploying only that technology. This is not a market-based solution, it's not aligned with the geopolitical strategies of the countries, and so none of these designs will scale beyond perhaps the 14 units of the old CANDU derived Indian design.

Russia is serious about icebreaker and landed small reactors, but Russia is not going to shape a global market for them. They might build a few in far northern communities, with predictable concerns. China is the only country doing significant expansion of nuclear generation, and it's already closing in on double-digits of technology variants, a failure condition. The US could re-focus on small PWRs, but there's no particular political will at the federal level to push for that.

No scaled manufacturing, no cost reductions. Nu Scale's expressed hope is to get its cost of generation down to only double the current wholesale cost of wind and solar generation, around \$65 per MWh.

Third, *both remote communities and brownfield coal generation plants have major security exposures*. As nuclear technologies and fuels are highly proscribed and limited due to nuclear non-proliferation strategic goals, and as concentrated radioactive

Cost Aera	Per reactor per year (\$millions)	Full lifecycle per reactor (\$millions)	Total across fleet (\$millions)
International	\$8.2	\$1224.4	\$165,300.0
National, state, municipal	\$25.9	\$3880.9	\$523,920.0
Site	\$18.0	\$2700.0	\$364,500.0
Total	\$52.0	\$7805.3	\$1,053,720.0

material is highly desirable for terrorists for dirty bombs, the entire supply, operational and waste chain requires significant overlapping circles of defense.

These requirements don't go away because the nuclear reactors are smaller.

Per reactor allocation of all security costs for US fleet. Table by author published in 2021.

And these security costs are big, and mostly hidden in federal, state, and municipal subsidies. Remote areas still require these additional security costs, and they will likely be higher simply due to the additional challenges of securing remote areas with high transportation costs. Brownfield coal generation sites don't become more economically viable with massive security upgrades and unproven technologies.

*Without economies of scale, there will be no fast deployment of SMRs.* They need to be standardized, shippable units. Right now, the units under construction and Nu Scale are on track for the median of a decade for construction. Nu Scale is promising twelve units in operation by 2029, but the \$1.4 billion bail-out it received after several municipalities walked away from the rising costs and schedule don't suggest that's realistic.

## 8.3 Are There Other Problems with SMRs?

Yes, yes there are, three of them.

First, *they don't take advantage of vertical scaling.* As discussed, they are highly unlikely to achieve economies of scale of manufacturing due to the sheer number of competing technologies and the lack of any strategic imperative to resolve that issue. But in addition to that horizontal scaling challenge, they don't scale vertically either. Thermal generation units get more efficient as they get bigger, up to a point. That's why most coal and nuclear generation is closer on a per boiler or reactor basis to a GW of capacity, not a third or a tenth of that. There are technical reasons for this, but much of it has to do with the optimum diameter of pipes for most efficient fluid and steam transfer compared to the materials required for them. Bigger diameter pipes move a lot more fluid without nearly as much material. SMRs forego those efficiencies of vertical scale. Amusingly, Gates' Terrapower is designing a 1200 MW capacity reactor, so they seem to have received the vertical scaling memo. Of course, that just puts them back into the same cost problem as normal reactors.

Second, *decommissioning a nuclear reactor is a billion dollar, 100-year venture.* That's been shown empirically by reactors under decommissioning in several countries. The US hold back accounts for roughly a third of those costs, so the tax payer will be on the hook for the rest, about \$70 billion. SMRs will require the same duration and proportional cleanup costs. Taking the Nu Scale deployment, there are intended to be twelve 60 MW reactors for a total of 720 MW of capacity. That suggests in the range of \$720 million for cleanup. While I'm sure SMR advocates expect the reactors to be returned to a centralized processing site for decommissioning, no country in the world

has managed to build a centralized nuclear waste repository, so this premise is deeply unlikely.

Third, *no nuclear reactor is commissioned with private insurance alone*. Every country with a nuclear generation fleet has enacted legislation which caps private liability at some level, and puts any liability above that level onto the shoulders of taxpayers. In the US at present that's \$13 billion. It sounds like a large number, and it is but as was pointed out earlier, Fukushima's total liability is in the trillion USD range. The number of countries willing to sign up for that liability is shrinking globally, not growing.

## 8.4 So who is advocating for SMRs and Why?

At present we see SMR earmarked funds in both Canadian and US federal budgets, \$150 million in Canada and 10 times as much in the US, mostly for research and development with the exception of over a billion to NuScale to, in theory, build something. In Canada, four provinces—Alberta, Ontario, New Brunswick and Saskatchewan—have joined forces in an SMR consortium. Bill Gates' Terrapower has received another \$80 million, as has X-Energy from the US DOE.

The failure conditions of small modular reactors are obvious. The lack of a significant market is obvious. The lack of ability to create a clear winner is obvious. The security costs are obvious. The lack of vertical scaling to thermal efficiency is obvious. The security risks and associated costs are obvious. The liability insurance cap implications are obvious. So why is all of this money and energy being thrown at SMRs? There are two major reasons, and only one of them is at all tenable.

Let's start with the worst one. The Canadian provinces which are focused on SMRs are claiming that they are doing this as a major part of their climate change solutions. They are all conservative governments. Only one of those provinces has a nuclear fleet, although New Brunswick has one old, expensive, and due-to-retire reactor, as well as a track record of throwing money away on bad energy ideas, like Joi Scientific's hydrogen perpetual motion machines. One of the provinces, Ontario, has been actively hostile to renewable energy, with the current administration cutting up 758 renewables contracts and legislating a lack of recourse as a very early act after election.

So why are they doing this? Because *it allows them to defer governmental climate action while giving the appearance of climate action*. They can pander to their least intelligent and wise supporters by asserting that renewables are not fit for purpose, while also not doing anything about the real problem because SMRs don't exist in a modern, deployable, operable form yet.

The other major reason gets back to renewables as well. 15 years ago it was an arguable position to hold that renewables were too expensive, would cause grid reliability issues and that nuclear in large amounts was necessary. That's been disproven by both 15 years of failures of nuclear deployments, but more importantly plummeting

costs and proven grid reliability with renewable generation. Now almost every serious analyst agrees that renewables can economically deliver 80% of required grid energy, but there is still debate from credible analysts about the remaining 20%.

Mark Z. Jacobson and his Stanford team are at the center of this debate. Since the late 2000s, they've been publishing regular studies of increasing scope and sophistication on the thesis of 100% renewables by 2050. The 2015 publication saw a lot of pushback. At the time, my assessment of the fundamental disagreement was that the people who published a criticism of it thought the last 20% would be too expensive, and that both nuclear and carbon capture and sequestration would be necessary and scaled components.

Personally, I've done various aspects of the math, looked at grid reliability and transformation data from around the world, and looked at ancillary services requirements, and I think Jacobson and team are right. Further, since we all agree that renewables are fit for purpose for 80% of the problem we should deploy them as rapidly as possible.

