Yasumitsu Tanaka
Michael Norton
Yu-You Li *Editors*

Topical Themes in Energy and Resources

A Cross-Disciplinary Education and Training Program for Environmental Leaders

Springer

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Editors
Yasumitsu Tanaka
Michael Norton
Yu-You Li
Tohoku University
Sendai
Japan

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Foreword

While many accept the premise that we need to move rapidly to a more sustainable society, the current pace of change is failing to reverse current adverse trends in population growth, climate change, ecosystem loss, species extinctions, and other key indicators of unsustainable development. Indeed, recent reviews of the world's progress towards sustainability (or rather lack of progress) have started raising the question whether sustainability is still possible (see Chaps. 1–3). In particular, the growth in greenhouse gas emissions and increasing resource consumption threaten a crisis in environmental sustainability if these trends are not reversed soon.

This situation has led to initiatives in Japan to nurture a new generation of environmental leaders who can influence individual, business, and governmental priorities and help promote the development of a more sustainable society. These programs face the challenges of providing participants with the knowledge, motivation, and skills necessary to influence and lead others towards a more environmentally sustainable future. Such courses are now offered at a number of universities; some through a dedicated degree, others where environmental leadership training is provided as an overlay on the student's primary activity, such as research in an engineering graduate school. Where the "environmental leader" training is an "add-on", ensuring that the EL training creates synergy with the student's basic educational and research purpose presents a particular challenge.

This book is based on the experience of the Environmental Leadership Training Program (ELTP) within the Strategic Energy and Resource Management and Sustainable Solutions (SERMSS) project of the Graduate School of Environmental Sciences of Tohoku University. The ELTP has been designed to be highly flexible and allow students who are carrying out research across a wide range of different disciplines (science, engineering, and humanities) to participate in the same program. The ELTP comprises a range of lectures to provide knowledge of sustainability and specific environmental problems and solutions, active learning to encourage personal skills development, fieldwork for practical experience, and internships to provide intensive training opportunities—all built on the foundation of the student's basic scientific or engineering research. A key objective is to nurture leaders with an ability to use their knowledge and personal skills to develop policy and international business strategies for the next generation. A critical component is thus teaching strategies relevant to energy and resources. This book is a compendium of the lectures provided during the 2013–2014 academic year in this area from leading experts in each field.

Concerning the book's structure, Chap. 1 provides background to the sustainability challenge, the role of environmental leadership training, and how this has been applied in the Tohoku University ELTP, and gives an overview of the course content. The remainder of the book looks at a broad range of sustainability issues and strategies in the fields of energy and resources; finally, we conclude with some analyses of common themes and insights gained from these courses and their effectiveness in environmental leadership training. We hope the book will be valuable to others interested in raising the awareness of science and engineering researchers in environmental issues and also to those wishing to obtain a swift overview of some of the key technical issues related to energy and resources.

Professor Kazuyuki Tohji
Dean, 2010–2014
Graduate School of Environmental Studies
Tohoku University
Summer 2014

Professor Toshiaki Yoshioka
Dean, April 2014–
Graduate School of Environmental Studies
Tohoku University
Summer 2014

T. Yoshioka

Preface

This book is a compilation of lectures entitled “A Strategy for Energy and Resources”. These lectures comprise one of the Environmental Leadership (Training) Program (ELP) activities. I am managing the ELP with my colleagues, and teaching is one of my responsibilities. ELP falls within the Environmental Education Training Program supported by the Science and Technology Agency (JST). This essentially means that it is “supported by funds for integrated promotion of social system reform and research and development of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT)”.

JST selected 17 Japanese universities for implementing the ELP. The purpose of this program is to foster young environmental leaders to lead the world in raising environmental consciousness, especially in Asia and Africa. Tohoku University was included in 2010 through the strong leadership of Prof. K. Tohji, the former dean of the Graduate School of Environmental Studies (GSES).

The formal name of the ELP at Tohoku University is “Strategic Energy and Resource Management and Sustainable Solutions” (SERMSS). The features of SERMSS are the following:

The key words are energy, resources, and water.

To nurture young, international environmentally aware leaders who are outstanding students of the Graduate School of Tohoku University as well as many stakeholders such as other universities, companies, and government bodies.

We look to heighten the professional research ability of students as we also seek to be practical so that our students will achieve comprehensive skills together with a bird’s-eye perspective of the issues.

For these purposes, we started SERMSS with Prof. Y. Y. Li and Prof. K. Tohji and the cooperation of many teachers and other staff. We invited Prof. M. J. Norton and Prof. J. E. Plagens to join the program. I believe that the success of SERMSS and publication of this book have been realized with their cooperation.

This book is a compilation of key 90 min lectures. Each lesson is under the direction of the GSES faculty members teaching in their field of expertise. We know that the concept of the environment covers a huge scientific and social realm and has a complex relationship with many important issues. Furthermore, a vast number of useful books already have been published. We also know that it is very difficult to consider all environmental issues in only one volume. Still, we dare to publish this book because the environment is a most serious issue and we wish to position this publication of the environmental education and research activities of Tohoku University as one link in the total lineup of environmental studies.

Doubtless many of our readers are well aware of global warming as it provokes widespread abnormal weather in many areas all over the world. Environmental issues encompass more than just global warming, such as problems with resources, waste disposal, and manmade chemicals. The food and water supply—even the air (atmosphere)—are causes for concern now. In this book, we consider the following terms and their implications: “Sustainability”, “Overshooting”, and “Tipping Point”. We also consider “Science and Technology” and “Social Science”, which are manmade, and “Nature”, which is the capacity and balance of our earth. And we do not forget the aspirations of “Dreams” and “Hope.”

There are those who say that “our lifestyle can never return to bygone days.” Is this true? Please do not be confused by such statements. Our future and actions should never be determined and forced upon us by other persons. It is especially important that young people judge things for themselves and decide their own course of action. Unfortunately, some people take the wrong way in following their own desires because they have been caught up in greed. They sometimes forget the real purpose of life, and they only try to obtain material goods, authority, or a high position. It is important to have one’s own opinion and purpose.

I think that the present lifestyles of the developed countries greatly exceed suitable levels. There is much futility, injustice, and inequality. I also think that, while our science and technologies are outstanding, there are some lines of research that would best be left alone. I question whether manmade technology will be able to supersede nature. Until now, humans have acquired much knowledge and technology from nature. The result is that humans now have the power to destroy natural forests, rainforests, tidelands, coral atolls, rivers, lakes, even mountains. But can we exert the same creativity and beauty of nature? Will our technologies surpass nature? I worked many years in the field of research and development in natural science. I both admire and believe in science and technology. Still, I am aware that science and technology alone cannot solve these problems. We need the cooperation of many stakeholders in the social sciences.

I believe there are two pressing issues at present. One is the depletion of energy and resources. The second is far more serious and important, namely, that human activity has surpassed the capacity of the planet and its ability to cleanse itself. The outcome is that humans are destroying the balance of the earth. We have to change our lifestyles, especially in developed countries. And the developing countries must never repeat the same failures as the developed countries. When humans functioned within the capacity of the planet, they were a part of the total. But since the Industrial Revolution, human activities have increased exponentially. This is the main reason we have destroyed our earth’s equilibrium.

We ask young students in our classes to imagine what life was like 40 or 50 years ago. This question is very useful for them to dialogue with their parents and grandparents. It is always very useful to remember the past. Next, we ask them to think about the present. And then we ask, “What do you think? Is the present better than the past?” We then ask them the next follow-up question, “Please imagine the future 40 to 50 years from now. Will it become better than now?”

I am at the age where I do not expect to be here in 40 or 50 years. However, the young students of today will be living in this future. They must look to their own future of 40 to 50 years from now. This is not only for them but also their children, grandchildren, and descendants. They cannot shirk from this. The young people of today have a big responsibility for their future and that of the earth’s. They will someday know the answer to the question of whether the future will be better than today.

I like the saying of the American Indians that “We have to consider the next seven generations.” (Or: “In our every deliberation we must consider the impact of our decisions on the next seven generations.” –From the Great Law of the Iroquois Confederacy–). This means that we have a responsibility for our children, grandchildren, and beyond. And I like the next saying from Japan: “Asking for little, and knowing sufficiency”「少欲知足」. And I like the idea of being “one with nature”「万物一体」.

Finally, I would like to take this opportunity to express my gratitude to many people. Thank you to the faculty members who have willingly undertaken the writing of each chapter of this book. I know that they are very busy. I would like to thank Prof. M. Norton for working with the authors closely to make the book valuable to both expert and general readers and for the time-consuming editing in English, and to my other co-editor Prof. Y. Y. Li for his advice and support throughout. I also appreciate the efforts of Ms. Y. Sasahara and Ms. M. Sasaki in helping us with organization and many matters, and also offer my thanks to our colleague Prof. J. E. Plagens for all his support for ELP. My gratitude also goes to the former dean Prof. K. Tohji and the new dean Prof. T. Yoshioka.

