Malaysian Journal of Chemical Engineering & Technology 2 (2019) 41–56

Malaysian Journal of Chemical Engineering & Technology

Journal Homepage: www.mjcetfkk.uitm.edu.my

On the historical role of chemical engineers in sustainability transition

Masayuki Horio

Graduate School BASE, Tokyo University of Agriculture and Technology, Koganei, Tokyo, Japan

Corresponding email: myhorio06@ca.wakwak.com

Abstract

The chemical engineers' historical role is defined and discussed based on the understandings on the sustainability transition, on its meaning in the human evolution, and on the present social struggle for the transition issues. First, by reviewing the history of chemical engineering, a stepwise development with roughly 30year intervals was demonstrated. Moreover, it is revealed that chemical engineering is now facing a situation where it can/must define its subject area as the whole socio-metabolic system and its target as sustainability transition. Through philosophical and sociological arguments, concepts of human existence, society and social system, production/consumption, exchange and economy, politics and policies, information, science and technology are clarified with a hope that these issues can be incorporated into chemical engineering principle in the future. By analysing the social actor structure, the significance of academic societies in the above struggle is discussed.

Article Info

Article history:

Received date: 24 March 2019
Accepted date: 22 May 2019

Keywords:

Chemical engineering
Historical role
Definition of technology
Sustainability transition
Social deliberation

1.0 Introduction

The world's rapid economic growth reached unprecedented level already in the 1980s and the concern of developed countries has shifted from simple linear growth to more sophisticated 'reflexive modernisation' with smart risk management as first proclaimed by Ulrich Bech (1986). In accordance with the recognition of a wide spectrum of negative aspects of the economic and technological developments and how to overcome them via democratic approach has become the concern of the philosophical discourse on technology as can be found in Langdon Winner (1986) and/or Andrew Feenberg (1999). Since then, the world looks like running further toward an unsustainable end at almost mid-21st century in an unprecedented speed in the following three ways: First, anthropogenic global environmental problems, including climate changes by atmospheric greenhouse gas accumulation, oceanic pollution with fragmented plastic wastes, and accumulation of high level nuclear wastes, which needs at least careful control over ten thousand years, are all reaching critical situations. Second, rapid developments in information and life sciences/technologies are reaching a level where they could undermine the foundation of human dignity. Third, the world political and economic governance seems to be degrading to a critical situation due to loosened world power balance and to the outbreak of destitute populations and refugees in and from global South and from war-worn Mideast. Let us call these situations 'sustainability transition problems'.

The first two transition problems have sprung out from the big technological leap and economic booming in the post-World War (WW) II period, where we find energy shift from coal to petroleum, wide utilisation of synthetic fibres and plastics, development of integrated circuits and all varieties of electronic appliances, computers, sensors and measuring instruments, dissemination of automobile, and related social infrastructures, etc. The outcome of the surge of artefacts produced by the 20th century's (20C) technology can be seen everywhere in our life. Indeed, none of them are irrelevant to the contribution of chemical engineering.

Changing the above unsustainable and high-carbon socio-technological system of 20C into a sustainable one by implementing a low-carbon 21st century-technology system is a must for survival of humans on earth. But successful 'sustainability transition' would be achieved not only by technological effort but also through political and sociological strives, because the norms, and the social systems relevant to the present technical systems are basically founded and run on the fossil-energy based economy. Regulations, legal systems, educational and other institutional systems, cultural preferences, etc., for sustainable society can be constructed only through careful but intensive social actions including economic incentive design, guidance and consensus-building. In the long term perspective, everyone on the earth would find satisfiable merits in the sustainability transition. Of course, some may not welcome the change because it cannot be free from reforming of the present economic and political power structures.

Geels (2002) presented a perspective for a sustainable technology's tread starting from niche market to the mainstream in relation to many social factors. Indeed, as reviewed by Kern and Rogge (2017), issues of sustainability transition and of implementation of sustainable systems have been significant themes in policy and sociology studies.

Turning our eyes on chemical engineering, social issue has been, albeit in a narrow sense, one of its central issues since it has been devoting to unify various unit operations and phenomena into a process and to scale up and commercialise, or in other words, to implement into society. The background principles of chemical engineering were chemistry and mechanical engineering. Having stem out from them, the development of chemical engineering principles has created and implemented into society many efficient and economic industrial processes and products by integrating reactions, separation, heat and mass flow over a wide range of temperature and pressure particularly in the post WW II industrialisation.

Thus, chemical engineering's role has been pretty good in pursuing just "How to implement new inventions and ideas into society". However, in the time of sustainability transition, "What should be implemented?" is the central issue.

The concept of 'social implementation of technology' has stem from the following three roots:

1) Management of Technology (MOT) originated in the United States in the 1930s (Blockhoff, 2017).
2) Science, Technology, Society studies (STS) formed gradually after the 1950s.
3) Public Policy Implementation studies originated in the UK in the 1960s (Barrett, 2004).

MOT's stance is close to that of classical chemical engineering's in the sense that their major concern has been commercialisation of one's own technology in the competitive market. On the same track as MOT, social implementation of the research and development (R&D) outcomes is requested strongly by funding agents in recent program/project managements.

As noted above, more argument is needed on "What technologies or systems should be implemented?". In the era of sustainability transition, we need much wider way of thinking than that of MOT. The same can be said to other two group's arguments.

In public policy implementation, more issues are coming into the sphere of technology, engineering, and science, where much more quantitative approaches should be effective than the arguments so far made in public policy area. Since chemical engineering allows us to avoid technological risks quantitatively in a variety of problems, it is now becoming ever more important to join public arguments for future design in the period of sustainability transition.

Thus, argumentation among professionals of different realms and ordinary citizens are becoming critical since social implementation of sustainable systems can create both technical controversies and conflicts of interests.

In the rapidly changing society, from linear to reflexive development, perception of history becomes necessary to define "What should be invested/implemented?" and "What should be divested?". As widely recognised, the three sustainability transition problems mentioned in the beginning have been inducing philosophical and historical debates vigorously over the human future as raised by Ray Kurzweil (2005), Yujin Harari (2016, 2018), Paul Mason (2016), and many others. Islamic scholars are also challenging the issue as can be found in Mohammad Hashim Kamali et al. (eds.) (2016).

But when the term technology comes into the argument it becomes apparent that we still lack common theoretical foundation to envisage the future. This is the reason why I intend to review chemical engineers' achievements in a long term historical perspective and to overview the technology related issues from essential viewpoints.

So, we first examine chemical engineering principle's historical evolution and clarify that now it is time for chemical engineers to proactively define their role in overcoming the sustainability problems.

Second, we make clear that any human society holds a specific 'social metabolic system' in which technology exists as its 'mechanism,' no matter how loose its structure is. To avoid misconception that society is a rigid organisation, some discussions on production and consumption, exchange and economy, politics and policies, information, science and technology are to be made.

Third, we examine the social actors' behaviour in the transition period and look forward to a social platform, led by chemical engineering societies, to induce constructive arguments on transition.

2.0 Evolution of Chemical Engineering and its present

The role of science in society is to seek objective truth, to provide information necessary for the welfare and survival of mankind and to support innovation. It should also support justice in various disputes and political scenes and further realisation of reasonable consensus and resolution at various scale of societies down to regional communities.

Among the disciplines, chemical engineering is a process engineering science that focuses on integration of phenomena of greatly different types and scales to establish a process of a wide scale range from them. It can be a process in a 50-m height chemical reactor to a nano-scale dispersion/reaction process. Chemical engineering has so far demonstrated its distinctiveness much different from chemistry, applied chemistry, mechanical engineering etc., which consisted of the original background of chemical engineering in late 19th century. Interestingly, a quick review of the history of chemical engineering presented in the following will reveal that every 30 years' periodisation is possible in the evolution of chemical engineering principle in the past. Furthermore, it will reveal that chemical engineering is now facing a situation where it can/must define its subject area as the whole social-metabolic system and its target as sustainability transition.

Chemical engineering has started as an academic field that combines chemistry and engineering with the aim of scaling-up laboratory ideas and industrialisation, by quantitatively expressing phenomena, material/energy balance and methodology of control and optimisation of process systems. The term "Chemical Engineering" originates back in 1901 in Handbook of Chemical Engineering (1901; revised 1904), the first of such kind by George E. Davies (1850–1907). It was prepared through his series of 12 lectures at the Manchester School of Technology (now part of the University of Manchester) from 1887. "Davis was unique in organising his text by the basic operations common to many industries—transporting solids, liquids, and gases; distillation; crystallisation; and evaporation, to name a few"[1]. In US, Course X, a four-year chemical engineering curriculum combining mechanical engineering with industrial chemistry, was created at MIT (Massachusetts Institute of Technology) by chemistry professor Lewis M. Norton (1855–1893) in 1888 influenced by developments in Germany and UK. Course X was modified "in a way that would clearly distinguish chemical engineering as a profession"[2] by William H. Walker (1869–1934) and continued to exist until 1920 when Chemical Engineering Department was founded.