However, *it's very reasonable to make a side bet or two to ensure coverage of that last 20%*. I don't mind research dollars spent on SMRs, which is all most of the SMR expenditures amount to, outside of the Nu Scale bailout (which is added to the Ohio \$1.3 billion bailout, which is added to the annual \$1.7 billion overt federal subsidy, which is added to the annual hidden \$4 billion security subsidy which is added to the \$70 billion unfunded cleanup subsidy, which is added to the uncosted and unfunded taxpayer liability). Spending a few tens of millions of dollars in rich countries to ensure that we have that last 20% bridged is reasonable.

But the people asserting that SMRs are the primary or only answer to energy generation either don't know what they are talking about, are actively dissembling or are intentionally delaying climate action.

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Martin Wolfersdorff and Heinz Plaumann\*

## 9 Repurposing tires – alternate energy source?

**Abstract:** Tires are complex articles by virtue of chemistry, usage and disposal. They have served Humanity at powerful “enablers” for connecting the World by transportation and commerce. However, they also pose environmental issues primarily after their relatively short service lives. This chapter touches these various aspects from “cradle to grave”.

**Keywords:** asphalt modification; burning rubber; disposal; fabrication; rubber; tires.

### 9.1 Introduction

Over 300 million new tires are produced annually in North America alone [1] and several billion globally. Arguably, tires are the most sophisticated and undervalued composite [2] comprising of a number of chemically different elastomers, steel or high-performance fibers (Kevlar®) for belting, fillers, some reinforcing (carbon black, modified silicas), extender and processing aids, along with a vulcanization package. Typically, a passenger vehicle tire has a service life of 50,000–80,000 km and during that time loses about 2 kg of material as road wear and dust [3]. Beyond passenger vehicle tires which carry billions of people safely every day, truck and industrial tires also carry heavy loads over millions of kilometers over all manner of roads.

At the end of useful life these tires suffer various disposal fates, only few of which reflect globally accepted principals of Green Chemistry [4].

This chapter will highlight the challenges by providing information about tire fabrication, usage and invoking the 3Rs – Reduce, Reuse and Recycle – with some future outlook for enhancing enviro-friendliness.

### 9.2 Tire fabrication

Tires are complex composites and their fabrication is an equally complex process [5] (see Figure 9.1). In general, the process entails high-energy mixing of elastomers, fillers, processing aids, extender oils, lubricants like zinc stearate), sulfur as part of a curative in a high intensity mixer such as a Banbury© machine. Up to a ton of material can be mixed in a single batch. This compounded rubber is then masticated further on roll mills to ensure uniformity. This is then calendared into sheets used in tire construction.

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\*Corresponding author: Heinz Plaumann, QuantumQik Careers, 24374 Curtis Drive, Brownstown, MI 48134, USA, E-mail: [hmplaumann@gmail.com](mailto:hmplaumann@gmail.com)

Martin Wolfersdorff, Wolfersdorff Consulting, Berlin, Germany



Figure 9.1: Tire cross-section.

Typically, a tire contains several chemically distinct elastomers (Figure 9.2 – Tire Performance Triangle) – each serving a specific function: natural rubber and styrene-butadiene copolymers often make up the tire carcass for their durability and strength, cis-polybutadiene is important in the tread formulation, EPDM imparting ozone resistance to sidewalls, and butyl or halo butyl rubber giving air impermeability to the inner liner.

Actual tire-building, even today involves much hand-layup, entails applying the sheets of rubber onto a building-drum in correct sequence dictated by the final tire, as well as steel and polyamide belting reinforcements and bead wire. The “green” tire is then placed in a heated, high-pressure mold for curing, often usually an hour at over 130 °C. The tire is inspected and tested for quality before being shipped.



Figure 9.2: Tire performance triangle.

## 9.3 The tire challenge

With so many billions of tires in circulation, the environmental problem is clear:

- What options exist for handling such a large volume of cast off, spent rubber in the form of tires once beyond their useful life? Presently about 60% is used as fuel, 25% stockpiled, disposed in landfill or illegally dumped, 5% is used in civil engineering application, and a small portion for producing articles such as playground matts or comfort matts for dairy cattle [1].

With the bulk of the mass being synthetic rubber and carbon black, what technologies exist or can be envisioned for “harvesting” this hydrocarbon energy or converting it into other articles or forms? Of course, rendering the tire into a more useful form in itself requires anergy investment: Grinding the tires into useful particulate, separation of non-hydrocarbon materials like fibers.

Our discussion here will embrace the 3Rs of Good Environmental Practice – Reduce, Reuse and Recycle [6].

### 9.3.1 Reduce

Conceptually, this involves either reduction of number of tires or increase in service life. The former speaks to broad adoption of alternative forms of transportation, rather than use of the tire as a primary load-bearing component for either human mobility or freight. Several chapters in this volume attest to the shifting technologies for energy generation, but none, save this one deal, with one of humanities’ primary consumption of energy – mobility of people and goods.

Considerable research dealing with tire design and performance of formulated compounds (using functionalized silica fillers in place of carbon black) has yielded increase the service life of tires [7]. However, much of the progress is constrained by performance within the Tire Performance Triangle (Figure 9.2).

### 9.3.2 Reuse

For reuse of tires, our thinking turns to the various components of tire construction: Does this refer to rubber crumb, still vulcanized and containing filler, additives and fibers? For discussion purposes let us agree this refers to vulcanized rubber, still black filled but fibers removed. Such ground material can be used with a suitable binder for production of utility articles like playground equipment/matts or other such cushioning materials (cattle comfort matts) depending upon particle size distribution, it has found some utility in fillers in plastic and related processing [8, 9]. Such crumb has found utility in fillers for plastics and other materials, with the intention of the rubbery domains being energy absorbing domains hence “toughening” the substrate.

A collaboration of Michelin and Enviro converts tire materials into plethora of materials including carbon black, rubber-based products (new tires and wheels, conveyor belts, anti-vibration products) and pyrolysis oil. About 90% of the recovered material is re-used in products and the remaining 10% combusted for power generation. In their 2020 press release they claim most tires now considered as waste can be recycled into raw materials. Further investments by Michelin, this time with Pyrowave [10] are closing the loop with plastics, tires and rubber.

One of the authors (HPP) has direct experience with several technologies falling in the “re-use” category. For a number of years a coal-fire power plant supplemented its energy source burning ground tire rubber, stripped of belting and other materials, with the stacks being appropriately scrubber to prevent sulfur-dioxide emissions. The plant has been converted completely to natural gas fuel since 2010. Coincidentally, it is not uncommon for stockpiled tires become the fuel for serious long burning fires, undoubtedly very significant environmental disasters [11].

With ground tire rubber being closely akin to asphalt as used in road construction, a logical application would be for use in hot-mix paving applications. In fact, during the 1990s Florida required addition of ground tier rubber to asphalt for new road construction [12]. With direct experience in asphalt modification technologies (several patents and conference presentations), one of the authors (HPP), I learned that with two main shortcomings of asphalt in roads – when hot, it deformed resulting in rutting and when cold became brittle resulting in fracture and pot-holes. The addition of vulcanized rubber crumb overcame these two problems inadequately and many test sections of road had to be replaced within a few years. Additionally, BASF entered the tire-reuse race in partnering with Pyrum© to produce pyrolysis oil for use in plastics, coatings and as a fuel [13]. An approach to dissolve and recycle rubber from tires also shows promise but is in early stages of development [14].