I would also like to give a word of thanks to my parents, wife, and son.

And I thank every reader who has picked up this book. It is our hope that this book will be helpful to all of you, if only in a little way. I close with my best wishes for a happy future for everyone in the hopes that the global environment will proceed in the direction of true sustainability.

September 2014

Yasumitsu Tanaka
Tohoku University

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Chapter 1
Nurturing Environmental Leaders Among Science and Engineering Researchers—Tohoku University Approach

Michael Norton and Yasumitsu Tanaka

Abstract This chapter sets the scene for the book by explaining the background reasons why Japan decided to support a range of environmental leader programs. Current trends in growth of both population and economy are placing demands on the Earth's ability to supply resources or absorb the wastes. This is widely recognized but the current socio-economic system is currently not adapting and exhibits system failures in prioritizing growth over sustainability. Japan's environmental leader programs are designed to nurture human resources who can help lead society towards a transition to a more sustainable socio-economic system. Tohoku University's environmental leader program is described in this chapter and the background to the course materials on which this book is based introduced.

Keywords Environmental leader · Sustainable development

1.1 Why Do We Need Environmental Leaders?—The Failure to Develop Sustainably Under Current Systems

The term 'Sustainable Development' (SD) entered the global stage in 1987 when the World Commission on Environment and Development reported (WCED 1987). This, commonly referred to as the 'Brundtland Report', defined SD in terms of meeting the needs of the present without reducing the ability of future generations to meet their own needs. The WCED identified a number of targets for a more sustainable development path (Table 1.1) and World Leaders accepted the aim of sustainable development at the Rio Earth Summit in 1992; yet despite the many international, national and local 'sustainable development' initiatives, there is little evidence that the nature or pace of human development has become any more sustainable.

M. Norton (✉) · Y. Tanaka
Environmental Leader Program, Tohoku University, Sendai, Japan
e-mail: norton@mail.kankyo.tohoku.ac.jp

Y. Tanaka
e-mail: tanaka@mail.kankyo.tohoku.ac.jp

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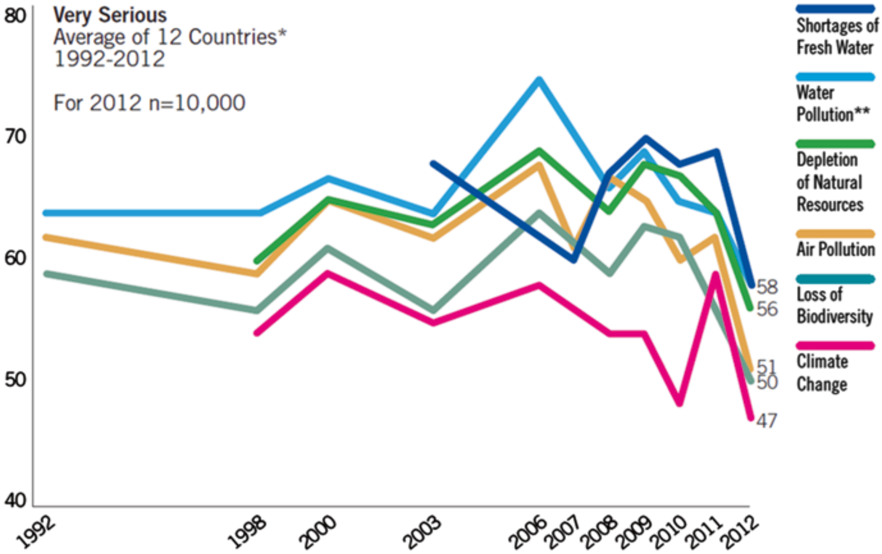
Table 1.1 Trends identified by WCED in 1987

Hunger and poverty increasing	Literacy not improving
Lack of safe water and shelter	Lack of fuel
Gap between rich and poor widening	Desertification
Deforestation	Acid precipitation
Greenhouse gases and global warming	Ozone hole
Toxic materials and the food chain	

There have been many reviews of global sustainability progress; for instance the Millennium Ecosystem Assessment review (MEA 2005), reviews before the 2012 Rio+20 Summit, and a more recent and comprehensive analysis carried out by the Worldwatch Institute (2013). While there has been rapid economic growth and associated improvements in social and economic welfare in many parts of the world, almost all global environmental indicators continue to worsen, while economic and social objectives of sustainability (inequality, basic needs, gender equality, reproductive health and population, etc.) have also failed to be achieved, despite economic growth having increased global GDP from $ 16.2 trillion in 1987 to $ 71.2 trillion in 2012. UNEP's Global Environmental Outlook (UNEP, 2012 GEO-5) cautions that "*if humanity does not urgently change its ways, several more critical thresholds may be exceeded, beyond which abrupt and generally irreversible changes to the life-support functions of the planet could occur.*" Current trends threaten to undermine or reverse progress on development and severely constrain opportunities for a prosperous future.

Knowledge of the state of the world and its environment is better than it has ever been; yet it appears that we are unable to act on this knowledge to find a way of curbing the excessive impact of human activities on the planet. With democracies and globalization such strong drivers of the current socio-economic system, strong public support and momentum is increasingly important to require (or at least allow) governments to grasp such intractable challenges as global warming, deforestation, biodiversity loss and extinctions, or population issues. However, tracking surveys on the global public's assessment of the urgency of key environmental problems shows concerns have decreased at the same time as scientific assessments of the threats have strengthened (Fig. 1.1). Meanwhile the 'virtuous circle' of 'green consumers' demanding and rewarding a 'greener' business model also appears to be stagnant. Surveys such as National Geographic's and GlobeScan's *Greendex,* across 17 countries show little growth in sustainable consumer behavior since the survey's start in 2008 (Sustainability and Globescan 2013). Reasons include skepticism about company 'green-wash' and the unfortunate reality that individual efforts are only worthwhile when reinforced and supported by broad government and private sector action.

Against the background of this negative assessment of the ability of current economic and social systems to evolve to a sustainable development path, one limiting factor has been seen as inadequate education in sustainable development, and a lack of leadership in all key parts of society- political, administrative, corporate



* Average of Brazil, Canada, China, France, Germany, India, Indonesia, Mexico, Nigeria, Turkey, UK, and USA. Not all questions were asked in all countries in all years.
** Not asked in Brazil, Canada, and France.

Source: Globescan Radar, 2012

Fig. 1.1 Public opinion on the seriousness of global issues. (From Fig. 3.1 of Sustainability, Globescan 2013)

and technological. Japan assumed a leading role in international actions on Education for Sustainable Development (ESD) through its proposal for the UN Decade of Education for Sustainable Development (2005–2014)[1]. It is thus no surprise that Japan should also seek to make a contribution to the environmental leadership gap we have just described.

1.2 Japanese Initiatives in Environmental Leadership: The Background to the Tohoku University Project

Japanese support of environmental leader initiatives emerged from Innovation 25 (Cabinet Office 2007) which looked at Japan's needs to be competitive in the twenty-first century, and how to stimulate innovation towards a sustainable development path. I25 noted that without controlling global warming and over-use of natural

---

[1] DESD had five objectives 1. Give an enhanced profile to the central role of education and learning in the common pursuit of sustainable development. 2. Facilitate links and networking, exchange and interaction among stakeholders in ESD. 3. Provide a space and opportunity for refining and promoting the vision of, and transition to sustainable development—through all forms of learning and public awareness. 4. Foster increased quality of teaching and learning in education for sustainable development. 5. Develop strategies at every level to strengthen capacity in ESD.

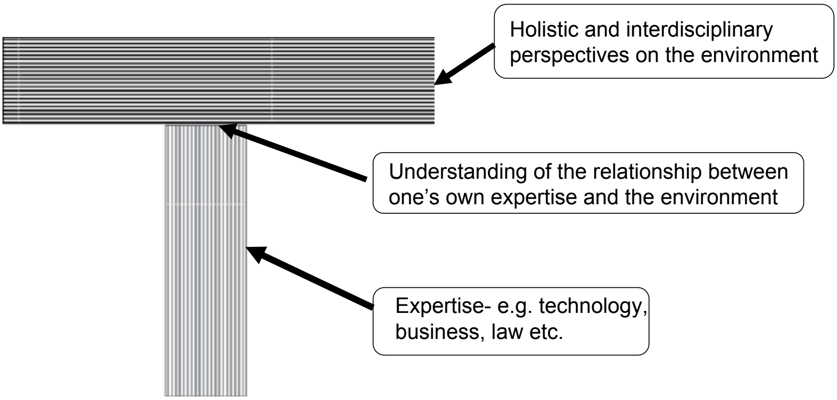


Fig. 1.2 Vision of the T-shaped environmental leader. (MOE 2008)

resources, the global environment and economy may collapse, and among its recommendations was one to "*foster leaders in the global environment area*". I25's vision was that environmental leaders fostered in Japan would comprise "*Young people from the world, including Asia*" who *"will be actively involved in environmental businesses of the world*" and "*contribute to the realization of the environmental-friendly economy in their home countries.*"

Innovation 25 was followed up in the 'Plan for an Environmentally Leading Nation' in 2008 which emphasized that global environmental problems pose a serious challenge to humanity's well-being (Cabinet Office 2008). These analyses led both the Ministry of the Environment (MOE) and the Ministry of Education (MEXT) to introduce Environmental Leader initiatives.