Such movement immediately affected Japanese engineers that time. Kotaro Shimomura (1861–1937), an engineer and chemist and the founder of a private engineering school in the present Doshisha University, translated Davis' Handbook into Japanese around 1903. Albeit it was not published, he created the term 'Kagaku Kogaku' ('Chemical Engineering' in Japanese). In 1908, Iwazo Suzuki (1884–1951) entered the chemical engineering course of MIT as the first student from Japan. The MIT's move toward the formation of chemical engineering in 1920 by Warren K. Lewis (1882–1975) as its head and the publication of "Principles of Chemical Engineering" by Walker, Lewis and McAdams (1923) urged Japanese universities to introduce chemical engineering laboratories and courses. The first chemical engineering department in Japan was "Chemical Machinery" department of Kyoto University founded in 1940 (cf. Jimbo (1986)).

Thus, to draw a line between the cradle period and the self-sustaining period for chemical engineering principle, let us take the foundation of Chemical Engineering Department of MIT in 1920 as the milestone.

At that time the principle of chemical engineering was expressed by the concept of "unit operations" which allowed to look at different industrial processes from realistic viewpoint finding common operations and physical laws among them and developing unified engineering approaches. The concept was first proposed by Arthur D. Little (1863–1935) in 1916 after he joined MIT and then adopted in the book by Walker, Lewis and McAdams.

However, already in this early period pioneering work that encouraged the next break was proceeding. One example of it can be found in the absorption of gaseous species into liquid by Hatta (1932) and Higbie (1935), where phenomena were expressed in a set of differential equations and valuable relationships were derived by solving them. Such a mathematical approach later became the mainstream as embodied by Peter V.

---

[1] https://www.sciencehistory.org/historical-profile/george-e-davis (retrieved on Feb. 16, 2019).

[2] MIT ChemE History: https://cheme.mit.edu/about/history/ (retrieved on Feb. 24, 2019)

Dankwerts (1916–1984) after the war (cf. Amundson (1986)).

But it was the time to the war. The demand for gasoline was rapidly increasing, which posed a problem of accumulation of kerosene and heavier oil fractions as distillation residues. After the success of Houdry's TCC process with moving beds, fluid catalytic cracking (FCC) development was initiated by Standard Oil of New Jersey (now Exxon-Mobil) by forming Catalytic Research Associates (CRA), a consortium of five oil companies, including Anglo-Iranian Oil (now BP), and Dutch Shell, two engineering construction companies and a German chemical company. CRA researchers adopted the idea of W. K. Lewis and Edwin R. Gilliland (1909–1973) of MIT to handle catalyst powder like fluid, which is now called fluidisation. After the pilot plant test from 1940, the first FCC unit was erected and started operation at Baton Rouge, La., In 1942. It was the very beginning of both fluidisation engineering and chemical reaction engineering.

The success of fluidisation was a milestone of chemical engineering's shift from separation to reaction/reactor engineering. Fluidisation principle was applied to various processes and flowered worldwide in the economic growth after the war.

Since 1942, construction of fluidisation science followed, shifting its paradigm roughly every ten years starting from phenomenology and achieving essential understanding of the phenomena (Horio, 2013). Such process of paradigm shift seems to follow the three-stage development law of Mitsuo Taketani (1911–2000), a particle physicist and theorist. His three stages are 'the phenomenology stage', 'the structural stage' and 'the essential stage' (Taketani, 1942). Each stage is kicked off by the appearance of a new paradigm. In fluidisation research the essential stage was kicked off in 1963 by John Davidson's book, "Fluidized Particles," which ignited a complete reorganisation of the theoretical framework of fluidisation science from the fluid mechanic viewpoint. However, such a recurrence to mathematical, fluid mechanic and physicochemical fundamentals took place not only in fluidisation area but also all over the chemical engineering science as a new wave of engineering science.

This new wave in the post WW II, chemical engineering was induced by Dankwerts as reviewed by Amundson (1986). He modified Higbie's penetration theory for static surface and developed the surface renewal model, a new approach for mass transfer across turbulent interfaces or bubble-to-liquid absorption (Dankwerts, 1951). He then advocated on residence time distribution (Dankwerts, 1952).

After this induction period a full-scale endeavour was started early in the 1950s to construct transport theory, chemical reaction engineering, system dynamics, control and optimisation, and numerical simulation. This bore fruits in the early 1960s in the form of challenging books: Bird et al., "Transport phenomena" (1960), Aris, "The optimal design of chemical reactors: a study in dynamic programming" (1961); Lapidus, "Digital computation for chemical engineers" (1962); Levenspiel, "Chemical Reaction Eng." (1962); Kunii-Levenspiel's "Fluidisation Engineering" (1973), etc. Indeed, the period after Dankwerts (1951) was for such a dramatic refinement of the theoretical structure of chemical engineering conception. Thus, we can define the period from 1950 as the period when essential principle of chemical engineering has been established.

It was early in the 1970's that an entirely reborn scientific structure of chemical engineering was introduced into chemical engineering education courses. Since then, more than 500 chemical engineering departments have been introduced in universities all over the world.

However, it was the time of maturing for conventional process industries. Computer aided design (CAD), process simulation, and digital control became popular. Both the maturation of chemical engineering science and the progress in computer capacity changed the chemical process industry (CPI) drastically into a more matured industry as described by (Himmelblau and Riggs, 2012): "During the period 1960 to1980, the CPI also made the transition from an industry based on innovation, in which the profitability of a company depended to a large degree on developing new products and new processing approaches, to a more mature commodity industry, in which the financial success of a company depended on making products using established technology more efficiently, resulting in less expensive products."

However, from the late 1960s the chemical engineering methodology gradually penetrated into other fields that traditionally had not established reaction engineering or process engineering methods, such as iron and steel making, coal utilisation, cement production, heavy industry and other industries of semiconductor, fermentation, bio, pharmaceutical, etc. In addition, it has deepened relationships in the automotive field through materials, exhaust gas cleaning and recycling.

In coal gasification and combustion, C. Y. Wen (1928–1982; cf. Wen and Lee , 1979) was the pioneer.

Iwao Much (1924–1987; cf. Muchi (1966), Muchi, Moriyama (1972)) and Julian Szeckely (1934–1995; cf. Szekery and Themelis (1971)) were those in the iron and steel making by introducing mathematical modelling approach. Koichi Iinoya (1917–1998) was one of the few founders of powder technology area.

In the early 1980s, it became obvious that applications of chemical engineering principle in the field of electronic industry as well as biotechnology brought a new initiative into chemical engineering in the sense that they requested more detailed treatment for phenomena and processes down in the molecular level, which urged another leap of chemical engineering. Such new waves were summarised and demonstrated in "Frontiers in Chemical Engineering, Research Needs and Opportunities", a report published in 1988 by a committee chaired by Neal R. Amundson (1916–2011) in US National Research Council. Accordingly, it can be said that a new period of chemical engineering began around 1980.

Since then, the object field of chemical engineering has been sprawled very much. It is not the scope of the present article to overview it in detail, but the diversity of current chemical engineering study can be seen from the text mining of the title of perspective papers in AIChE Journal from 1999 to 2018 (Fig. 1).

Nevertheless, the very core of the chemical engineering principles lies in the methodology of integration of basic phenomena into innovative processes through the following three pathways:

1) application of conservation law of mass and energy with mathematics, incorporating thermodynamics, diffusion, stochastic process, reaction, mass flow, heat transfer, etc., with their relevant rate expressions.
2) integration of elemental processes and scale up, overcoming process inefficiency or emission due to bi-products and pursuing near closed processes, and process intensification.
3) design and operation of nonlinear complex systems with simulation, analyses for stability, sensitivity and dynamics, optimisation and control.

Although many of these principles can be shared in other engineering sciences, they all have not been sufficiently consolidated in an academic field other than chemical engineering.

Nevertheless, chemical engineering that had covered almost all industrial activities was still sticking subjects inside of production processes mostly based on fossil-fuel energies. But the global warming and climate change issues changed the situation around 1988 when James Hansen of NASA Goddard Space Centre testified in US Congress that it is 99% true.