A very innovative and esoteric tire reuse strategy in the 1970s was to dispose of tires off the coast of Florida creating an artificial reef for growth of coral and other sea life. About 700,000 tires were placed into the Gulf of Mexico but failed to produce the desired results, possible because of changing currents, climatic conditions, blooming of processing oil to the surface of the tires. Several tens of thousands were subsequently exhumed and disposed of otherwise [15].

### 9.3.3 Recycle

The direct “recycling” of tires is imaginable by taking a spent tire carcass and so upgrading it to be ready for service again (Figures 9.3 and 9.4). Mostly tires are rendered spent when their tread has worn to the point of being unsafe. Extension of the life of heavy truck tires, aircraft, utility vehicle and others by applying a new tread is widespread – ca. 18 million tires retreaded in 2006 [16–18]. However, the technology



**Figure 9.3:** Tire recycling processes.

Technology	Select Players	Pros	Cons
Micronized Rubber	Lehigh Technologies	Commerically Proven Accepted by Tire Industry	Rubber Still Vulcanized. Low level use a filler
Devulcanization	Phoenix Innovation Tyromer	Of interest as high value-added Product	Poor business track record Polymer blends
Carbon Black Recovery	Delta Energy Ecolomondo Pyrolyx Reklaim	Semicommercial Broad range of applicability	Capital Intensive Tire industry not accepting yet

**Figure 9.4:** Where Scrap Tires Go. M. McCoy, Chemical and Engineering News, April 20, 2015.

although proven is seldom applied to consumer passenger tires – discomfort on the road, safety concerns and inexpensive new tires.

## 9.4 Path forward – outlook

As we have seen, the everyday vehicle tire can indeed be processed through to 3Rs to rendered them to be less of an environmental challenge. However, what else can be done?

- New “tire/wheel” technology – Michelin and others have experimented with suitable tire replacements (Tweel® wheel) in which as reprocessasble tread (for example thermoplastic polyurethane) can be bound to a suitable tread material (Figure 9.5). Thusfar, these have been applied to utility vehicles awaiting commercialization to others.
- Changing cultural mores to slower speeds to reduce wear and improve tire life.
- Continued research to improve formulation and tire design.

Without a doubt, tires are among our best Technical Friends – Enjoy the ride!



**Figure 9.5:** Alternative Wheels – Michelin’s Tweel®.

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Joji Watanabe\*

## 10 Finance for Green Chemistry through Currency Mix

**Abstract:** Introduction of green chemistry will require a large sum of finance to conduct basic research and develop applications at various research institutes in the public and private sector. To meet the financial needs, the author suggests a change in the currency system commonly applied in most countries to a mix of debt currency and equity currency, in which the latter means currency directly issued by the government, thereby avoiding arguments on the upper limit of government bond issuance. In most advanced economies potentially with large excess supply capacities, bad inflation never takes place as long as workers can work in peace under good securities, and as long as additional budget can be used in proper manners. This new currency issuance system for sufficient public funding will not only support research and realization of green chemistry, but also solve social problems by assisting the underprivileged, etc.

**Keywords:** China; currency mix; debt currency; debt trap of its own currency; equity currency; Japan.

### 10.1 Green Chemistry requires finance

Green chemistry is a very challenging agenda because of incremental costs and investments to apply, although it can provide positive long-term impacts in the history of mankind since we started our lives on the earth several millions years ago.

Our efforts to implement green chemistry can lead us to significant environmental benefits and innovation. However, we need to cover the costs for needed research, investments, and applications even after technologies are well developed.

We now recall what happened when we started experiencing negative impacts on our environment through industrialization applying developed technologies in a large-scale for about 50 years after the end of World War II in 1945.

In Japan, the first Law on Public Pollution Measures were enacted in 1967 having faced with major pollution disputes e.g., Itai-Itai Disease and Yokkaichi Asthma. This law was superseded by new Law on Basic Pollution Abatement Measures in 1993.

Serious cases of air/water pollution were found at one of the four national industrial zones of Japan. Kita-Kyushu city became known for its polluted air full of smog and dirty sea water; once called “dead sea” in which even *Escherichia coli*

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\*Corresponding author: Joji Watanabe, NPO All Life Line Net, Environmental Science Corporation, Itsuro Bldg. 4F, 3-7-2, Kanda-Nishiki-cho, Chiyoda-ku, Tokyo 101-0054, Japan, E-mail: watanabe\_j@nifty.com

normally found in human guts cannot survive due to industrial toxic sewage from local industries. The city of Yokkaichi in another industrial zone known as an industrial center of petrochemical industries had nearly 100,000 air pollution-related patients in 1960s–1970s.

In the industrial zones of Japan, the Japanese citizens used to feel happy to see colored flue gases for some years after new plants and factories were erected and many of the citizens were hired to work and receive good salaries there. However, after many of their children and senior citizens got asthma, dermatitis, even nervous disorders, etc. the society had to go through disputes, conflicts, and long-term litigations.

Although the industry side admitted that their plant operations had impacted the environment badly, they were not able to decide to compensate for disorders of too many patients. Rather they believed that they cannot survive in the global competition against advanced economies in the US and Europe, if they must pay for the environmental and human damages.

Such litigations lasted many years, even more than 40 years in case of Itai–Itai Disease, not because the industries cannot find appropriate technologies, but because solving the problems would require large costs for technical applications and investments.

## 10.2 Questions raised on currency and economy management

### 10.2.1 Currency matters, but ...

Currency has been a kind of enigma or an issue most scholars majoring in economics have been told to avoid studying for some reasons. First, because the reality of currency should not be known widely as such because bankers want to keep it in secret to outsiders, particularly as regards the fact that any bank including major ones may go bankrupt if all the customers try to withdraw some money at once. Secondly, neoclassical school of economists e.g., Alfred Marshall assumed that currency creation is outside the scope of their studies with their complete mathematical system based on assumed rational human behavior and a market equilibrium. Thirdly, Keynesian economists support that money supply is mainly a matter of open market operations by the central bank, and do not believe that an economic system can be modelled with so many players of commercial banks to affect money supply through bank loans.

The Bank of England in its educational website titled “Money creation in the Modern Economy” explains as follows:

When a bank makes a loan, for example to someone taking out a mortgage to buy a house, it does not typically do so by giving them thousands of pounds worth of banknotes. Instead, it credits their bank account with a bank deposit of the size of the mortgage. At that moment, new money is created. For this reason, some economists have referred to bank deposits as “fountain pen money”, created at the stroke of bankers’ pens when they approve loans.

Whenever a bank makes a loan, it simultaneously creates a matching deposit in the borrower’s bank account, thereby creating new money. This description of how money is created differs from the story found in some economics textbooks.

This means the economics textbooks have false statements, and it is no wonder, most people have misunderstandings on our currency and economy.