The MOE's response was the Environmental Leadership Initiative for Asian Sustainability (ELIAS) in Higher Education (MOE 2008). Three types of environmental leader were envisaged:

1. Those capable of developing comprehensive strategies which integrate the environment, the economy and society.
2. Environmental experts (pollution prevention, environmental assessment, protection and management).
3. Those whose primary skill is elsewhere but who have the ability to integrate their own area of expertise with environmental and sustainability objectives.

The third category envisages leaders with a range of skills in the economy, but who also have a commitment and motivation towards sustainability. Figure 1.2 illustrates the concept of this 'T-shape' leader; the horizontal bar reflects the knowledge and commitment to sustainability, resting on top of the vertical bar representing individual skills (management, researcher, policy-maker, engineer, etc.).

MEXT's response (through its Japan Science and Technology Corporation (JST)) was the International Environmental Leaders Training Program (ELTP). The ELTP establishes "*centers or systems to foster environment leaders, who will*

Table 1.2 Asia and Africa international environment leaders training program. (JST 2012)

Project	Organization	Adopted
Global environmental leaders education program for designing a low-carbon world	Hiroshima University	2008
International center for human resource development in environmental management	Kyoto University	2008
International environmental leader program	Nagoya University	2008
Environmental leader double degree program	Waseda University	2008
Asian program for incubation of environmental leaders	Tokyo University	2008
Strategic program for fostering environmental leaders	Tsukuba University	2009
Women environmental leaders to promote local ESD	Kobe College	2009
Rearing program for basin water environmental leaders	Gifu University	2009
Creating a sustainable environmental leader program	Hokkaido University	2009
Leadership program in sustainable living with environmental risks	Yokohama National University	2009
Strategy and practice of field-oriented education for leaders in environmental sectors	Tokyo University Agriculture and Technology	2009
International leader training program for sustainable use of water and resources	The University of Kitakyushu	2009
East Asia environmental strategist training program	Kyushu University	2010
Environmental leader education to design a high level society with co-existence between ecosystems and humanity	Shizuoka University	2010
Environmental innovators for a future creative society	Keio University	2010
Groundwater environmental leader program	Kumamoto University	2010
Strategic energy and resource management and sustainable solutions	Tohoku University	2010

take the leadership to solve the environmental problems in developing countries" (JST, 2012). As a result of this support, universities have been selected to develop various aspects of environmental leadership training (Table 1.2).

The proposal under the JST ELTP from Tohoku University was based on pre-existing research and teaching in a number of fields underlying sustainable energy and resources (e.g. geothermal, solar, batteries, metal resources, materials, recycling, energy management and other technologies) and a high proportion of overseas students for masters and doctorate degrees. The ELTP proposed to tap into academic disciplines on human security, Asian regional policies, the full range of energy, resources and water expertise in the Graduate School of Environmental Sciences, environment and technology management and other relevant aspects. Special features included were liaison offices in other regional universities (initially China, Vietnam, Indonesia), international internships for doctoral students, and the integration of the environmental leadership components with the graduate student's research discipline, involving double supervision by the student's research professor and the ELTP.

The proposal was accepted by JST and commenced in 2011 as the Tohoku University Strategic Energy and Resource Management and Sustainable Solutions (SERMSS) program. It has developed new courses to train environmental leaders capable of identifying problems and designing strategic solutions to energy, resource and water challenges, especially in Asia and Africa. Its mission is to foster international and environmental leaders who have advanced expertise in the field of energy and resources, water management and can apply their management skills, practical ability, and overall knowledge to develop policy and international business strategies for the next generation. It is anticipated that graduates from outside Japan will return to their mother country with advanced research and strategy skills in energy and resources. They will be able to apply not just their strategic knowledge but also an international outlook, use their negotiating skills to contribute to policy actions in governments, NGOs, and society, or in businesses (Tohoku University 2012). Let us now consider some of these special aspects in more detail.

1.3 Tohoku University ELTP Course Design/Special Characteristics

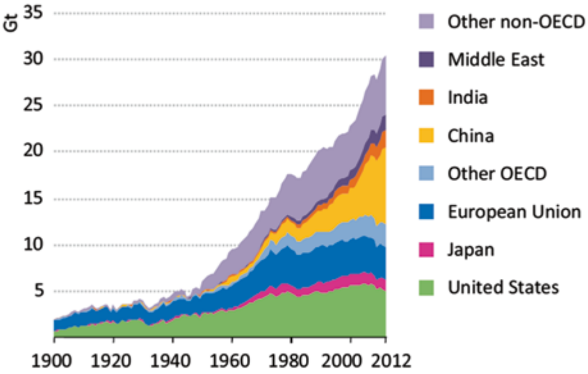
1.3.1 The Importance of Environmental Leadership in Asia and Africa

Tohoku University's special focus is on Asia and Africa. Two of the most serious concerns over environmental sustainability relate to the consumption of energy (and its associated responsibility for the majority of anthropogenic CO_2 emissions), and overall consumption of natural resources. Just a simple history showing how the origins of these two drivers have changed in recent decades illuminates the increasing importance of Asia now and Africa in the future.

CO_2 Emissions from Energy Sources of energy-related CO_2 emissions from different countries are shown in Fig. 1.3 (OECD/IEA 2013). These have grown from below 3 Gt 100 years ago to 31.6 Gt in 2012—a rise of over 10-fold. However the dominant source of the emissions of 100 years ago (Europe and USA) now only accounts for ~40% of global emissions, with the majority coming from China, India, Middle East and other non-OECD countries including Africa.

Just in the 10 years from 2000–2010, the contribution of OECD countries to global emissions has dropped from 54% in 2000 to 41%. Looking at Africa, its

Fig. 1.3 Energy-related CO_2 emissions by country, 1990–2012 (copyright OECD/IEA. Figure 1.11 in OECD/IEA 2013)



overall emissions have grown from 248.7 Mt CO_2 in 1971 to 929.7 Mt in 2010. Emissions have doubled since 1984. Asia's growth rate has been even faster, increasing from 434.1 Mt in 1971 to 3,330.6 Mt in 2010, having doubled since just 1995 (IEA 2012).

In addition, other major sources of GHG emissions due to land use change are extensive in Asia—particularly the replacement of natural forests in Malaysia and Indonesia to produce Palm Oil. In particular, Indonesia is the world's third largest emitter of CO_2 (accounting for 4.5 % of global emissions) of which approaching 80 % originate from deforestation and land use changes which cause peat-lands to dry and burn (UNFCC 2012).

The critical importance of national policies in determining the future path of global warming can be shown in trends in the two largest emitters- USA and China. US emissions of carbon dioxide from fossil fuels fell by 200 Mt in 2012 due in part to a transition from coal power to natural gas, but also due to active national and state-level policies to encourage renewable energy—especially wind and solar. European emissions have also been reduced as a result of strong renewable energy policies. China has also started to implement specific policies to reduce the rate of growth in GHG emissions through energy efficiency and renewable energy initiatives and, as a result, growth in emissions (300 Mt in 2012) was one of the smallest annual increases in recent years; mainly because China has achieved a substantial drop in emissions per unit of electricity (Fig. 1.4). Future options include for China to price its carbon emissions, adding an additional economic incentive to switch from high-carbon sources—particularly coal power use.