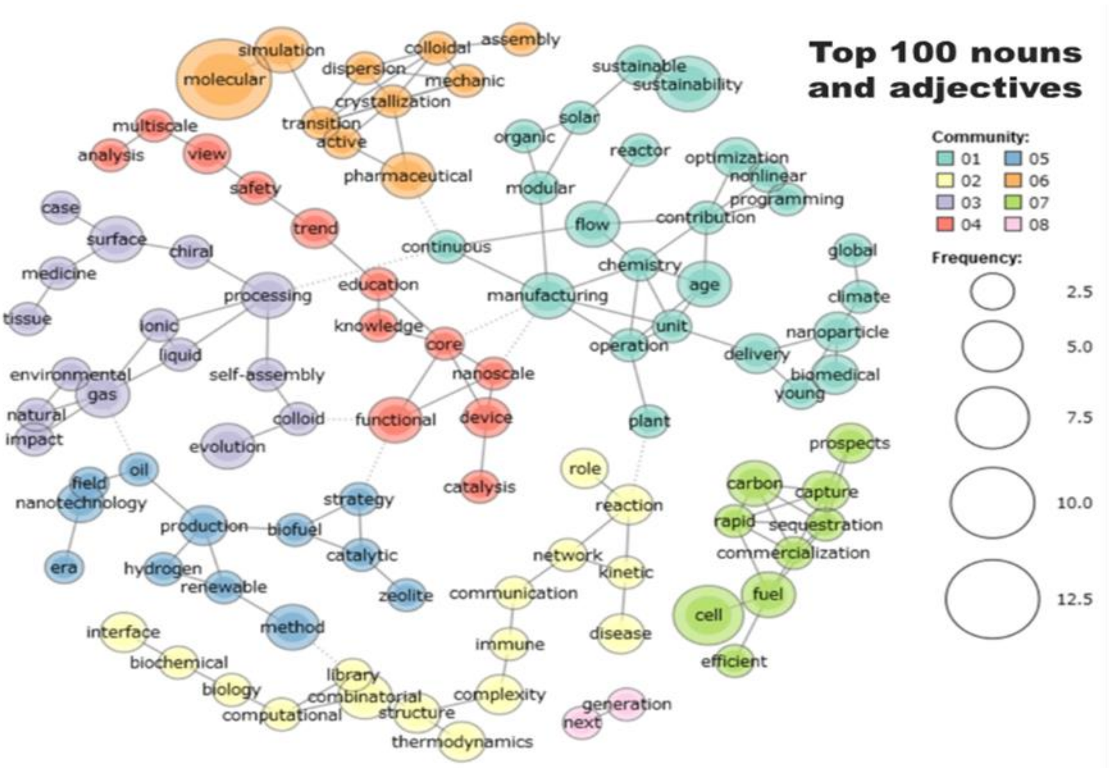


Fig. 1: Chemical Engineering's recent focuses estimated by datamining titles of perspective papers in AIChE J. from 1999 to 2018 by KH coder

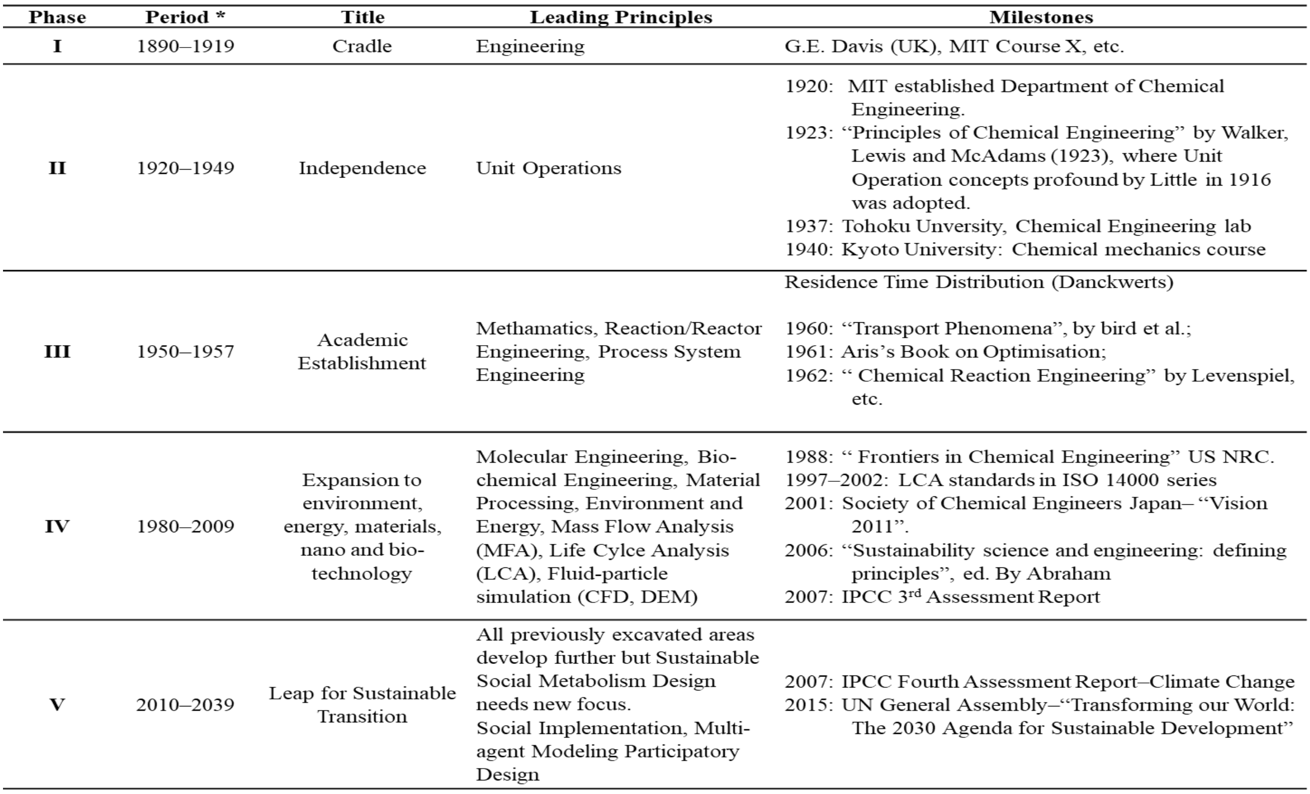
In the beginning, it was not as seriously recognised as it is now. It was only after the IPCC 4th report (2007) that the reduction target of greenhouse gases (GHGs) at year 2050 was set above 80 to 90% of 1990 value for developed countries. In December 2015, at Paris Climate Conference (COP21) over 190 countries reached the Paris Agreement aiming to reduce the greenhouse gases emission substantially to prevent global temperatures from increasing more than 2 °C above the temperature before the beginning of the Industrial Revolution and also aiming to pursue efforts to limit the temperature increase even further to 1.5 °C. It entered into force on November 4, 2016 and has been signed by 197 countries and ratified by 185 as of January 2019. Since this demands almost zero GHGs emission beyond 2050, transformative design of the whole mass and energy balance of the earth system including human activities has become an imperative issue to solve much before the year 2050.

Many chemical engineers have moved out of production processes of factories into the civic society in the area of environment, first in waste management and recycling, air pollution control and water treatment. Then they started taking leadership in developing new methods to deal with environmental and global warming issues, such as a metric system Life Cycle Assessment (LCA) for greenhouse gas emission from human activities. As the founders of Industrial Ecology, Roland Clift (1942-) has been one of the pioneer chemical engineers in such movements (cf. Clift- Druckman (Eds.) (2016)).

In 2015, UN grand assembly adopted "Transforming our world: the 2030 Agenda for Sustainable Development." But who guides the society for the implementation of sustainable socio-technological systems? Chemical engineers have a potential of designing sustainable social mass and energy processes based on their principles/criterions listed before. Their openness to a variety of problems also indicates their potential of designing the social process necessary for the transition by sharing the idea with stakeholders and citizens for implementation. It means that chemical engineering is expected to outgrow from the present discipline for 'chemical process systems' to the whole 'social metabolic systems,' whose concept is discussed later in 3.2.

Table 1 summarises the above discussion on the periodisation of the historical development of chemical engineering. However, so far, most of the technical issues that chemical engineering has been dealing with are clearly those belong to the owner of the technology or to the subjective actor. In contrast, many civic societies' issues are multi-subjective.

Table 1 : A rough periodisation of the history of chemical engineering and its future.