Another misunderstanding widely accepted and deeply believed by the people, officials and economists in Japan is that high proportion of accumulated government bonds is not good because it can be a big financial burden for the future generations. However, one of the sub-reading materials at US business schools “Money” [1] clearly explains the opposite truth on the national debt in Chapter 13 SHOULD WE WORRY ABOUT THE NATIONAL DEBT? as follows:

A budget deficit requires that the government either prints money or borrow to cover the deficit, and most modern governments choose to borrow (that is, sell government securities). As a result, we acquire a national debt, embodied in the form of government bonds; the total of the government securities outstanding is the national debt. ...

All evidences of debt must appear on two balance sheets, and government securities are no different from any other IOU in this respect. ...

After all, money is a financial asset, which implies that someone else there has a corresponding liability. If liabilities go up as rapidly as assets, the country as a whole (including both the government and the private sector) can be getting no richer. ...

By the same token, however, exactly the same logic also implies that another favorite conservative incantation is equally false: namely, the belief that increasing the national debt makes a country poorer. ...

To become poorer-to reduce its net worth-a country must reduce its holdings of real assets; curtail its production of real goods and services. Increasing the national debt, no matter how high, cannot in and of itself make a country poorer so long as it is owned internally. ...

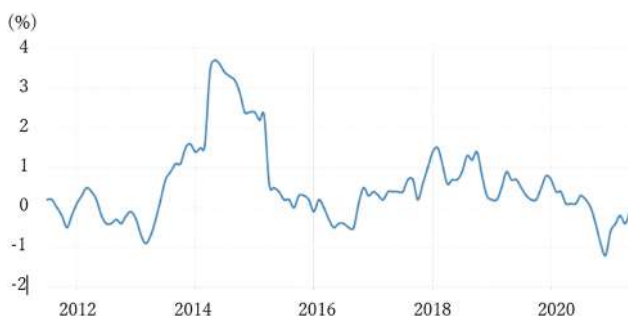
Nor does an increasing national debt, just because of its size, impose a burden on future generations.

As long as the debt is held internally, neither the interest nor the principal represents a dead weight on the backs of our children and grandchildren.

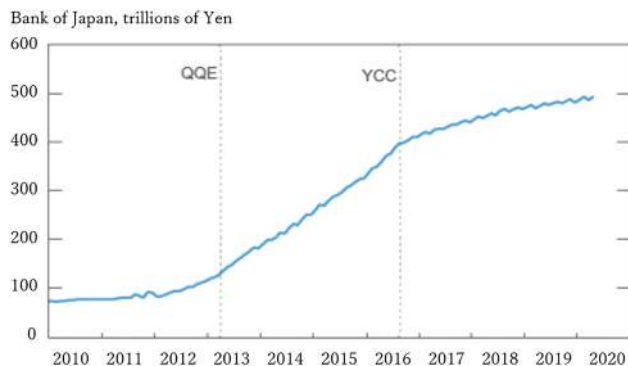
## 10.2.2 A big question after “Abenomics” in Japan

In Japan also, it has been a matter beyond the scope of most economists up to late 2010s when some people started questioning to the fact that the inflation target of 2% under Abenomics [2] since 2013 had not been achieved, except only in 2014 as shown in Figures 10.1 and 10.2 below. In Abenomics, an extremely high level of monetary easing (increase in money supply) was conducted by the Bank of Japan (Central Bank of Japan) which purchased government bonds of Yen 60–80 trillion/year, the size far beyond any historic record, in spite of serious warnings by many economists that hyperinflation will take place and bring Japanese economy to a total disaster due to excessive money supply.

Having noticed that inflation has been well controlled since 2013, Japanese economists started arguing when they saw the message by one of the US presidential candidates, Bernard Sanders a democrat running with an economic advisor: Professor Stephanie Kelton with an economic theory Modern Monetary Theory (MMT), because



**Figure 10.1:** Inflation in the recent years of Japanese economy. Trading Economics Ministry of Finance, Japan.



**Figure 10.2:** Qualitative & quantitative easing (QE) for yield curve control (YCC). Ministry of Finance, Japan.

MMT can explain why Japan's economy had not given any signals of hyperinflation or potential default in the nation's economy in spite of massive monetary easing since 2013.

## 10.3 Management of national economies

### 10.3.1 Three groups of vessels A, B, and C in each economy

Having analyzed Abenomics of Japan, which did not produce expected results on inflation, I presume that economic advisers had comparatively a simple economic model with a large single vessel in the economy. For instance, they believed that if the central bank purchases government bonds, an adequate amount of money will go to consumers and companies willing to use money, thereby increasing demands and cause inflation over 2%. However, this did not happen, because their model was too simple.

Comparing the economy to chemical process, any economy has three systems or groups of vessels. In each are so many vessels as in Figure 10.3.

Group A (Money producers) has a money production system with those vessels engaged in money production, such as Central Bank, Ministry of Finance (MOF) and many other commercial banks. The Central Bank produces money by purchasing government bonds (securities), company shares, other financial products, and foreign currencies from mainly commercial banks, whereas MOF issues government bonds and coins [3]. The commercial banks purchase government bonds, and in return provide money in the bank accounts. The commercial banks are also money producers in the market by giving loans to companies and individuals.

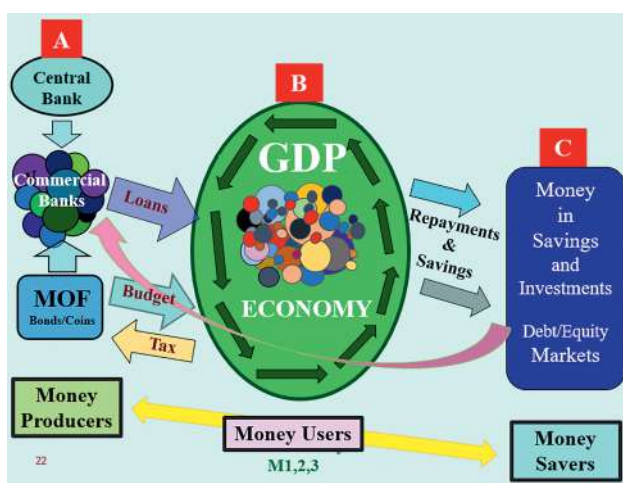


Figure 10.3: Three group of vessels A, B, and C in the economy.

Group B (Money users) has a system consisting of individuals, companies, and NPOs doing transactions. All of them are circulating money from one to another in line with their activities to form GDP all year round. They all receive money by manufacturing/supplying products and services for other individuals and companies, and pay money to individual workers as salaries, to purchase materials, products, and services from other economic entities including public institutes, companies, and individuals.

GDP is one of the major concerns for any government, whose objective is to enhance economic development to gain higher GDP. However, the total GDP decreases or shrinks due to recession or when warnings are given by some economists. Also the total sum of money circulating in GDP decreases when the government budget goes down, consumers conduct savings or loan repayments to cope with economic downturns. That means GDP vessel has big holes at the bottom influenced by human emotions, through which money goes out of vessels in Group B to Group C.