Such modest progress underlines the importance of providing human resources to staff the switch in priorities from just economic and technological development, to sustainable development which can reverse the serious environmental side-effects of current paths. At present, global emissions of CO_2 are closest to Scenario A2 in the 2007 IPCC report (IPCC 2007), which is associated with an average global temperature rise of 3.6–5.3 °C. This is well above the international consensus of a 'safe' maximum warming of 2 °C. Limiting planetary warming to 2 °C requires much more substantial and urgent measures in all countries. Strong environmental

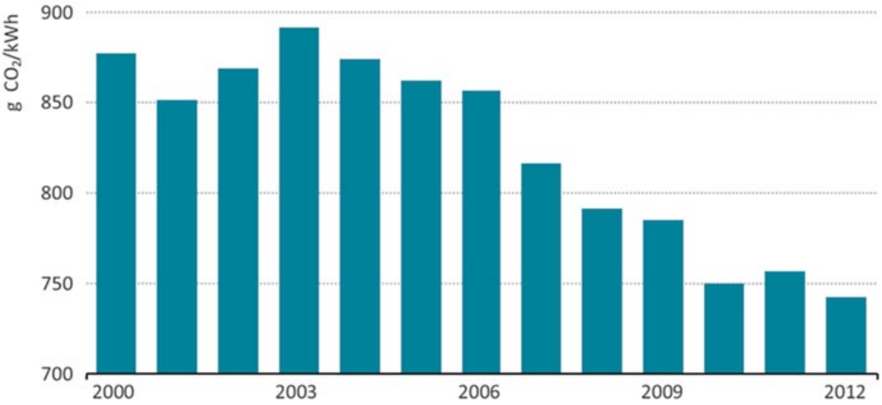


Fig. 1.4 Chinese CO_2 emissions per unit of electricity generation. (Copyright OECD/IEA. Figure 1.9 in OECD/IEA 2013)

leadership is thus critical to continuing and strengthening measures to reduce emissions in the future; equally the lack of leadership in solving the annual forest destruction and burning cycle in Asia can undermine even the modest progress made elsewhere.

Renewable Energy With the dominance of the energy sector and its reliance on fossil fuels, no strategy to combat global warming can succeed without a substantial shift from fossil fuels to renewable sources of energy. The renewables sector is showing high growth rates, but major technological challenges (particularly in materials and engineering) remain to either reduce the costs of alternative technologies, or invent new approaches to resources not yet capable of being effectively harnessed (marine energy in particular). Human resources to contribute and lead such efforts are required.

Natural Resources Natural resource consumption is already estimated to be 50 % above the sustainable level (Global Footprint Network 2012) with projections of increased demand continuing with rising population and consumption of goods (Fig. 1.5). By 2050, annual consumption could triple to 140 billion tons of minerals, ores, fossil fuels and biomass per year unless economic growth can be decoupled from natural resource consumption (UNEP 2011). Such levels are many times what is sustainable, underlining the scale of the challenges to reduce consumption through more efficient usage, recycling, substitution of high environmental impact materials with those of lower impact and other measures. As the UNEP report says, achieving a decoupling of resource consumption from GDP "*demands an urgent rethink of the links between resource use and economic prosperity, buttressed by a massive investment in technological, financial and social innovation*".

The source of this increasing demand is shown in Fig. 1.6 where the growth in the proportion of resources consumed by China and Asia stands out. Africa's proportion of the global total appears stable, but looking at resource extraction and

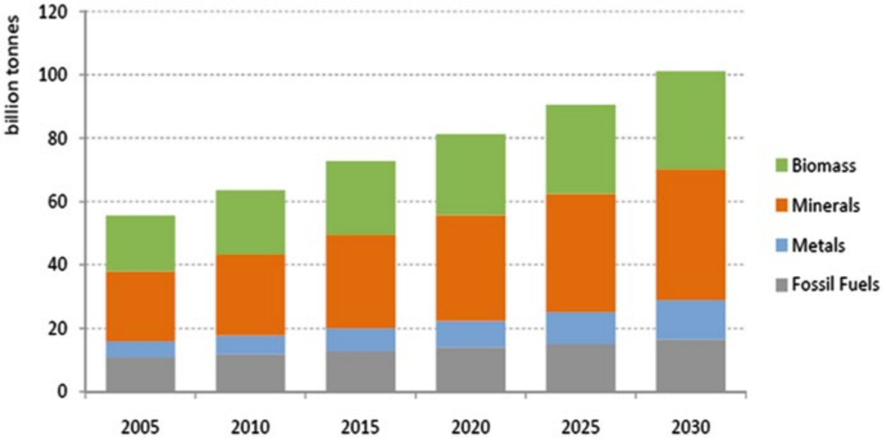


Fig. 1.5 Growth of worldwide resource extraction under current ‘Business as usual’. (Friend of the Earth Europe/SERI 2009)

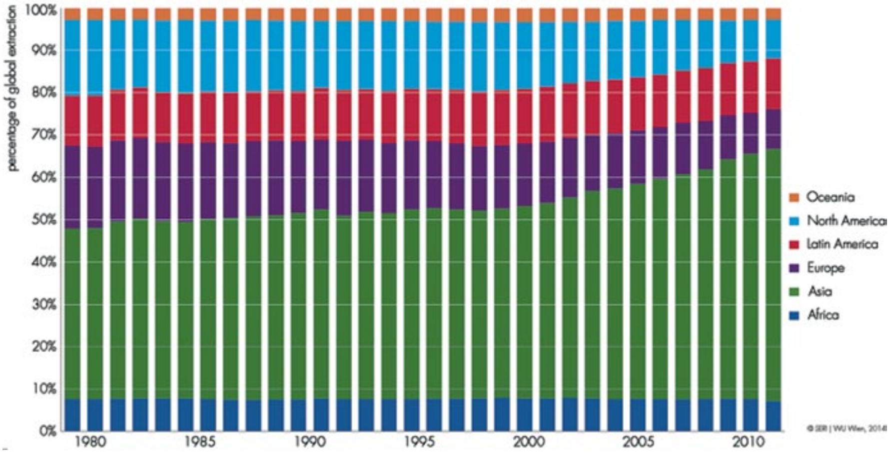


Fig. 1.6 Shares of global resource extraction by world region. (SERI/WU Vienna 2014)

consumption per unit of GDP (Fig. 1.7), Africa is the continent with the highest resource intensity, with African countries consuming almost 7 kg of domestic resources per dollar of GDP produced; compared with a global average of ~1.5 kg/GDP$ (FOE 2009) due to the dominance of resource-intensive mining in African economies.

Future Demand Trends Two further key factors make Africa increasingly important in determining whether global sustainability is achievable: population growth and projected economic growth rates. IMF (2013) projections show that while GDP

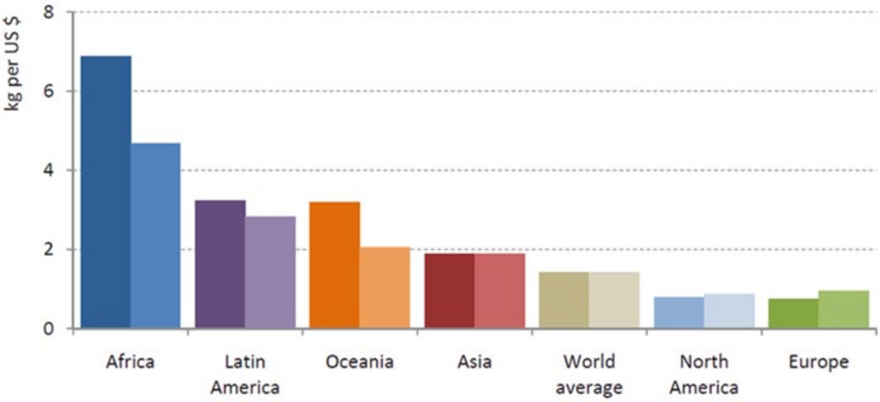


Fig. 1.7 Extraction (*left* bar) and Consumption (*right* bar) in various regions (kg/$GDP2000). (Friends of the Earth Europe/SERI 2009)

growth is expected to remain for China at 6 % or above, rates for the rest of Asia are lower. In contrast, a majority of African countries (19) are projected to exceed the 6 % GDP growth rate, while an additional 16 will be between 4 and 6 %. Only four African countries are projected to have growth rates below 4 %. Africa's demand for energy and resources will thus become increasingly important; a trend illustrated by the increasing attention given to the continent by Japan, China and Korea as a source of resources and potential markets.

Current world population of 7.2 billion is projected to increase by 1 billion over the next 12 years and reach 9.6 billion by 2050 (UN 2013). This growth will mainly occur in developing countries, and over half is expected to take place in Africa. Indeed, 9 of the 10 countries with the highest population fertility rates are currently found in Africa[2]. For these reasons, the fate of the world will be highly dependent on future development paths for Asia and Africa, supporting the priority afforded by the JST Environmental Leader Training Program.

1.3.2 Teaching Environmental Leadership: Appropriate Approaches

As pointed out by Norton (2012), teaching sustainability in environmental leader programs requires particular attention to be paid to:

- **Students**. Potential environmental leaders are Masters or Doctorate students in the Graduate School of Environmental Sciences (GSES) covering a range of disciplines from sciences through engineering to humanities (GSES 2012). The

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[2] These are Niger 7.58; Somalia 7.10; Chad 6.85; Mali 6.80; Timor-Leste 6.53; Burundi 6.52; Dem. Rep. of the Congo 6.50; Angola 6.50; Uganda 6.38; Afghanistan 6.33 (UN 2013).

environmental leader qualification would be in addition to their science or engineering Masters or Doctorate. Clearly, the attractiveness of this extra qualification to future potential employers is an important factor.