Phase	Period *	Title	Leading Principles	Milestones
I	1890–1919	Cradle	Engineering	G.E. Davis (UK), MIT Course X, etc.
II	1920–1949	Independence	Unit Operations	1920: MIT established Department of Chemical Engineering. 1923: "Principles of Chemical Engineering" by Walker, Lewis and McAdams (1923), where Unit Operation concepts profound by Little in 1916 was adopted. 1937: Tohoku Unversity, Chemical Engineering lab 1940: Kyoto University: Chemical mechanics course
III	1950–1957	Academic Establishment	Methamatics, Reaction/Reactor Engineering, Process System Engineering	Residence Time Distribution (Danckwerts) 1960: "Transport Phenomena", by bird et al.; 1961: Aris's Book on Optimisation; 1962: " Chemical Reaction Engineering" by Levenspiel, etc.
IV	1980–2009	Expansion to environment, energy, materials, nano and bio-technology	Molecular Engineering, Bio-chemical Engineering, Material Processing, Environment and Energy, Mass Flow Analysis (MFA), Life Cylce Analysis (LCA), Fluid-particle simulation (CFD, DEM)	1988: " Frontiers in Chemical Engineering" US NRC. 1997–2002: LCA standards in ISO 14000 series 2001: Society of Chemical Engineers Japan– "Vision 2011". 2006: "Sustainability science and engineering: defining principles", ed. By Abraham 2007: IPCC 3rd Assessment Report
V	2010–2039	Leap for Sustainable Transition	All previously excavated areas develop further but Sustainable Social Metabolism Design needs new focus. Social Implementation, Multi-agent Modeling Participatory Design	2007: IPCC Fourth Assessment Report–Climate Change 2015: UN General Assembly–"Transforming our World: The 2030 Agenda for Sustainable Development"

* The period boundaries are only rough indications.

To cope with such situations, Chemical engineers now need to hold some fundamental understanding on social issues in its principle. Furthermore, it is about time for chemical engineers to equip with channels to a variety of social affairs and to organise a constructive argument with their principles/criterions among people from different professional arenas.

Beyond such activities together with investigation into the achievements of social and humanity sciences, there could be a chance for chemical engineering to develop novel socio- technological methods for sustainability transition.In the next section some philosophical or sociological discussions are presented reviewing fundamental categories in socio-technical issues.

3.0 Concepts for Socio-technological Systems

To argue about social issues in this article, it would be effective to treat them in a way that can be incorporated into the theoretical framework of chemical engineering in the future. Concepts to deal with chemical processes such as flow system, steady state, discrete element, population balance, residence time distribution, contact time and/or reaction rate can be also effective in analysing many social phenomena. However, the society is equipped with apparatuses much foreign for chemical engineering such as governments, armed forces, companies, legal systems and communities. Significant phenomena in the society such as economy, politics and/or consensus building are also quite different from phenomena in chemical processes. So, in this section, preliminary arguments are presented to construct a kind of overview for chemical engineers to define their roles in the socio-technological domain for sustainability transition.

It should be noted here also that rather essential discussions are intended in this section although they seem to have been taken outdated over decades among philosophers and sociologists. It has been avoided in STS since its "Empirical Turn" (Achterhuis , 1999) of around 1980 by Wiebe Bijker (1987) and others with their social constructivist approach toward the detailed empirical study on the process of technology realisation and adoption by the society. Or in other words, a big move into the detailed sociological analysis on technology innovation as social phenomena solely from empirical and phenomenological viewpoints became possible after the collapse of ‘official Marxism.’ However, as expressed by Paredis (2011) the constructivist approaches tend to just follow “What happened and how?” and cannot present alternative pathways nor guidelines, toward sustainable future, for instance. Thus, discussing some basic concepts for engineering’s endeavour toward sustainable socio-technological systems may create some potential value in relation to social sciences. In the following it is intended to shed clear light on technology and socio-technological system, by visiting terms such as human existence, social metabolic system, production/consumption process, labour process, exchange and economy, politics and policy, information and communication, science, technology, and scientific and technological labour. They are all related to collective human survival on earth. The key factor here is the relationship between information and reality.

3.1 Human existence and technology

Human society equipped with language, money, government and nation, agriculture and industry etc. is based on the existence of special creature ‘human being.’ From the viewpoint of discrete element simulation (DEM) in particle technology or of agent-based simulation (ABS), a human being is an extraordinary discrete element that makes its motion based on its complex thinking and feeling system and on a variety of interactions, i.e., communications, with other elements. Such elements have been created based on the remarkable evolution of human brain through use of tools, fire-eating, upright biped walking, cooperation in hunting, etc. in the transition period from apes and over millennia afterwards.

From the definition of ‘technology’ to be introduced later in 3.8, expressions by writing letters, which evolved from communication known as pictography (picture writing) and ideography (idea writing) also should be included in ‘technology,’ particularly, in ‘social technology.’ Completion and dissemination of the letter system by around 5300 BP (Mattessich, 2002) encouraged objectification and awareness of mental activity, until the concept of ‘mind’ was established around 2500 BP (Jaynes, 1976), Adkins, 2003). Then brought about were the conception of mercy, perfect virtue and love by Buddha, Confucius and Jesus, respectively. It was an information technology revolution in archaic period that made brain possible to aware self-thinking, to reflect and to think about future as provoked by Julian Jaynes (1920–1997).

Religions can also be understood to belong to a genre of social technology. To maintain peace and to save social distortion Muhammad (570–632) later delivered Islamic tenet that focused much more on everyday practice and social wellbeing, which can be understood as an advanced phase of religion focusing more on the social than the previous ones.

Thus, we can be confident that there is no separation between human existence and 'technology in a broader sense.' A human existence is a biological element equipped with physiological mechanisms for survival but having strong power for sophisticated internal information processing with language and external communication.

However, a human existence is finite in both space and time and the environment is a huge existence. To keep living he/she must intake material and energy from and excrete wastes to the environment. This is an exchange process that resembles a gambling process. As classical ruin problem in random walk theory tells, the probability of a gambler's ultimate ruin, against an infinitely rich adversary, starting from a finite amount of money within finite number of trials is '1.' Thus, an eternal life for such finite existence is physically impossible. This is why living organisms have been trying to survive with their limited life due to programmed life span and genetic reproduction system as confirmed by Oohashi et al. (2003).

3.2 Society and Social metabolic System

'Society' is a collective survival style of species. Once, human survival was conducted only on hunting and gathering, i.e., on natural productivity. Then, they invented cultivation of crops, animal domestication, mining and metallurgy. Since then, humans have survived by social (i.e., collaborative) production and consumption with agriculture and industry, i.e., with artificial productive power.

The whole integrated system of productive power composes a 'social metabolic system,' which includes not only people in the society but also all the artificial infrastructures such as houses, buildings, farmlands, factories with machines and plants, railways, highways, harbours, airports, water supply, sewage systems, broadcasting systems, satellites etc. and produces and distributes mass and energy necessary for human life. The mass and energy flows into and out of the society and their flows inside the society with the above infrastructure resemble the metabolic activities of lives. The concept of social metabolism originates from Justus von Liebig (1803–1873) and other 19C chemists and appreciated by Karl Marx (1818–1883) and used in his writing (cf. Martinez-Alier, 2004). In the 1970s the concept was spontaneously reborn from the social mass flow analysis (MFA) study together with LCA as well reviewed by Fisher-Kowalski and Hüttler (1999).

Here, a remark should be added that the system is not rigid but loose and dynamic like a thermodynamic system consisting of freely moving molecules. Any person who is an element of the system has a freedom to claim against it to modify the system by raising voices and by organizing a counter power or otherwise to move to other places (in the case of classical social organism theory of Herbert Spencer (1820–1903) this point was not clear and his concept was used together with his social Darwinism in Nazi's genocides.)

Thus, we must be very precise in using the term 'social system'. However, the claim by Latour (2002) that "there is no society, only a network of actors (AN) exists" is an extremal presumably brought as a reaction against ideologies that inclines to totalitarian thinking. Nations and companies have enforceability. Not all persons in the society have well developed to an autonomous individual. Treating society simply as individuals' network is a reductionism that tend to neglect the organisational aspect which restrain individuals.

Peoples' lives are very much dependent on the social system including public education and social welfare. Any member of a state is born and educated in the system. Under such a situation it is difficult for a citizen to completely reject the behavioural rules requested by the system as a free person. This is the very point of the "freedom of thought" as one of the minimum human rights in modern constitutional laws.

However, AN analysis is still an effective research method to investigate the social process in detail. More importantly, it is effective to avoid political labelling and to urge people to behave individually for justice.

3.3 Production/consumption

Including all the activities in the society from individual's and organisations' viewpoint, 'production' can be defined as widely as possible as "a general activity for creating a state or a thing of value for the survival of a subject by acts of the subject." The three production factors, i.e., 'instrumental equipment,' 'raw materials' and 'labour forces' compose productive power. Production and consumption are inextricably linked. Production cannot be performed without consumption of valuable things. This wide definition of production also includes so called reproduction activities, e.g., eating, bearing children, education, recreation and cultural activities, and all other activities including destruction and/or criminal acts. The meaning of technology is to be defined as essentially as possible based on this wide definition of production in 3.8 and 3.9.