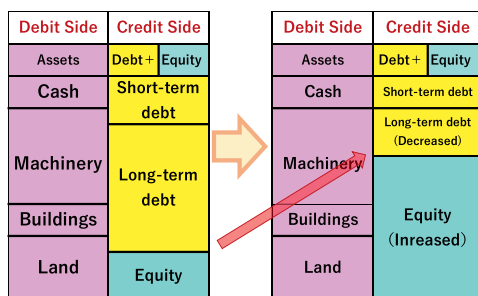
Group C (Money savers) is where money is saved and accumulated, consisting of commercial banks and insurance companies, all of which receive money in various manners. For example, commercial banks serve individuals and companies to keep their money in their savings accounts. Also the commercial banks receive money as principal repayment and loan interests, which reduce the total sum of circulating money in Group B. In this way, some of money in circulation in GDP in Group B goes to Group C.

### 10.3.2 Understanding MMT in view of chemical process

Dr. Frederick Soddy, a British scientist who received Nobel Prize in chemistry published four books on currency and economy from 1921 to 1934. He analyzed a fundamental problem in the economy that financial debts grew exponentially at compound interest, but the real economy was based on exhaustible stocks of fossil fuels. Considering this from the opposite side, not only fossil fuels, but also all materials, even air and water on the earth have upper limits in the respective amounts, but any currencies like numerical values can be issued as much as necessary. We can accept this fact quite easily because we now live in the digital world, which means any government of its own currency can issue money digitally as much as it needs in semi-conductor memory (see Figure 10.4).

As an economist experienced in advisory services for developing countries, but formerly a chemical process engineer within Royal Dutch Shell group, I suggest several key points in management of our modern economy as follows:

- a. Hyperinflation (bad inflation) never takes place in advanced economies with large supply potentials as far as the people can work to produce/supply goods and services in peace and good security under democratic governments. In managing our economy, inflation or consumer price index should be the most important parameter to watch in setting the government budget.



Too much debt for repayment

Debt replaced by increased equity

**Figure 10.4:** DES for turnaround management of a company.

- b. All the currencies in the world up to today are called “Debt Currencies” because creating loans/debt is the only method to produce additional currency because it is produced through bank loans, or government bonds to be purchased by commercial banks and the central bank.
- c. Government bonds (treasury bills in US) and the currency (or money) has the same meaning in finance. They are debt for issuing institutes (government/central bank), but assets for those who keep them. If you buy any government bond, that is your financial asset just as your money.
- d. Debt Equity Swap (DES) is often conducted for turnaround management of companies with high proportion of debt comparative to owners’ equity incl. retained earnings accumulated, thereby reducing the debt burden.
- e. DES is a simple method to reduce government bond accumulated in the market every year. For instance, the central bank’s buying of the government bond from banks, etc. is conducting DES, because government bond is changed into currency in the market, because government bond purchased by the central bank is no longer a burden for the Treasury (Ministry of Finance).
- f. The other innovative method of DES is issuing the currency by the government (not by the central bank) and reducing the amount of government bond issuance in the annual government budget. This is innovative because the currency issued by the government is considered as equity currency, not debt currency.
- g. The objective of our economy management is neither controlling money or debt, nor any sectors of the market in monetary terms, but is to keep a nation-wide system to supply adequate amount of goods and services for those who need them, rather than watching numbers of economic indicators.
- h. Money or currency is only one of elements for the government to control to keep sound market of goods and services. Money is lubrication oil for exchanging goods and services, but the amount of money can be any number as much as necessary as far as the inflation is well controlled.



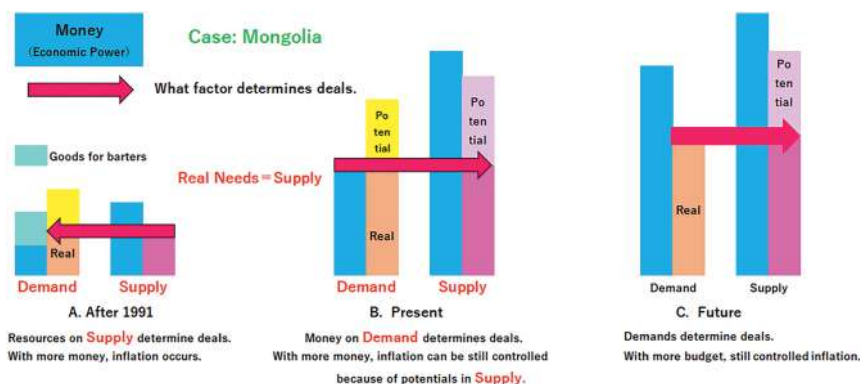
### 10.3.3 Misperceptions in economy management

Having observed Abenomics not achieving the inflation target of 2%, I felt frustrated, because controlling a single parameter, either one of temperature, pressure, or flow per hour is a simple task in case of process control in chemical plants. Having studied some papers and economic data on the recent past performance of the Japanese economy, I found the following misperceptions in light of chemical plant operations:

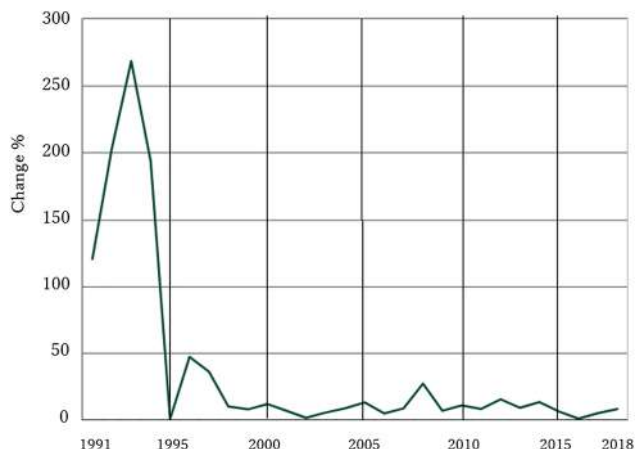
- Any economy of a single currency has numerous vessels and pipelines, although economic theories can only assume only a limited number (a few to several) of vessels or layers as mathematical equations can accommodate. So, even massive purchase of national bonds by the Bank of Japan did not increase sum of money in vessels directly connected to inflation, consumptions, and GDP. Money only increased in the bank accounts of commercial banks within the Bank of Japan, but not in the market, because the Bank of Japan bought government bonds from the commercial banks which have bank accounts in the Bank of Japan.
- Inflation and GDP growth was expected by monetary easing, but GDP vessels have too many holes at the bottom. Major holes were seen in vessels owned by major companies and wealthy individuals who did not additionally use money to buy things so as to cause inflation, but put away earnings into banks and financial market; which increased stock prices, or repaid their loans only to reduce the total sum of money in circulation forming GDP.

### 10.3.4 No worry after development with good supply capacities

During my engagement as a consultant for the government of Mongolia since early 2019, I developed Figures 10.5 and 10.6 showing respective phases of economic development of Mongolia, A, B, and C. to suggest that bad inflation would never take place as long as people can work in peace and good securities, once potentials of supply capacities



**Figure 10.5:** Three phases of economic development A, B, and C.



**Figure 10.6:** Inflation in Mongolia since 1991 through 2018.  
Trading Economics.

exceed the demands. This means that any government of national economies with potentially enough supply capacities can issue as much government bonds as necessary, but only by monitoring the general inflation.