- **Motivation**. One of the primary objectives is to teach environmental sustainability in a way which motivates students (Fig. 1.2). Motivation requires students not just to learn about, but to understand and sympathise with the fundamental importance of sustainable development–especially the requirement for environmental sustainability through harmonising human activity with the environment.
- **Personal skills**. A necessary condition for leaders is the ability to effect necessary change towards sustainability. Related personal skills include those for engaging and persuading others of the need for change, engaging stakeholders and envisaging and negotiating solutions.

The Tohoku University ELTP Course is available to students from a range of disciplines, and thus adapts the T-shape model in Fig. 1.2 to apply the common themes of environmental leadership to a range of research disciplines. Moreover, performance is assessed by both the ELTP tutors and the student's own research supervising professor. Within the overall structure, different variants of the training courses exist for Masters and Doctorate students. In addition, classes in the graded ('Regular') course are open to other students just wishing to obtain a basic understanding of sustainability and environmental problem solutions (referred to as the 'Basic' course).

1.3.3 Environmental Leader Course Curriculum

The ELTP curriculum is in Table 1.3 and allows students to access teaching on international aspects, sustainability and environmental problems, problem solution identification and in leadership training. In addition to lectures and special seminars, fieldwork opportunities are offered each year, and an internship is also provided. Grades for the ELTP are combined with grades from achievements in the main research field to give the assessment of overall performance. Each year 12 students are accepted in the Regular course and 8 in the Basic course (total of 80 over 4 years).

Let us now consider some of the curriculum content in more detail.

Sustainability Foundations This course provides students with a grounding in the concept and implications of environmental sustainability. The course follows the structure in Fig. 1.8. It starts with historical problems which led to concerns over environmental sustainability, initial responses through regulations and principles, and how despite these, continued growth in population and economic consumption have led to the current global scale of pollution problems and resource depletion. Social issues of poverty, inequality, literacy and health combined with these environmental issues to give the initial concept of Sustainable Development (WCED 1987). The course then reviews how SD has since developed, and examines the underlying global issues of biodiversity, climate change, resource depletion, pop-

Table 1.3 ELTP curriculum

Course title	Contents
Sustainability foundations	Origin of the sustainability issue, detailed analysis of current challenges and the system failures which lead to unsustainable development
Environmental management and sustainable business	How companies can adapt their business to develop more sustainable approaches and find opportunities from sustainability
Environmental leader practical training and seminars	Developing interpersonal and intercultural skills on the international stage
Solution creation	Processes of creating new technologies, strategies and technologies
Energy and resources	Understanding the current energy and resource situation and potential strategies for a sustainable future
Water and urban environment	Focus on the supply, management and treatment of water in cities
Fieldwork	Visits to environmentally-focused companies and local administrations
Internships	Periods of internships nationally or internationally suited to the student's own field of expertise
International environmental leader symposium	Collaboration with partner universities in Asia to organise joint symposium on environmental leaders

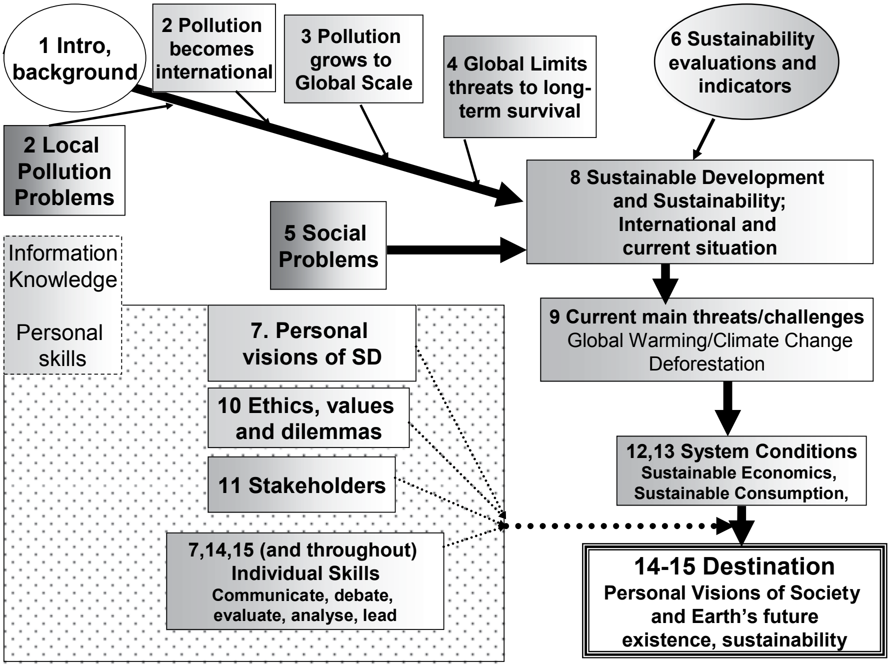

Fig. 1.8 Sustainability Foundation Course concept. (Norton 2012)

ulation growth, economic imbalances within and between societies, poverty, etc. It then focuses in more detail on the key environmental sustainability challenges of global warming and climate change, reviews the basic economic and market failures which have led to current unsustainable trends, and reviews some of the alternative approaches to economic indicators and measures of success, including sustainable production and consumption (Norton 2012).

Sustainability requires effective communication, dialogue and negotiation between different groups and stakeholders to develop sustainable solutions. Elements aimed at building social skills for sustainability and for encouraging motivation are shown in the left hand lower half of Fig. 1.8. Active learning includes asking students to evaluate the sustainability of their own lifestyles, and by two main projects (MacVaugh and Norton 2011).

The first project emphasizes that there are no fixed scientific definitions or rules for SD, and individuals decide their own priorities and opinions. Students are asked to think about which aspects of SD they think are most important, discuss with another student and present to the class their initial conclusions and how (if at all) they change as a result of the discussion. The second project envisages futures. It is carried out in four stages; looking back at the past and comparing with now; considering the effects of the changes on health, energy and resources; looking at any aspects of the past seen as preferable to current lifestyles; and envisaging the future.

Environmental Management and Sustainable Business Many of the postgraduates researching at the GSES will join businesses where their environmental leadership skills may be applied. Unfortunately, many organizations do not see sustainability as a priority, and it can be a tough challenge for a new recruit to try and exert influence on an issue which is not their organization's main focus. This course thus focuses on the interaction between business and sustainability, and how businesses can respond to sustainability and even include in their business objectives, targets for a more sustainable world.

Issues in sustainable development which impact on business range from meeting environmental regulations to more comprehensive social and workplace issues. The course reviews indicators and tools for assessing performance in sustainability and in reporting sustainability. It also looks at supply chain pressures such as carbon reduction and rules on toxic substances and recycling. It then moves on to alternative planning and analytical approaches, such as The Natural Step and Natural Capitalism models for analysing business models and identifying ways of integrating sustainability into strategy. Finally it covers the many fields where sustainability thinking is driving innovation and new markets in ethical markets, energy efficiency, natural resources recycling and renewable energy, and other issues such as government strategy, eco-design, sustainable organizations, 'Bottom of the Pyramid' and ecosystem services.

This course also emphasizes that companies respond to environmental leadership at the political level. An illustration of the importance of such leadership is Japan, which has varied considerably. On the main sustainability indicator of carbon dioxide reduction, the new government in 2009 set a target to reduce 2020's CO_2

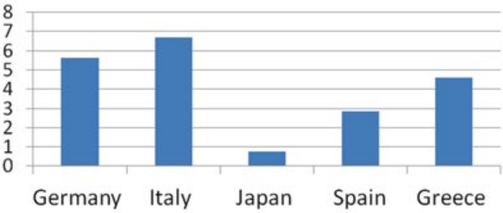

Fig. 1.9 Penetration of solar photovoltaic energy in Japan and some European countries (% of electricity generated). IEA (2013)

emissions by 25 % (1990 baseline). The disruption following the 2011 earthquake and tsunami led to the shutdown of nuclear power making this target difficult, and the current government replaced the 2020 25 % reduction target with one allowing a 3 % increase in CO_2 emissions. Japan already had a slower uptake of renewable energy compared with European Union countries with more challenging targets (Fig. 1.9), suggesting that stronger rather than weaker political leadership in this area is still required to reduce the current high degree of fossil fuel dependency.

Water and Urban Environment Water is a special resource for life, industry and the large cities and urban environments. This course studies the conservation, utilization and circulation system of water based on different points of view, including water quality, water quantity, pollution and remediation. The water environment management methods for supporting the sustainable development of cities and society are explored, with particular emphasis on the Asian countries of Japan, Korea, China, Vietnam, Thailand, Indonesia and Malaysia. These issues are addressed at the level of global water resources, the utilization and circulation of water to support life and industry. The management of water supply and sewage systems for cities is also addressed. The role of environmental standards and risk assessment, eutrophication problems and pollution and remediation of groundwater is also covered together with technological solutions using physical method (membranes), chemical methods and biological methods.