Here, ‘instrumental equipment’ includes not only tools, machineries, plants and land but also things such as plant species, chemical catalysts, and even social rules such as standards, regulations, safety measures, etc. In a microscopic production process, ‘raw materials’ can be nothing but technological products, as seeds and saplings in agriculture, chemical reagents in chemical process es and steel in mechanical industry.

In productive labour, humans make ‘dialogues’ with other two factors, i.e., raw materials and equipment. This cognitive aspect of human involvement in technology was advocated first by Heidegger (1953) but not deepened much to understand real production process.

In modern production processes the labour forces are divided into many part labours and machines help integrate labours. This contrasts with artisans’ cases where labour division is not much and artisans themselves control the whole production processes.

The progress of technology and automation decreases the part of labour directly installed in the production process. In large scale automated chemical processes nowadays, the contribution of physical labour is very small, but the weight of more intelligent, i.e., surveillance, supervision, maintenance etc., has been increased.

A production process is achieved by combining production factors and by letting them to operate together. The activities of entrepreneurs and engineers to integrate production factors and to conduct the whole process are necessary activity to maintain and govern the technological and economical essence of the processes as first pointed out by Schumpeter (1934).

Fig. 2 illustrates production process viewed differently by an artisan or a working individual and by an entrepreneur.

3.4 Exchange and Economy

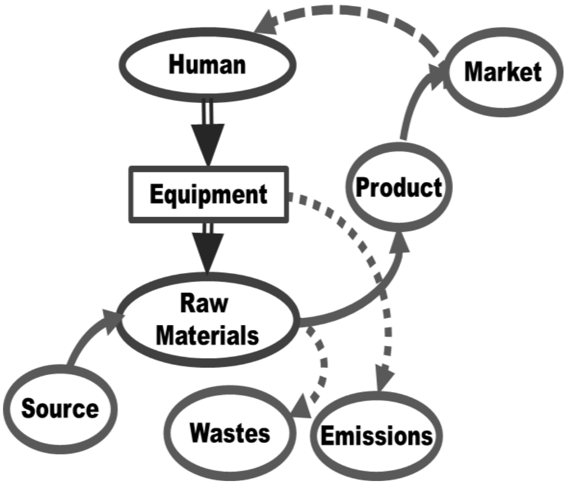
Social metabolism is conducted through process of exchange among individuals and organisations. There are the following three types of exchanges (Karatani (2014) (note: wording rephrased maintaining the original meaning):

1) Market economic exchange: free and competitive exchange of goods, labour, money, etc.,
2) Governance exchange: tax and governance exchange for freedom, safety and security, etc.,
3) Reciprocity exchange: exchange of aid, care, solidarity with goods, labour/activities, money, etc.

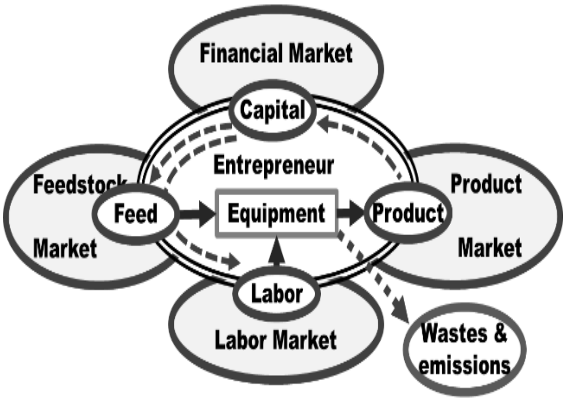
Market economy is only one type of exchanges. In the sustainability transition, niche market for regional or mission-oriented products has been said to take more significant roles (Geels, 2002).

3.5 Politics and Policies

‘Politics,’ which is related to the above-mentioned “governance exchange,” is the process to define public goods and values and to determine the share of them, not with violence but with indication of intention and arguments and on an initially agreed platform. Eloquence and legitimacy are effective factors in the arguments. But sound argumentation process could be trampled if a majority is hold on the platform through favouritism and corruption and if fallacious ideas, i.e., ‘ideologies,’ dominate the argument.



(a) individual worker’s view



(b) entrepreneur’s view

Fig. 2: Production system overlooked from different viewpoints (where double lines show work actions, dotted lines indicate by-products and broken line shows cash flow or gain from exchange).

‘Policy’ is the scenario to handle public goods and values for public objectives. In the modern society, policy elements are quite widely spread in complicated structures. Also, the climate changes, natural and technological disasters and environmental pollutions affect everyone. Accordingly, who are benefited and who are not are not always clear and, even if the dichotomy of political group exists, there arises a possibility of policy design being conducted in a much rational manner to benefit majority of the society. Nevertheless, any technical discussions may accompany political nature since it is often related to public policies and to distribution of values. In some situations, professionals are facing a kind of responsibility test where his/her performance and advocacy can affect the life of many socially vulnerable people. In the sustainability transition period, the professionals' leadership for the long-term future is necessary but it is not always free from short-sighted political games.

3.6 Information

'Information' is a key factor to understand life, science, technology and society but its essential definition is seldom presented in textbooks of information engineering.

'Information' is a virtual thing that indicates a real thing meaningful for the survival of living beings that are finite and always facing the risk of death. Nishigaki (2004) admirably said "Every information is basically 'life information' linked to cognition and observation by life."

'Structure' and 'mechanism' are categories included in information. They are extracted and unveiled from existing phenomenological things by scientific scrutiny.

3.7 Science

'Science' is a set of sure universal information obtained about things surrounding human beings, a set of methods to obtain certainty, and collective human activities to obtain sure information. There is a rich accumulation of thoughts about science back from Francis Bacon (1561–1626; cf. Bacon (1620) to John D. Bernal (1901–1971; cf. Bernal (1954), (1967)) and to Thomas Kuhn (1922-1996; cf. Kuhn (1962)). But here delving more about science is avoided since our focus is on technology.

3.8 Technology in a narrow sense

Interestingly, technology is not a production process itself nor a productive power itself. It is some structure contained in the productive power. It reveals some rational mechanisms in its operating stage.

'Technology' is "the 'mechanism of production process' in its wider sense, contained in and revealed by productive power, which is constructed through conscious or heuristic application of objective laws and knowledges." This is an improved version of the previous definition by the present author (Minami (1973), Horio (2006), where technology was defined simply as "the mechanism of productive power." Among 'knowledges' in the above definition, 'existing elements of technology' are also included as discussed by Arthur (2009). But there are always unknown parts in the mechanism, which subject to research for improvements (Horio, 2011).

It should be worth to note here that in the productive power, in its narrow sense, labour forces have not only trained muscles and attentiveness but also experiences, licenses, understanding of rules, and moreover knowledge of the whole process, which are nothing but a part of 'mechanism of production process' the labour force contributes to let the process perform appropriate. The reason why such an intelligent capacity is required for labour force is because the working process itself is essentially an intelligent and cognitive process.

However, in modern industries such cognitive activities are conducted with a thick support from engineering sciences. Whenever some malperformance of a production system appears, workers and engineers must investigate the causes and then design counter actions based on scientific methods. This is the 'communication' between humans and materials in the modern production processes highly technological and scientific, which Heidegger (1954) did not appreciate.

A technology is an intellectual property. Although any technology may become obsolete with time, it does not wear out like ordinary products. It is possible to 'read' technical information even from aged elements of its productive power. Technology is easy to reproduce based on information read directly from existing productive power or from documents and/or on engineers' knowledge. Without legal protections it is difficult to establish it as a good.

The above definition resembles, albeit only slightly, with Heidegger (1954)'s: "Technology is 'Enframing' (i.e., 'artificial structure')." There, his intention was to close-up the relation between the Enframing and humans. It is probably because technology for him was like something created by strangers, which force him and other people to change their valuable tradition and culture. Heidegger's understanding of technology has affected many Post WW II environmental thinkers and activists because the original picture of technology-human relationship was resembling to modern technology-environment relationship. However, his definition did not appreciate the workers' nor engineers' labour and practices in the production process, did not deepen the relation among information, science and technology and did not indicate the way to overcome the problem of technology-human and technology-nature relationships. Carrol (2017) recently defined technology as “something inherently intelligent enough to either function, be used to function, or be interpreted as having a function that intelligent beings—human or otherwise—can appreciate, something devised, designed (by primary intention), or discovered (by secondary intention) serving particular purposes from a secular standpoint without humankind creating it, or a significant beneficiary of rationally derived knowledge that is “used for” a purpose without itself necessarily being translated into something material that “does” autonomously, or dependently when used.” This is a phenomenological piecemeal definition. To comprehensively grasp technology, its character and relationship with significant categories, such as information, science, productive process and human labour, we need to understand technology essentially.