- A. (After 1991) shows the economy of Mongolia after 1991 and is also the model after the World War II of Japan. In Mongolia from 1991 through 1995 after the collapse of the Soviet supply management system in 1990, the people started suffering from shortages of fuels, foods, and other industrial goods which, otherwise, should have been supplied from Commonwealth of Independence States (CIS) countries. Because of the shortages, high inflation over 50% persisted early 1990s.

Those days, many people started barter trading across borders. In this model, available resources to supply are extremely limited, and such limited resources are the determinant factor for the total transactions: GDP in the economy. Therefore, if more money is supplied, inflation will go up due to limited goods.

- B. (Present) is the current economy of Mongolia where people with limited purchasing power still want more quality goods and services. Some inflation but fairly controlled in the range 5–15% has been seen every year after 2000, except 27% in 2008 due to the Lehman shock. If more money is supplied in the hands of the people, they buy more, but some competition in the supply market would not allow high inflation.
- C. (Future) is the economic model of Mongolia in the future and is current Japan in the recent 30 years where both sides: demand and supply have enough economic power and enough resources overall, but with substantial unused potential supply capacities. However, the people's desire to get more goods and services is limited keeping deflationary pressure all the time.

In phase C, the limited desire on the demand side is the determinant factor of GDP, regardless of the amount of money infused constantly into the money market from the central bank of Japan as one of the government policies. This shows that monetary policy has its limitation.

MMT gives interesting insights on needs/impacts of currency creation at each development stage of our economy, although some economists in Japan are still worried about possibilities of hyper-inflation or default of the government in the future because of increased budget to assist companies and individuals during this pandemic.

However, simply referring to the mathematics in economics as shown below:

$$Y(\text{GDP}) = C(\text{Consumption}) + I(\text{Investment}) + G(\text{Government}) + X(\text{Export}) \\ - IM(\text{Import}).$$

and when C, I, and X become very small, the government should take a major role of infusing money into the economy to make the balance and prevent many of the economic entities from going bankrupt.

## 10.4 Cases of debt trap; Japan, Sri Lanka, and Mongolia

The following three countries, Japan, Sri Lanka, and Mongolia seem to have no simple exit from their debt traps, respectively, in different manners. Many economists believe that there will be no simple remedial measures to cope with these debt traps. However, in my view as a chemical process engineer, solution is not considered difficult once you understand all these debt traps have come from a fundamental defect of the currency system prevailing in the world as today's standard.

### 10.4.1 Japan; low economic growth in the recent 30 years, yet contributing to China

The Japanese government looks extremely slow in dealing with COVID-19 demanding the people to stay home, in view of the fact that the number of infected patients in Japan has been less than 3–5% of other advanced countries.

Even the central gov. appropriated yen budget: US\$14 billion for emergency measures, the local governments have not used it at all, because local government officials believe use of budget is not good because it will create financial burdens in the future. Moreover, because of inadequate public funding in the recent 30 years, they have cut down the number of civil servants, and social medical support system, such as the number of local health care centers including medical experts.

The current Japanese have a psychological “Debt trap” due to frequent announcement by the Ministry of Finance that the Japanese government has the largest public debt of 260% of GDP in the world, although MMT [4] explains that any amount of the accumulated government debt by issued government bonds is not a problem because it is another way of increasing money circulation in GDP to take care of emergencies and the underprivileged, and also to accommodate sound economic growth in good times.

In today’s world, our currencies are regarded all digital and fiat ones irrelevant to holdings of gold, without any material upper limit in stark contrast to any materials or substances on the earth. However, the Ministry of Education in Japan does not provide enough budget for conducting academic research at universities to the extent that a professor in the engineering faculty at a regional public university receives only several hundreds of dollars/year as research fund.

Although Japan has the second largest number of Nobel laureates after US in the recent years, the professors in Japan cannot suggest to any academically excellent students that they should pursue research career after graduate programs. Because most Japanese politicians and high-ranking officials at the Ministry of Finance mistakenly believe the government budget should not exceed the tax revenue, often reiterating that ideally no government bond should be issued to supplement the tax revenue for the government.

Unfortunately with adequate funding at universities in China, some Japanese professors/researchers often go to China to visit their counterpart research laboratories in the recent years. Moreover, among approximately 600 Japan-based high-tech manufacturers of state-of-the-art machines, electron microscopes, analyzers, etc., many moved to China to establish sales offices and even manufacturing sites there for China’s research activities.

Japan has many well experienced researchers and excellent young brains for research, together with world-class high-tech manufacturers, but not enough budget from the government. This is leading the whole system to contribute to development of China with more aggressive initiatives. This is caused by a general but simple misperception that the government bond is bad, coming from the inflexible currency system of the world standard that the government cannot issue digital currency of her own.

### 10.4.2 Sri Lanka; controlled by China

Sri Lanka has been in a big “debt trap” owing to Chinese loan scheme such as “One Belt, One Road” initiatives, with which the government of Sri Lanka developed large-scale infrastructure projects e.g., Hambantota Port opened in 2010, Norochcholai coal power plant commissioned in 2011 and Mattala Rajapaksa International Airport opened in 2013, etc. and the recent total debt to China amounted to US\$ 9 billion,

the burden too big to repay for the government of Sri Lanka. As a result, 99 year contract was made with the Chinese company: China Merchant Port Holdings Limited for \$1.12 billion in 2017 to let them occupy the port, strategically excellent due to its location open to the Indian Ocean. According to IMF, Sri Lanka's foreign debt balance is about \$56 billion. It accounts for 69% of the country's GNI in 2019 [5].

However, if three major banks of US, EU, and Japan form a consortium and issue equity currency in US\$, Euro, and Yen, all the debt to Sri Lanka can be nullified quite easily. Other than repaying all the debt to China for the government of Sri Lanka to nullify the total loans from China, no bad effect will take place in the global market because all the infrastructure projects have been completed and no activities will be taken.

### 10.4.3 Mongolia; constrained sound economic growth

Although Mongolia has abundant natural resources, enjoying trade surplus quite often by exporting coals, copper, gold, other minerals, the economy of Mongolia had a big sum of foreign currency debt equivalent to over 250% of GDP [6] whereas the domestic currency debt as small as 0.26% of GDP at the end of 2019 (see Table 10.1).

Money creation is of vital importance for any nation with her own currency like Mongolia to enable its sound economic development. However, in case of Mongolia, they cannot increase the amount of her own currency: MNT [7] because of the currency system for the following two reasons.