Environmental Leader Training A further course aims at improving communication skills in English as a major international language. Students have practice in expressing their opinions, debating, and negotiating for the purpose of boosting their persuasiveness on the international stage. Contents of the course range from a review of the dynamics of speaking and listening to practice in skills for reading and writing. This includes a study of phonetics and pronunciation for confidence in speaking, listening, and presenting. There is also exposure to the rhetoric of English both for organizing presentations and understanding academic research papers. The emphasis is always on practical, authentic content. Another component of the course is to heighten awareness of issues in intercultural communication. Frameworks for analyzing and appreciating cultural differences are made available.

Through these lessons in effective communication in English, and by offering opportunities for discussions and debates, the objective is to help students' language and interpersonal skills. In particular, the course focuses on understanding different stakeholder viewpoints, in communicating ideas, negotiating outcomes with other stakeholders, developing an international analytical perspective, applying logic, using analytical and reasoning skills, and gaining practice in analyzing and debating specific environmental themes.

Solution Creation and Energy Resource Strategy This series of lectures aims to encourage students to learn ways to create technology, understand policy making, and systems to deal with the issues confronting countries, corporations, or local governments beset with environmental problems. Analysing case studies helps students develop the skills to discover the essentials of problems and develop the ability to solve them, including creating new business systems. The focus on energy and resources starts with an understanding the past and the current global environment, before considering potential futures for the Earth and humanity. The course looks at the relationship between energy generation/consumption, resource mining/utilization/ alternative technologies, and water resources, all of which are important for the future environment and a sustainable society.

Fieldwork and Internships A range of options are offered to students through fieldwork, which comprises group visits to environmental businesses, waste treatment facilities, and the like. For instance in 2012, visits were made to wind generator sites, precious metal recycling facilities from electronic waste, one of Japan's Eco-towns, local water treatment and sewage works.

Internships are an important part of the ELTP because they offer an opportunity to bring together environmental issues with the specialism of the individual student. Internships are thus more personalized than fieldwork, and internships relevant to the research field are sought (often proposed by the student and decided in consultation with the research supervisor). Examples included wind power organizations in China for a Chinese student researching wind power introduction; waste water treatment in Egypt for an Egyptian student researching hydrogen production from sewage treatment; and an environmental nanotechnology lab in the USA for a Japanese nanomaterial researcher. The internships can also help in developing skills in collecting information, data analysis, and developing strategies through the practical training received at international companies, research organizations, and governmental agencies.

International Environmental Leader Symposium An annual joint symposium is held with other Asian university partners to allow students and researchers from participating universities to share their research related to environmental sciences, technology and environmental leadership. Partners have included universities in Vietnam, China, Indonesia, Thailand and Malaysia. Each symposium is associated with fieldwork in the host country which contributes to learning about foreign cultures and the current situation on environmental activities, measures and policies.

Qualifications and Awards Graduating from the ELTP course is a qualification in addition to the basic Masters or Doctorate award for research in the group to which the student belongs. The qualifications and contents are summarized in Table 1.4.

Table 1.4 Qualifications available on graduation from the ELTP

Course	Requirements	Qualification
Basic Environmental Leader Training Course	Development of comprehensive ability including international perspective, practical ability, management ability and strategic planning skills	*Environmental Leader Training Certificate* *Professional Master/Leader for Sustainable Environment* (for students who excel)
Masters Researcher Environmental Leader Training Course	Two-year professional education and advanced practical education program	*Environmental Leader Master Certificate (ELMC)* *Professional Master for Sustainable Environment (PMSE)* (for students who excel)
Doctorate Researcher Environmental Leader Training Course	Advanced and professional research and internship	*Environmental Leader Doctor Certificate (ELDC)* *Professional Director for Sustainable Environment (PDSE).* (for students who excel)

1.4 Content of this Book

A key contribution to the Energy and Resources and Solution Creation components of the ELTP are special lectures on a range of subjects provided by experts in the many environment and resource-related fields at Tohoku University. These cover a range of topics in renewable energy, energy storage, resource conservation and recycling, new waste treatment or energy-related technologies, as well as environmental management issues. The special classes provided during the 2013/2014 academic year are the basis for the subsequent chapters.

In Chap. 2, Professor Tanaka provides some background on the ELTP program itself and to the series of lectures which comprise the specific course on energy and resources. He looks at some of the historical pollution problems in Japan from both a legal and cultural perspective and introduces to the students ethical issues which underpin concerns over sustainability.

In Chap. 3, Professor Taniguchi looks at the limits to resources and economic growth inherent within a closed system (even as large as the Earth) and the implications of studies such as ‘Limits to Growth’ on the future of society. He introduces various indicators of environmental impact and the major differences between the environmental loads of different societies. The dire future which awaits us if we do not modify current trends makes a vision of a sustainable society even more urgent, and requires us to re-orientate the aims of the economy away from material growth to human well-being and happiness. One example of a country which possesses some of these characteristics (Cuba) is examined.

After the above lectures have provided some important background, we move to a number of lectures on specific aspects of energy. Chap. 4 looks at the technology and potential application of fuel cells in the provision of energy, and Professor

Kawada reviews the potential for the 'Hydrogen Economy' and the demands that would make for fuel cells. Hydrogen's strengths and weaknesses as an energy carrier are examined, and the current development and commercialization of PEFC and SOFC fuel cells in transport and domestic combined heat and power systems reviewed.

In Chap. 5, Professor Smith focuses on the role of supercritical fluids in energy and green chemical processes. Energy remains the single most critical foundation for a healthy and buoyant society, yet its generation increases threats to global sustainability. Supercritical fluids can offer low-energy systems; for instance by producing 4 kW of heat from 1 kW of electricity. They can also contribute to lower energy of mixing and new materials, leading to a range of green chemical processes. This chapter introduces the reader to a range of potential environmentally friendly futures involving these processes.

Chap. 6 focuses on a source of renewable energy which could be very significant in Japan and similar geologically active zones, with a review by Professor Hashida on geothermal energy and its potential. Geothermal energy has the advantage of heat and electricity with minimal environmental impact. The various types of geothermal energy extraction (both passive and active) are reviewed and the relevant factors for the design of geothermal energy extraction systems detailed. Mathematical models to simulate engineered geothermal systems are introduced and the role of injection to achieve a sustainable level of geothermal power generation described.

In Chap. 7, Professors Tanaka and Tohji introduce a 'small' energy and solar energy storage DC-based system developed at Tohoku University. This is based on technological development of systems which will allow current centralized energy systems to be replaced by more dispersed and multiple low-energy renewable sources. Such a system poses challenges both in maximizing possible sources of small energy and also in developing the batteries necessary to deal with their intermittent supply. This chapter describes the systems which run on limited sources of DC energy, and the interaction between the supply sources and the batteries to provide systems which are resilient to blackouts from natural disasters.

In Chap. 8, Professor Li and colleagues review the potential of waste biomass available from wastewater treatment and other sources to provide alternative fuels such as bio-hydrogen and bio-methane. In this chapter, various fermentation approaches are introduced and how these can be adjusted to produce biomass energy through single and two-phase fermentation technologies. Such technologies can also be used to apply biogas technology to wastes such as cattle manure, chicken manure and sewage sludge.

The next section of the book moves to themes of resources and their efficient use or re-use. The first contribution (Chap. 9) is from Associate Professor Matsubae who reviews the importance of phosphorus and the phosphorus cycle in agriculture. Supplies of phosphorus are limited and this poses a potential limit on future agricultural development. To make the maximum use of available supplies, it is important to develop a sustainable phosphorus resource management approach across the whole international phosphorus demand and supply network. This chapter describes a model of the international flow of phosphorus from sources to applications, and presents various scenarios for its future demand and supply. New sources of phosphorus may well be required, including from existing waste sources such as steel-making slag.

In Chap. 10, the challenge of finding constructive uses for many waste materials is illustrated when Professor Takahashi looks at a new approach to finding productive uses for sludge from the construction and sewage treatment industries. A method has been developed to produce a fibre-cement stabilized spoil to allow such materials to be recycled and used either in agriculture soils or landfills. Processing methods and experimental results from using the resulting sludge are presented in this chapter.

In Chap. 11, the focus shifts to another important area in recycling –waste plastics, where Professor Yoshioka considers the challenge of obtaining high-value products through recycling the many different varieties of plastics in the waste stream. PET can be recycled as raw material for reprocessing PET, but other types of plastics pose major challenges and are often recycled for only low value uses such as a source of heat. This chapter looks at current approaches to recycling plastics and how it may be possible to convert them into higher-value raw materials.