A technology is brought about as a result of integrating workers’ and engineers’ activities to build up a mechanism through design, application and trial and error. Such an activity can be called as ‘technological practice.’ Taketani (1947) defined technology as “conscious application of objective laws and knowledges in productive practices.”[3] His definition induced a decade of dispute on philosophy of technology in post WW II Japan because it closed-up the importance of human practice and consciousness on natural laws and knowledges. However, in his definition the aspect of heuristic trial and error in engineers’ practice was not explicitly appreciated. This tends to instigate us to underestimate the aspect of accumulated trials and errors in existing technology. Furthermore, the definition based on human activity has a fundamental difficulty to deal with the objectively existing technology. After all, Taketani’s definition is not the definition of technology itself but the time differential derivative of a technology formation process, i.e., technological practice. Fig. 3 illustrates the relation between technological practice and the resulting technology.

3.9 *Technology in a broad sense*

Technology can be also defined as the ‘mechanism of social metabolism’ because social metabolism consists of the whole production/consumption systems whose mechanism is the currently working technology. In social metabolism, we must appreciate not only elemental physical technologies but also elemental social technologies including legal systems, social institutions, languages and communication systems, currencies, people’s cooperation etc. Indeed, some equipment cannot be installed without governmental approval. Some valves of a plant cannot be opened under some environmental regulation. Thus, the definition of technology in a broad sense should include social mechanisms as well.

When we try to implement a technology into society in a competitive situation, we need a variety of ‘social technologies’ such as marketing, social recognition of tasks, consensus-building/decision-making, fund raising, equipment procurement, advertisement, enactment of laws, founding support organisations and institutions, etc. Social technologies also include criminal techniques that should be avoided/suppressed, such as intimidation, fraud and speech manipulation.

By summing up the above observation, Fig. 4 illustrates the technology’s multilayer structures including social elements and mechanisms. Furthermore, two additional points are important regarding technology in society: One is fairness of technology in the society; another is the fitness of technology to regional needs and resource characteristics, culture and habits, financial capabilities etc. These two are the fundamental requirements for appropriate technology (AT) as illustrated in Fig. 5. The point is to avoid mismatch

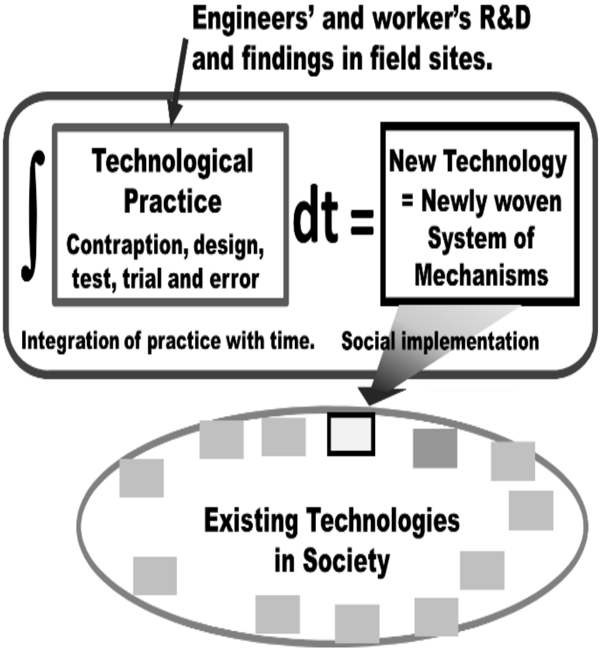


Fig. 3: Technology as a product of integrated technological practice.

---

[33] Translated from Japanese by the present author.

between design and the social need, which would be achieved well by stakeholder participated co-design and co-production. Originally the concept of AT has been developed for technology transfer to developing countries with the term ‘intermediate technology’ (Schumacher (1960)). However, even in developed countries, since conditions for technology is locally quite different, particularly in terms of resources, climate and culture, AT’s viewpoint is becoming more important in planning and designing.

4.0 Innovation dynamics and the way to social implementation of sustainable systems

Now that the fundamental concepts are shared as above, we can further focus our eyes on the social processes of changing the social metabolic system into a sustainable system by technology developments/adoptions and implementations. However, the process is highly ‘political’, in the sense defined before, with struggles among actors.

To analyse the ongoing energy transition in European Union, Lindberg et al. (2018) analysed key EU policies, information from websites, newspaper articles and interviews with policy makers and made clear that “a majority of actors favour a rather centralised configuration of the electricity system” (p.11) as shown in Fig. 6.

“Many of these actors are energy incumbents and their associates (p. 12).” However, about the adoption of renewables, “relatively broad agreement about the need for more renewable energy (i.e. a sustainability transition).” “Environmental NGOs and renewable energy associations, in contrast, have high ambitions for renewable energy and strongly favour a decentralised electricity system (p.12).” So, it is serious that even in European Union that has been leading the world politics for sustainability transition, the inertia of existing business is not small at all.

It is also interesting that in the EU’s politics at least the shift to renewables has achieved a kind of consensus and that the major political controversy is on the issue of ‘distributed or centralised.’ This controversy is, however, realistic and constructive if it is further discussed. However, the political debates can become much more ideological if some technologies which are still underdevelopment are dealt with as the Redeemer.

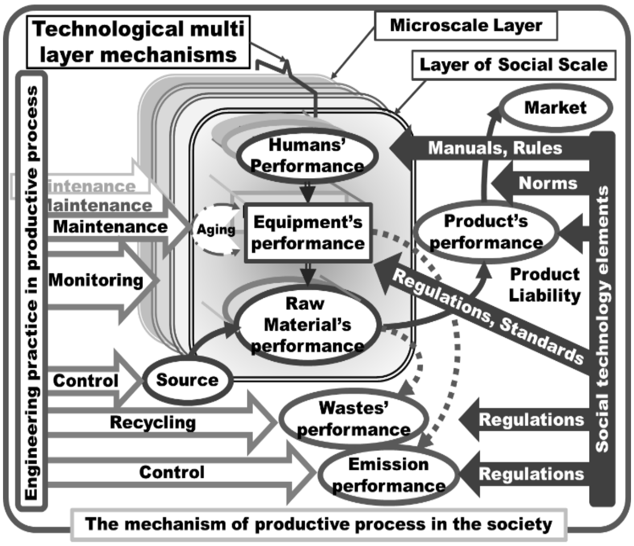


Fig. 4: Technology’s multilevel structure including social elements.

Fig. 5: Basic features of appropriate technology (Horio, 2013a).

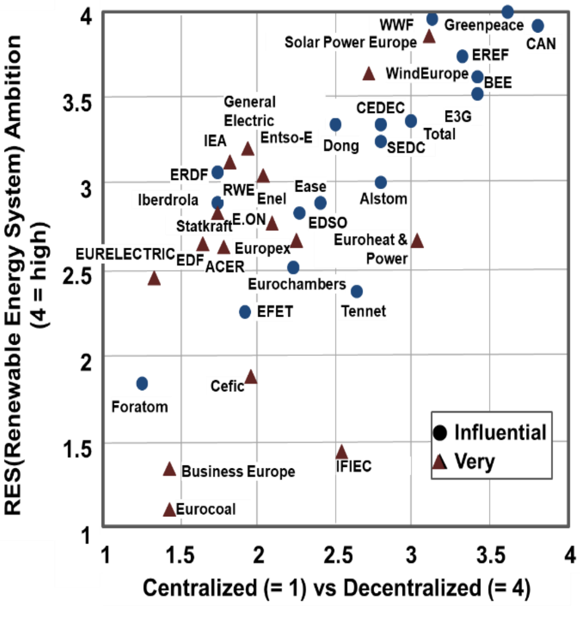


Fig. 6: Key actors and their policy preferences in EU (Lindberg et al. (2018)).

An example can be found in a report from IEEJ (Outlook 2018, 2017). It describes a scenario for decarbonisation for 2050 by allowing coal utilisation in long term, anticipating Redeemers such as next generation nuclear power, nuclear fusion, solar power satellite (SPS), hydrogen, carbon capture and utilisation (CCU), and or biomass energy with CCS (carbon capture and storage) (BECCS) would be an example. But, as far as the author's knowledge is concerned, nuclear power technology has not yet solved its high-level waste accumulation problem, and nuclear fusion and solar power satellite would never be commercialised by 2050. Concerning hydrogen vehicle, it is difficult to find much benefit in it, since the dissemination of 800 atm service stations for FCV (fuel cell vehicles) increases the risk of severe explosion in the urban area in long term, and since, in terms of green-house gas emission reduction, it is not efficient at all as already clarified by Bossel (2006). CCU to produce fuels from CO_2 is not necessary since transportation energy is going to be converted to renewables with the adoption of electric vehicles. For aviation, biofuels have good potential. Finally, potential of CCS is quite limited as already pointed out by Caldecott et al. (2016).