Firstly, they cannot issue their government securities or bonds due to high interest to increase their government budget for industrialization e.g., food processing to produce dairy products, and secondly businessmen prefer to get foreign currency loans at low interest rather than getting loans from domestic commercial banks at loan interest close to 20%/year. In fact, trading of government securities was initiated in cooperation with the central Bank of Mongolia in 2012 at the Mongolian Stock

**Table 10.1:** Mongolia's total debt.

Debt	Amount unit: million USD
Debt in foreign currency	30,599.63
Short term	2926.19
Long-term	27,674.44
Debt in domestic currency	78.25
Short term	37.45
Long-term	40.71
Uncertain	–
Gross debt	30,677.88

Bank of Mongolia. Statistics are prepared in accordance with IMS's SDSS standard as of 2019/12/31.

Exchange, but has been suspended since October 2017 because of its mounting pressure from high interest on the Treasury. Again in 2020 when the Treasury discussed re-issuing of the government securities, the suggested interest was 17%/year or so owing to the low credibility of the government of Mongolia.

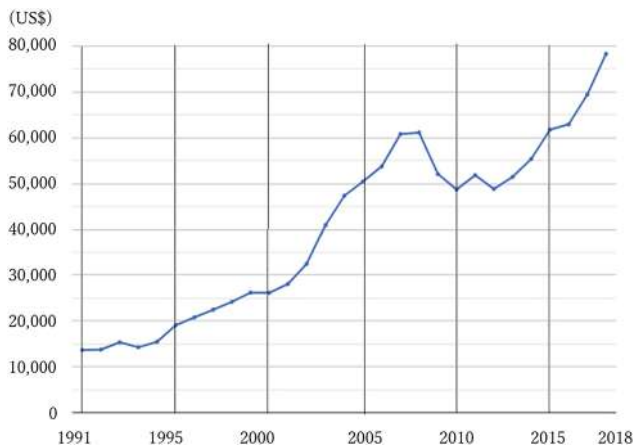
Currency can be created either through issuance of government securities or through loans from commercial banks in any country with its own currency, but both ways cannot be used in Mongolia, although there are potentially plenty of Mongolian entrepreneurs wishing to establish strong industrial bases other than those based on natural resources. Consequently, the Mongolian economy is serving foreign economies through repaying principals and interest of foreign currencies. In fact, quite often each one of family members in Mongolia works abroad and sends foreign currencies back home to sustain the livings of their families in Mongolia.

## 10.5 Mistakes by IMF in Ireland and Greece

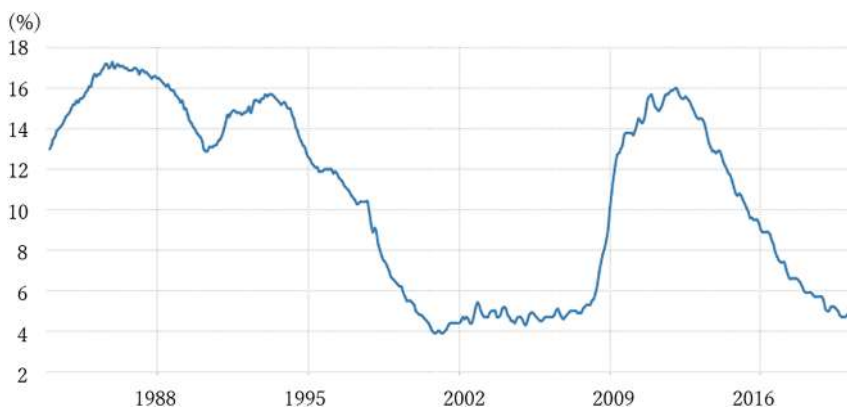
To formulate measures to improve economies of any countries, we should look at flows of goods and services in the market together with conditions of people's life such as unemployment, but should not focus too much on improving the macro-economic indicators, such as government debt or fiscal balance. Unfortunately, however, both Ireland and Greece had to go through extremely difficult periods of time for the people owing to interventions by IMF economists who focused too much on improving economic indicators.

Ireland, which used to be a colony of UK till 1921, known as one of the poorest countries in the western Europe, became an EU member country in 1973. In 1990s, owing to foreign direct investments, it achieved a high economic growth around 9% annually because of lower corporate tax 12.5% than the other EU countries. However, after the Lehman shock adversely affected the global financial system in 2008, the economy of Ireland had negative impacts in 2010, such as delayed loan repayments of housing loans which had been rigorously provided by banks in Ireland. For this, the government of Ireland provided guarantees and financial facilities to support banks in emergency. As a result, the government debt ratio per GDP went up from 40% to 80% along with the budget deficit increase from less than 3% of EU standard to 32% (see Figures 10.7–10.9).

To respond to the request from the government of Ireland, EU/IMF advised to implement stringent measures for three years since 2010 e.g., increased interests in housing loans. As a result, poor people left behind the economic boom had to suffer from expensive leases for a limited number of newly constructed houses. Consequently, homeless people increased four times as many as several years ago to nearly 10,000 [8]. The unemployment increased from less than 5% before the Lehman shock to max 16% in 2012. Also the government debt to GDP went up from below 30–120% in the same period. This means that the stringent measures by EU/IMF



**Figure 10.7:** Per capita GDP (purchasing power parity [PPP]) of Ireland from 1995 to 2019. WB data in Trading Economics.



**Figure 10.8:** Unemployment of Ireland from 1998 to 2020. Central Statistics of Ireland data in Trading Economics.

did not help improve, but worsen also the macro-economic indicators and the living conditions of the people in general.

However, if equity currency is issued by the government, Ireland's national debt would not have increased to 120% of GDP, and much milder measures would have been suggested by IMF, enabling a lower government debt and a lower unemployment leading to a smaller number of homeless people at the end.

In Japan foods loss is one third of the total supplied foods every year meaning that six million tons of foods is just dumped as wastes [9], although some poor people cannot eat and even kill themselves because they have no money. It should be



**Figure 10.9:** Government debt to GDP, Ireland from 1980 to 2018.  
Central Statistics Office of Ireland data in Trading Economics.

emphasized that simple austerity measures driven by macro-economic indicators never make sense when there are more than enough goods and services available for the whole population.

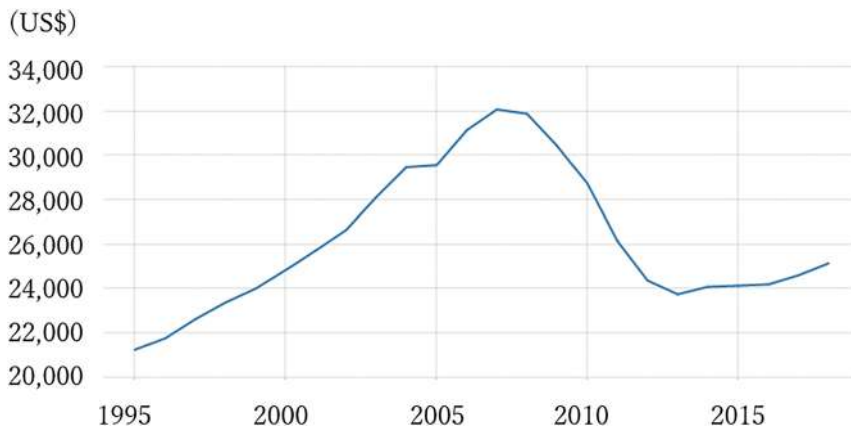
In other words, we should keep watching sound or constant flows of goods and services for those who need them, rather than trying to control macro-economic indicators.