The theme of efficient use of resources is developed further in Chap. 12 by Professor Kasai who looks at resource and environmental issues raised by the extraction and refining of iron. Recent resource and environmental trends in the steel industry are reviewed from the perspective of the mineral sources available, future population and economic trends, and the potential for meeting demands for steel in an environmentally-friendly way. Approaches such as using waste plastics as a raw material instead of coke to improve energy efficiency in steelworks are described, and a vision of sustainable iron and steel making developed.

The broader issue of resources and recycling of base metals is addressed by Professor Nakamura in Chap. 13. Mining of these metals (iron, copper, zinc etc.) causes major environmental damage through open mining techniques, and thus improving recycling rates has major environmental benefits as well as potential economic ones. This chapter looks at recycling technology for these metals and ways in which they can be recycled from sources such as shredder dusts and fly ash. Recovery of metal resources from waste electric and electronic equipment is also considered and a potential systems approach developed to the recycling of Japan’s valuable metals.

Associate Professor Managi in Chap. 14 raises a number of questions designed to encourage students to apply system-wide and lateral thinking. This is already one of the objectives in the ELTP, but is also expected to gain importance as the new approach to international global environmental change under the Future Earth international research initiative gains momentum. Future Earth is explained in this chapter and how it will require researchers to improve communications with society, requiring researchers to hone their communication skills and ability to envisage the interests and viewpoints of different stakeholders. Using the experiences following the 2011 Great Eastern Japan Earthquake and Tsunami, a number of issues and questions are raised to stimulate students’ thinking, analytical and communication skills.

In the final chapter, the editors offer a synthesis of the range of issues covered in this book and consider how our environmental leader students may have benefitted from this series of lectures, and how they interact and supplement the core courses provided in the environmental leader training program.

We hope you will find the following chapters informative on their own, and valuable as an educational resources in other learning institutions. Each chapter is self-contained, so readers can choose whether to study in the order in which they are presented, or go directly to a particular subject of interest.

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Chapter 2
Background on Energy and Resources Strategy

Yasumitsu Tanaka

Abstract This chapter sets the scene for the series of lectures on energy and resources provided as part of the environmental leader course. Many of the individual lectures (chapters in this book) focus on specific resource or energy issues or technical challenges but these have also to be seen as part of an overall picture, where human activities have reached a scale which can no longer be supported in a sustainable way. This chapter provides some of the background to placing these individual fields in this wider perspective by looking at some of the history of environmental problems in Japan, as well as some key current international issues including global warming and climate change, social issues including poverty, threats to biodiversity and sustainability's limits and balances.

Keywords Environmental pollution · Energy · Resource · Limits · Sustainability · Japan

2.1 The Environmental Leader Programs

As described in Chap. 1, the thinking behind Japan's Environmental Leader programs is that even though many agree that we need to move rapidly to a more sustainable society, the current pace of change is failing to reverse adverse trends in energy and resources consumption, population growth, climate change, ecosystem loss, species extinctions and other key indicators of *un*sustainable development. This situation has led to initiatives in Japan to nurture a new generation of environmental leaders who can influence individual, business and governmental priorities and help promote the development of a more sustainable society. These programs face the challenges of providing participants with the knowledge, motivation and skills necessary to influence and lead others towards a more sustainable future.

The Environmental Leadership Training Program (ELTP) within the Strategic Energy and Resource Management and Sustainable Solutions (SERMSS 2014)

Y. Tanaka (✉)
Environmental Leader Program, Tohoku University, Sendai, Japan
e-mail: tanaka@mail.kankyo.tohoku.ac.jp

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(Tanaka 2014) project of the Graduate School of Environmental Sciences (GSES 2014) was outlined in Chap. 1 and has been designed to be flexible and allow students who are conducting research across a wide range of different disciplines (science, engineering and humanities) to participate in the same program. The ELTP comprises lectures to provide knowledge of sustainability and specific environmental problems and solutions, active learning to encourage personal skills development, fieldwork for practical experience and internships to provide intensive training opportunities- all built on the foundation of the student's basic scientific or engineering research. The ELTP was introduced in 2011 and over 110 students have already completed the various types of courses (Basic, Regular, Masters and Doctorate courses).

The ELTP teaching curriculum was shown in Table 1.3 and allows students to access teaching on international aspects, sustainability and environmental problems, problem solution identification and in leadership training. Features of Tohoku University ELP are that we have a foundation of global environmental issues, the energy/resources/water. One course, as outlined in Chap. 1, is a series of lectures related to strategy for energy and resources, and is provided by professors in the GSES on various aspects of energy and resources in their own research fields. In this chapter, I set out some general background considerations which are provided to course students to help them put each of the specialised lectures into the broader framework of sustainability's multiple dimensions. I also hope this can be a useful background to readers of this book.

2.2 Background Issues

2.2.1 Environmental Issues

The ELTP is motivated by our wish to help solve key global environmental problems. First of all, we must consider what are these problems? The following can be listed:

- Global warming.
- Deforestation.
- Depletion of the ozone layer (both North and South Poles).
- Acid rain (now including ocean acidification).
- Desertification.
- Artificial hazardous chemicals (also including diffusion and trans-border movements of hazardous chemicals and wastes).
- Exposure of the public to pollution in developing countries.
- Decreases in biodiversity.
- Marine pollution.
- Two historically local forms of pollution (referred in Japan to as KOGAI because of their effects on the public) have also spread to become important global environmental issues; air pollution, and water pollution/shortage.
- Increase in quantity and complexity of waste from human society.

Table 2.1 Main messages of the IPCC 2013 5th Assessment. (IPCC 2013)

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia
Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850
Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90 % of the energy accumulated between 1971 and 2010
Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent
The atmospheric concentrations of CO_2, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-Twentieth century
Global surface temperature change for the end of the Twenty-first century is *likely* to exceed 1.5 °C relative to 1850–1900 for all RCP scenarios except RCP2.6. It is *likely* to exceed 2 °C for RCP6.0 and RCP8.5, and *more likely than not* to exceed 2 °C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. It is *very likely* that the Arctic sea ice cover will continue to shrink and thin and that Northern Hemisphere spring snow cover will decrease during the Twenty-first century as global mean surface temperature rises. Global glacier volume will further decrease
Global mean sea level will continue to rise during the Twenty-first century. Under all RCP scenarios the rate of sea level rise will *very likely* exceed that observed during 1971–2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets
Cumulative emissions of CO_2 largely determine global mean surface warming by the late Twenty-first century and beyond. Most aspects of climate change will persist for many centuries even if emissions of CO_2 are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of CO_2

Associated with each of these problems are some common factors; they all result from the rapid growth in human numbers and activity, in the rapid growth in the exploitation of resources, and the lack of any balance between consumption and its consequences. We have been attempting to deal with such pollution problems now for many years- particularly since the 1950s, and now know a lot about the environmental impacts of different types of emissions, how they spread and may or may not be degraded by the environment, how to measure and calculate toxic impacts, and how to mitigate the harmful effects of pollutants. Some of these major problems are under some degree of control (for instance the ozone layer depletion seems to have stabilised), but others such as deforestation, desertification and global warming show no signs of being placed under effective control. Only recently, the IPCC released the summary for policymakers in its 5th Assessment (IPCC 2013) which confirmed that global temperatures are rising as a result of emissions of greenhouse gases from human activities, that a further rise in temperature of up to 4.8 °C can be expected by the end of the century (depending on the degree of success in reducing emissions), together with a sea level rise of 26–82 cm (Table 2.1). A critical fact

Table 2.2 History of some major pollution events in Japan

1890: Ashio Copper Mine—Furukawa Co., Ltd
1937: Annaka public pollution lawsuit—Toho Zinc Co., Ltd
1910: "Itai-itai disease", caused by cadmium poisoning from industrial wastes in Toyama Prefecture—Mitsui Mining and Smelting Co. (successful lawsuit)
1956: Minamata disease (poisoning caused by industrial mercury pollution). Chisso Co. (successful lawsuit)
1958: Edogawa Fishing industry damage—Honshu Paper Co., Ltd. (Oji Paper Co., Ltd.) led to the Water Pollution Prevention Act
1960: Yokkaichi asthma—Caused by many companies: Yokkaichi Petrochemical Complex (successful lawsuit)
1965: Niigata Minamata disease—Showa Denko K.K. (successful lawsuit)
1968: PCB Kanemi rice oil disease incident
1970: First appearance of Tokyo photochemical smog
1970s: dust pollution due to studded tires; 1988: discontinued production and sale
Thalidomide baby lawsuit for drug-induced physical deformations, Smon (subacute myelo-optic neuropathy) disease medication scandals

The importance of legal action to combat major cases of pollution is shown in **bold**

which IPCC pointed out is that the level of warming is determined by the overall quantity of carbon dioxide in the atmosphere, and that to have a 2/3 chance of limiting warming to 2 ºC, the total emission since industrial revolution need to be limited to 1000 Gt carbon; *half of this* has already been used and at current rates, the rest will be emitted in the next 20 or so years. The largest causes of this global warming are human activity and excess energy consumption. For energy, see the described outline in 1.3.1. of Chap. 1.