Due to high economic competition, and to the pressures from consumers and stake holders, ordinary business decisions tend to be made based on only 3 to 5 years perspective. Thus, incumbent actors including industry groups, employers' associations and major labour unions tend to try not to lose present assets by the sustainability transition. Of course, it depends how they portray their future in what time scale.

There are certain number of pundits and some government sections strongly supporting the present system. In many cases, policies and R&D plans are made on the extension of the present system or on the ideological scenarios for the future and not on the perspective of disruptive changes that induce realistic sustainability transition.

However, the business and financial landscape is changing fast as indicated by the foundation of The Climate Group and its RE100 Project. With professionals from different sectors as well as with young scholars and students, we should discuss our future not tied by short term interests but based more on scientific evidences and on mid to long term needs.

Thus, the incumbents' issues must be compromised constructively for the sustainability transition. There, those ideological controversies should be overcome by quantitative investigation in the public.

5.0 New Responsibilities of Chemical Engineers and their Societies

Based on their officially neutral stance and relative independence from incumbents' business decisions, academic societies have a potential and responsibility of taking a lead toward argumentation for sustainability transition. Matter of course, depending on the contents of academic realms, some may not be able to pursue such a role effectively. However, chemical engineering seems to have an extraordinary transdisciplinary potential as already discussed in **2.0**.

Significant difficulty existing in the present chemical engineering is that it still has not equipped with rational principles to deal with the 'social' where stakeholders often have conflicting interests but no common languages.

Taking a case of planning a municipal solid waste disposal plant as an example familiar to many chemical engineers, the problem structure does not fit even a simple actor structure such as administrative vs. residents. More than ten rather independent subjective actors are involved in the decision-making process. The association of waste management, local assembly, local government offices, mayor, vice mayors, labour unions, civil society groups, regional agriculture, commerce and industry groups, regional construction businesses, and other related businesses. If waste management is supported by central government subsidy, relevant government sections and national policy makers may exploit leverage. Most of the local actors are lay actors to the technical aspects of waste management. Accordingly, it is not always easy for a contractee to identify friend or foe the collaborators including consulting companies.

Also, concerning environment and energy issues, it is important to organise collaboration among administrative divisions, for which they tend not to admit its necessity because the division structure has been 'rationally designed.' But the rationality may be only for the fossil fuel based social metabolic system. Collaboration among divisions is now a must for tackling global environmental issues and conduct transformative actions. To create collaborations among multiple agents, support from both engineering and humanity/social sciences should be necessary.

To deal with such cases, chemical engineers need languages and principles based on which they can create collaborations of various sectors and stakeholders to reach progressive, legitimate, people-friendly and environment-friendly solutions through democratic debates.

Since such collaborations are a highly multi-subject matter, it is necessary to have competent conductors/ facilitators to organise it. They need a capability to understand the basic context of each stakeholder in the collaborative team, and a capacity to crate imagination about what outcome, discoveries or new meaning the collaboration would create for each in its context.

Chemical engineers have, with their wide, stereoscopic and quantitative insight, a potential capability of the conductorship. Already in many countries many chemical engineers have become talented leaders in transdisciplinary landscape. Developing powerful methodologies further for sustainability transition is nothing but an endogenous project of chemical engineers. Chemical engineers' associations are thus expected to provide effective platforms for public arguments toward the sustainability transition.

6.0 Concluding remarks

In this article chemical engineers' role in the time of sustainability transition is discussed first based on the understandings on sustainability transition, its meaning in the human evolution history, and the present social struggle for the transition issues.

Second, the chemical engineers' role in the coming decades is projected by reviewing chemical engineering history from late 18C to present.

Third, through philosophical and sociological arguments, proposed are simple and clear understanding for concepts of human existence with technology, society and social system, production/consumption, exchange and economy, politics and policies, information, science and technology, so that these issues can be included in the chemical engineering theory in the future.

Finally, by analysing the social actor structure, the significance of academic societies, particularly of chemical engineering societies to create effective collaborative actions in the above struggle is stressed.

Comprehensive research and design programs are needed with multidisciplinary collaboration on many tough issues focusing on sustainability transition, regional energy independence, plastic problems, high level nuclear waste issues, etc. Also needed are, participation-based co-design methodology, implementation process analysis, normative/ institutional reform methodology, etc.

To intensify academic society's contribution in social argumentation and collaboration for sustainability transition/transformation, it would be great if, in the near future, open-source transparent database and simulation tools including MD (Molecular Dynamics), CFD (Computational Fluid Dynamics), DEM, ABS and other process simulation tools, even in their simplified versions like NetLogo[4], could be provided from academic societies with the real-time multi-presentation infrastructure such as HoloLens[5].

Acknowledgement

The author is grateful for the encouragement from Professor Noor Fitrah Abu Bakar of Universiti Teknologi MARA.

References

A. Feenberg, (1999). *Questioning Technology*. London: Routledge. ISBN-10: 9780415197557; ISBN-13: 978-0415197557.

B. Caldecott et al., (2016). Stranded Assets and Thermal Coal in Japan – an analysis of environment-related risk exposure. working paper, Smith School of Enterprise and the Environment. Oxford Univ. https://www.smithschool.ox.ac.uk/research/sustainable-finance/publications/satc-japan.pdf (retrieved on Feb. 24, 2019.)

B. Latour, (2001). Gabriel Tarde and the End of the Social, in *The Social in Question. New Bearings in History and the Social Sciences*, ed by P. Joyce. London: Routledge, 117-132.

C. Y. Wen, E. S. Lee (eds.), (1979). *Coal Conversion Technology*. Reading, MA : Addison-Wesley Pub. Co. ISBN: 0201083000.

D. Kunii, O. Levenspiel, (1973). *Fluidization Engineering*. New York: McGraw-Hill.

D. M. Himmelblau, , J. Riggs, (2012). *Basic Principles and Calculations in Chemical Engineering*. 8th Edition, Prentice Hall. ISBN: 9780132885478.

E. F. Schumacher, (1973). *Small is Beautiful -A study of economics as if people mattered*. London: Muller, Blond & White ltd.

E. Paredis, (2011). Sustainability Transitions and the Nature of Technology. *Foundations of Science*. 16 (2-3) 195-225.

F. Bacon, (1620). *Novum Organum*. (2000) *The New Organon*, ed. by L. Jardine and M. Silverthorne. New York: Cambridge Univ. Press. ISBN 10: 0521564832 - ISBN 13: 9780521564830.

F. W. Geels, (2002). Technological Transitions as Evolutionary Reconfiguration Processes: a multi-

---

[4] https://ccl.northwestern.edu/netlogo/ (retrieved on March 1, 2019.)

[5] https://www.microsoft.com/ja-jp/hololens (retrieved on March 1, 2019.)

level perspective and a case-study, *Research Policy*. 31 (8–9) 1257-1274.

F. Kern, K. Rogge, (2017). Harnessing Theories for the Policy Process for Analyzing the Politics of Sustainability Transitions: A critical survey. *Environmental Innovation and Societal Transition*. 27, 102-117.

G. Jimbo, (1986). History of Chemical Engineering in Japan (in Japanese), *Kagaku-Kogaku*. 50(13), 165-176.

H. Achterhuis, (1999). Introduction: American Philosophers of Technology, in *The American Philosophy of Technology – The empirical turn.* ed. by H. Achterhuis. Bloomington, IN: Indiana Univ. Press, 1-9. ISBN 0-253-33903-0.

H. Minami, (1973). Tasks of Engineering Sciences and the Science of Technology (in Japanese). *Journal of Japanese Scientists*. 8 (2), 70-75.

H. Spencer, (1860). The Social Organism, (First published in *The Westminster Review* for January 1860).https://www.uzh.ch/cmsssl/suz/dam/jcr:00000000-36d7-41d4-ffff-ffffc03113dd/Essay_Spencer_TheSocialOrganism.pdf (Retrieved on Feb. 24, 2019.)

I. Muchi, (1966). Chemical Reaction Engineering for Production of Iron and Steel (in Japanese). *Tetsu-to-Hagane*. 52(7), 1079-1097.

I. Muchi, A. Moriyama, (1972). *Metallurgical Reaction Engineering* (in Japanese). Yokendo.

IEEJ, *IEEJ Outlook 2019*, https://eneken.ieej.or.jp/data/8116.pdf (retrieved on Feb. 24, 2019.)

IPCC, (2007). *Climate Change 2007 Mitigation of Climate Change,* AR4, [Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., and Meyer L.A., (eds)] Cambridge University Press, Cambridge, UK and New York, NY, USA (2007); https://www.ipcc.ch/report/ar4/wg3/

J. A. Schumpeter, (1934). *The Theory of Economic Development.* English Edition, President and Fellows of Harvard College. (New Brunswick, NJ: Transaction Publishers, 1983. ISBN: 978-0-87855-698-4.)