In case of Greece, three authorities, EU, IMF, and the European Central Bank (ECB) worked together in so-called Troika to assist the government of Greece, which implemented austerity measures since 2010 for her inaccurate public statistics on the government debt estimated to have exceeded 100% of GDP. However, because of the reduced government budget to keep her fiscal balance, the unemployment rate, 13% in 2010 went up to about 28% in 2013 and the national product was reduced to a disastrous 75% of that in 2008. Moreover, the government debt in the range of 100–120% of GDP in years from 2000 to 2009, increased to a range of 160–170% from 2011 through 2015, causing a lot of strikes and demonstrations by labor unions in late 2010 as shown in Figures 10.10–10.12.

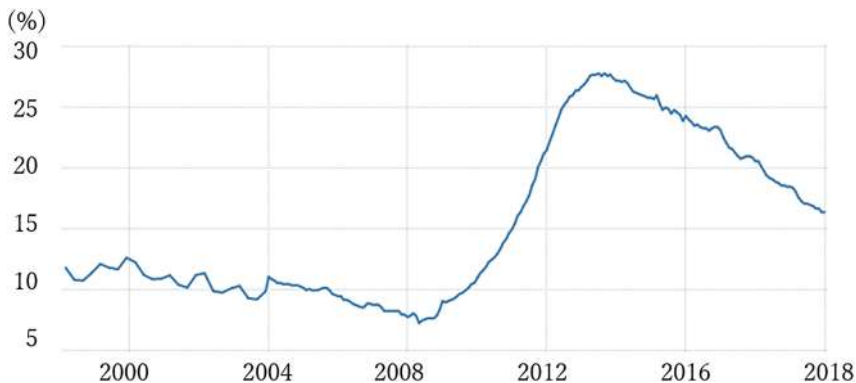
In spite of various advice by the IMF economists, most macro-economic parameters of Greece significantly became poorer and caused political disturbances towards the election in July 2019. This election was characterized as turned out with a majority of New Democratic Party as the first bailout government after almost a decade of recession.

Although IMF later admitted that they had underestimated negative impacts of their suggested measures, it is considered that mistakes came from the fact that IMF economists tend to focus too much on macro-economics, challenging to improve the numbers in a short period of time, especially national debt by tightening government's fiscal balance. IMF/EU did not implement comprehensive measures such as

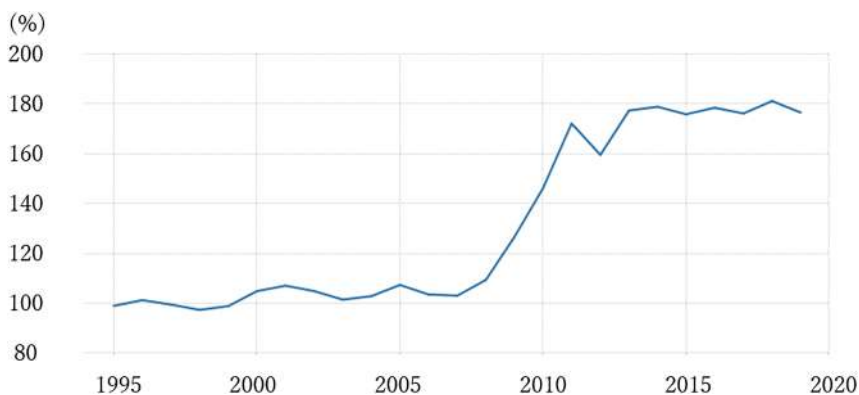




**Figure 10.10:** Per capita GDP in purchasing power parity (PPP) in Greece 1995–2020. World Bank (WB) data in Trading Economics.



**Figure 10.11:** Unemployment rates in Greece from 1998 to 2020. WB data in Trading Economics.



**Figure 10.12:** Government debt to GDP in Greece from 1995 to 2020. National Statistical Service of Greece in Trading Economics.

industrial renovations, improvement of workers' mindsets and skill levels, training and education, etc.

Words by MMT proponent professors are cited here:

Politicians are obsessed with something which does not matter (balancing their budget), and are ignoring many things which do matter a great deal for the future of the country. The government could and should be using its role as the currency issuer to promote full employment, social inclusion, ecological repair, and healthy private sector balance sheets. (An article from Conversation January 31, 2017 "Explainer, What is modern monetary theory?" by Steven Hail, Lecturer in Economics, University of Adelaide, Australia)

In fact "Politicians" in this statement should include many of the economists in Japan, IMF, EU, etc.

## 10.6 New technologies supported by currency mix can solve most economic problems

In our economies of advanced countries in general, we will never see bad inflation in daily goods and services as far as we keep peace and good securities with adequate competition in the supply market, because any excess currency goes to savings after one time use after disbursed, if too much is issued.

We should understand our advanced economies in light of the nature of currency, where the amount of currency should not be any constraint in establishing national strategies, because all currencies are just numerical values in the digital world.

Moreover, owing to constant advent and applications of new technologies, we now live in the world of non-scarcity including energy resource in our total living system.

Under the non-scarcity concept, we should more effectively control exploitation of all the resources. We will consider "Money is not that important." Likewise, "Materials are not that important." Probably keeping our environment and nature in good manners with balanced business and leisure time for the people will be more important than anything else.

Consistently sound high economic growth of Singapore since its independence in 1965 has been probably well supported by their special currency system where currency is issued by the Monetary Authority of Singapore (MAS) as one of the government organizations as explained in the website < <https://www.mas.gov.sg/> > below. In stark contrast to the Bank of Japan, MAS has not been maintained as just a central bank as in the following:

Our Mission

To promote sustained noninflationary economic growth, and a sound and progressive financial center.

Our Story

Prior to 1970, the various monetary functions associated with a central bank were performed by several government departments and agencies. As Singapore progressed, the demands of an increasingly complex banking and monetary environment led to streamlining of the functions to facilitate the development of a more dynamic and coherent policy on monetary matters.

In 1970, Parliament passed the Monetary Authority of Singapore Act leading to the formation of MAS on 1 January 1971. The passing of the MAS Act gave MAS the authority to regulate the financial services sector in Singapore.

MAS has been given powers to act as a banker to and financial agent of the Government. It has also been entrusted to promote monetary stability, and credit and exchange policies conducive to the growth of the economy.

In April 1977, the Government decided to bring the regulation of the insurance industry under MAS. The regulatory functions under the Securities Industry Act (1973) were also transferred to MAS in September 1984.

MAS now administers the various statutes pertaining to money, banking, insurance, securities, and the financial sector. Following its merger with the Board of Commissioners of Currency on 1 October 2002, MAS also assumed the function of currency issuance.

Today, constraints can be only found in our brain power and inadequate understandings among different sectors of the society, let alone some conflicts and disputes, working as barriers in information flows and commercial activities.

Now to smoothly implement somewhat high cost green chemistry, we can increase our public funding substantially by changing the concept of currency to support our new economy by means of optimum mix of debt currency and equity currency.

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