J. F. Davidson, D. Harrison, (1963). *Fluidized Particles*. London: Cambridge Univ. Press.

J. Jaynes, (1976). The Origin of Consciousness in the Breakdown of the Bicameral Mind. Boston: Houghton Mifflin Co. http://s-f-walker.org.uk/pubsebooks/pdfs/Julian_Jaynes_The_Origin

J. Martines-Alier, (2003). *Marxism, Social Metabolism, and Ecologically Unequal Exchange*. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.503.3541&rep=rep1&type=pdf (retrieved on Feb. 24, 2019).

J. Szekely, N. J. Themelis, (1971). *Rate Phenomena in Process Metallurgy.* Wiley-Interscience. ISBN: 0471843032, 9780471843030.

J.D. Bernal, (1954). *Science in History*. London: C A Watts & Co.

J.D. Bernal, (1967). *The Social Function of Science.* Cambridge. MA: The MIT Press.

K. Blockhoff, (2017). The Emergence of Technology and Innovation Management, *Technology and Innovation*. 19, 461-480.

K. Karatani, (2014). *The Structure of World History: From modes of production to modes of exchange.* Translated by M. K. Bourdaghs. Durham, NC: Duke Univ. Press. ISBN 978-0-8223-5676-9.

L. Adkins, (200). *Empires of the Plain: Henry Rawlinson and the Lost Languages of Babylon*. New York: St. Martin’s Press. ISBN 0-312-33002-2.

L. L. Carroll, (2017). A Comprehensive Definition of Technology from an Ethological Perspective, *Social Sciences*. 6(4), 126-145.

L. Lapidus, (1962). *Digital Computation for Chemical Engineers*. New York: McGraw-Hill.

L. Winner, (1986). *The Whale and the Reactor, A search for limits in an age of high technology.* Chicago: The Univ. of Chicago Press. ISBN 10: 0226902102, ISBN 13: 9780226902104.

M. A. Abraham (ed.), (2006). *Sustainability science and engineering: defining principles*. Amsterdam: Elsevier. (see C. Tunca, P. A. Ramachandran, M. P. Dudukovic, Role of Chemical Reaction Engineering in Sustainable Process Development; https://classes.engineering.wustl.edu/2009/spring/che505/additional/CRE%20in%20Sustainable%20Development.pdf (Retrieved on Feb. 24, 2019.))

M. B. Lindberg, J. Markard, A. D. Andersen, (2018). Policies, Actors and Sustainability Transition Pathways: A study of the EU’s energy policy mix. *Research Policy.* (in Press). https://www.sciencedirect.com/science/article/abs/pii/S0048733318302117?via%3Dihub#!

M. Fisher-Kowalski, W. Hüttler, (1999). Society’s Metabolism – The intellectual history of materials flow analysis, Part II, 1970-1998, *Journal of Industrial Ecology*. 2 (1) 107-136.

M. H. Kamali, O. Bakar, D. A.-F. Bachelor, R. Hashim (Eds.), (2016). *Islamic Perspectives on Science and Technology – Selected Conference Papers*, Singapore: Springer.

M. Heidegger, (1954). *The Question Concerning Technology* (original German version) in “The Question Concerning Technology and other Essays”, Translated by W. Lovitt, (1977). New York: Harper & Row, Publishers, Inc., 3-35.

M. Horio, (2006). ‘Symbiotic Technology’ in the Early 21C Ordeal, *Yearbook of the Artificial*. vol. 4, *Special Issue ‘Kyosei Culture and Sustainable Technology’*, ed. by M. Negrotti, M., and F. Satofuka, Bern: Peter Lang AG, 185-198.

M. Horio, (2011). After the 3-11 Nuclear Accidents How Do We Understand the Modern Technology-Human Relationship? – Through a discourse on Heidegger’s philosophy of Technology, *Ryukoku Journal of Policy Science.* 1, 43-61. ISSN 2186-7429.

M. Horio, (2013a). Why ‘Appropriate Technology’ Thinking is needed in the Modern Technological Society, *Waseda Journal of Human Science*. 26 (2) 163-179. ISSN1880-0270.

M. Horio, (2013b). Overview of Fluidization Science and Fluidized Bed Technologies, *Fluidized-bed Technologies for Near-zero Emission Combustion and Gasification*, ed. by F. Scala. Cambridge, UK: Woodhead Publishing, 3-41. ISBN: 9780857095411.

M. Taketani, (1942). On the formation of Newtonian mechanics, *Kagaku* (*Science*. in Japanese), 12, 307-311.

M. Taketani, (1946). Theory of Technology – Dedicated to intellectuals who fought persecution (In Japanese). (Originally published in a magazine *Shinsei*, February 1946), in *Problems in Dialectics* (New edition). Tokyo: Keiso-Shobo. ISBN-10: 4326750480; ISBN-13: 978-4326750481.

N. R. Amundson, (1986). P. V. Dankwerts - His Research Career and its Significance. *Chem. Eng. Sci.* 41, 1947-1955.

O. Levenspiel, (1962). *Chemical Reaction Engineering.* New. York: John Wiley and Sons.

P. Mason, (2016). *Post capitalism – A guide to our future.* London: Penguin Books.

P. V. Dankwerts, (1951). Absorption by Simultaneous Diffusion and Chemical Reaction into Particles of various Shapes and Falling Drops, *Trans. Faraday Soc.* 47, 1014-1023.

P. V. Dankwerts, (1953). Continuous Flow Systems: Distribution of residence times. *Chem. Eng. Sci.* 2(1), 1-13.

R. Aris, (1961). *The Optimal Design of Chemical Reactors: a study in dynamic programming.* Academic Press.

R. Clift, A. Druckman (Eds.), (2016). *Taking Stock of Industrial Ecology*, Springer. ISBN 978-3-319-20571-7 (eBook). https://link.springer.com/content/pdf/10.1007%2F978-3-319-20571-7.pdf

R. Higbie, (1935). The Rate of Absorption of a Pure Gas into a Still Liquid, *Trans. Am. Inst. Chem. Eng.* 35, 36–60.

R. Kurzweil, (2005). *The Singularity is Near: When humans transcend biology.*, New York: Viking Books. ISBN 978-0-670-03384-3.

R. Mattessich, (2002). The Oldest Writings, and Inventory Tags of Egypt. *Accounting Historians Journal.* 29 (1), 195-208.

S. Barrett, (2004). Implementation Studies: Time for a revival? Personal reflections on 20 years of implementation studies, *Public Administration.* 82(2). 249-262.

S. Hatta, (1932). On the Absorption Velocity of Gases by Liquids. II. Theoretical Considerations of Gas Absorption due to Chemical Reaction, *Tech. Rep. Tohoku Imp. Univ.* 10, 119-135.

T. Nishigaki, (2004). *An introduction to Fundamental Informatics – From life to society* (in Japanese; English translation: http://digital-narcis.org/Toru-NISHIGAKI/?lang=english). Tokyo: NTT Shuppan.

T. Oohashi, T. Maekawa, O. Ueno, N. Kawai, E. Nishina, K. Shimohara, (2003). Artificial Life Based on the Programmed Self-Decomposition Model: SIVA, *Artificial Life and Robotics*, 5, 77-87.

T. S. Kuhn, (1962). *The Structure of Scientific Revolutions.* Chicago: University of Chicago Press. ISBN 0-226-45808-3

U. Beck, (1986). *Risk Society: Towards a New Modernity* (originally published in German, 1986). London: Sage Publications. ISBN 978-0803983465.

U. Bossel, (2006). Does a Hydrogen Economy Make Sense? *Proceedings of the IEEE.* 94(10), 1826-1837.

US-NRC, (1988). *Frontiers in Chemical Engineering – Research needs and opportunities*. Washington D. C.: National Academy Press.

W. B. Arthur, (2009). *The Nature of Technology – What it is and how it evolves.* New York: Free Press. ISBN: 978-1-4165-4406-7.

W. E. Bijker and John Law, eds., (1992). *Shaping Technology/Building Society ―Studies in Sociotechnical Change.* Cambridge. MA:MIT. ISBN: 9780262521949.

W. H. Walker, W. K. Lewis, W. H. McAdams, (1923). *Principles of Chemical Engineering.* New York: McGraw-Hill Publishing Co.

Y. N. Harari, (2016). *Homo Deus: A Brief History of Tomorrow.* London: Vintage. ISBN 978-1910701881.

Y. N. Harari, (2018). *21 Lessons for the 21st Century.* London: Jonathan Cape. ISBN 1787330672.