2.2.2 Japan's History

Looking at Japan, the legal framework for dealing with pollution is influenced very much by our own country's historical experience of gross public pollution. The country's rapid economic growth during the 1950s and the complete lack of any environmental controls with the priority firmly on the economy, led to many local cases of dead rivers, gross levels of air pollution and also several toxic events including mercury poisoning at Minamata and Niigata, and food contamination by PCBs and cadmium. This history of events means that under Section 3, Article 2 in the Japanese Basic Environment Law, the main examples of environmental pollution and destruction include atmospheric pollution, water pollution, soil pollution, noise, vibration, odours and unpleasant smells, and land subsidence. We might also since add light pollution, obstruction of sunshine by buildings, dioxins, asbestos, hormone disrupting chemicals, hazardous chemicals, chemical allergies, cedar pollution allergies, and others. Some of the major influences on government legislation are listed in Table 2.2.

Table 2.3 Famous pollution incidents outside Japan and influential books or movies

Incidents
London Great Smog of 1952
Muse Valley incident of 1930
Los Angeles smog of 1945
Dorano pollution incident of 1948
Love Canal incident of 1978: enactment of laws for a Superfund
Environmental problems in developing countries such as Peking smogs
Books and movies with great impact
Rachel Louise Carson, “Silent Spring” 1962
Tomoyuki Tanaka produces “Godzilla vs. Monster of Chemical Ooze” 1971
Theo Colborn, John Peterson Myers, Dianne Dumanoski, “Our Stolen Future” 1996
Deborah Cadbury, “The Feminization of Nature” 1997
“Erin Brockovich” movie 2000
“The Day After Tomorrow” movie 2004
Al Gore, Jr., “An Inconvenient Truth” 2006

As can be seen from Table 2.2, Japan’s history of pollution events goes back many years—even to the nineteenth century and the first involvement of politicians in trying to solve a public pollution problem. This was well before the days of parliaments and laws, and in one example in the 1890s, Shozo Tanaka had to make a direct appeal to the Meiji Emperor to take action against the Ashio copper mine’s environmental damage to local citizens, farming, and forests. Perhaps this might be categorized as an early example of an environmental leader!

Of course Japan’s experience is not unique and has been mirrored across the world; many similarly famous incidents in other countries have led to new laws and regulations to try and overcome the basic problem of environmental pollution (Table 2.3). Some environmental issues have truly entered the public consciousness through books such as Rachel Carson’s “Silent Spring”, books on hormone disrupting chemicals (“Our Stolen Future” and “Feminisation of Nature”), and of course Al Gore’s “An Inconvenient Truth” on global warming.

In Japan, the gross impacts of pollution even entered the public consciousness through famous monster characters such as Godzilla! In the 1971 movie “Godzilla versus the Monster of Chemical Ooze”, the monster Hedorah (Fig. 2.1) was able to feed on pollution. In this way a pollution event in real life (Hedorah is the name for a waste sludge from paper production at Tagono-Ura, Shizuoka Prefecture) causing local social problems, became a theme and message reaching children around the world.

In tackling pollution problems, a contrast is often drawn between developed and developing countries. We can summarise the different influences and interactions between developed and developing countries and environmental issues in Fig. 2.2. This shows that some of the central environmental issues may appear at first sight

Fig. 2.1 Pollution in movies-the Story of “Godzilla vs. Hedorah”(1971 Toho Co., Ltd.)

to be more closely linked to one type of country; but in fact whether developed or developing countries, all are contributing to the problems and also must contribute to their solution.

2.2.3 The Overall Challenges

Let us now turn to the central part of this course where we try and answer the questions:

- What is the basic nature of environmental problems?
- What is their cause?
- How do we correct them?

First let us have a brief look at the second half of the twentieth century-Table 2.4 summarises the growth which has occurred between 1950 and 2000 in a range of indicators of human activity. Since 1950, global population has tripled, energy consumption has increased 15 times and global GNP increased about 21 times. During this period the environmental problems mentioned above have also worsened, requiring substantial expansions in environmental laws and regulations in the last 50 years in order to deal with the more urgent problems (Meadows (1999), Meadows et al. (2004). It is an understatement to say that the twentieth century was a century of rapidly expanding

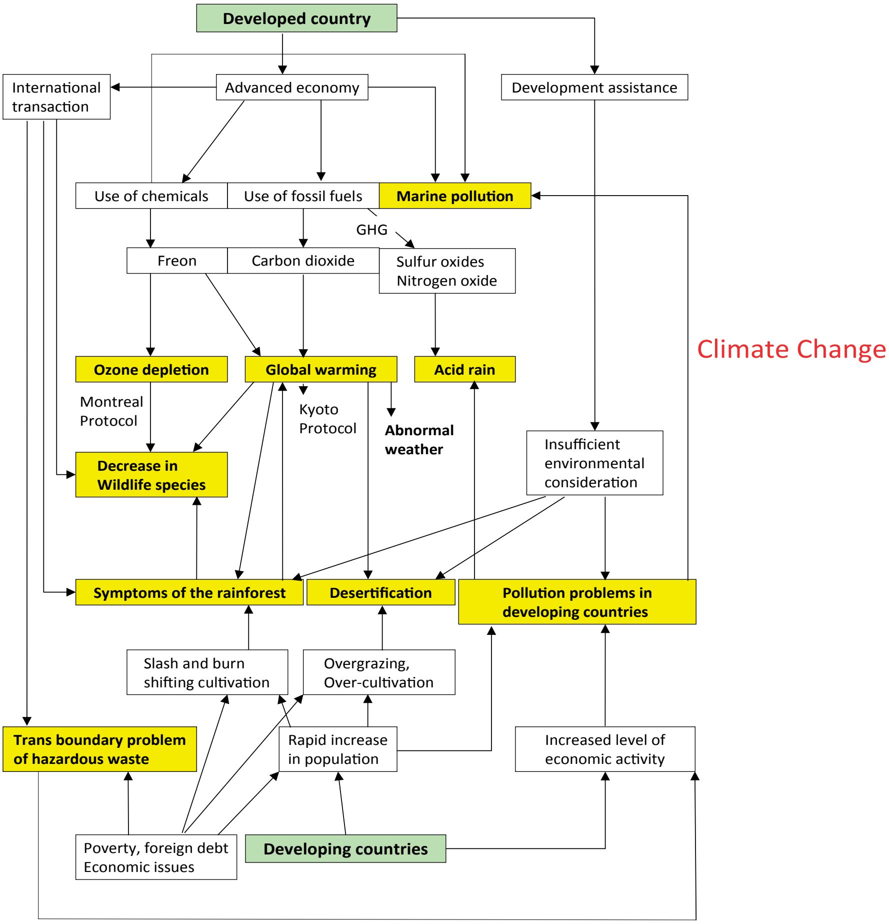

Fig. 2.2 Different origins and responses to environmental problems in developed and developing countries. (Source: Guide for Global Environmental Research Committee, edited by keywords related to the environment)

human activity[1]. The key six elements of energy, resources, chemicals, water, food, and atmosphere are all under stress as a result of growth in population and human activities. Driving all these is an apparently insatiable appetite of humankind in both numbers (population growth) and consumption (energy and resources). I see this ‘human desire’ as driving all these global trends. For example, the ecological footprint says current human activities have already greatly exceeded the capacity of our one Earth. In view of the state of the planet beyond the sustainability the

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[1] The next chapter (3) describes the consequences of continued growth and the limits to growth from environmental pollution and consumption of resources modeled by Meadows (1999), Meadows et al. (2004).

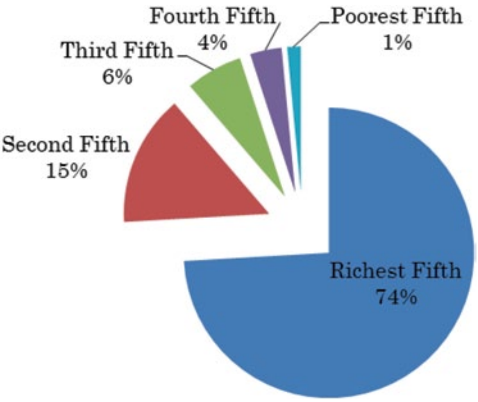
Table 2.4 Growth in the second half of the twentieth century

	1950	Changes 1950–1975 (%)	1975	Changes 1950–2000 (%)	2000
World population (100 million)	25.2	160	40.8	247	60.7
Registered vehicles (millions)	70	470	328	1030	723
Petroleum (million barrels)	3800	540	20,512	727	27,635
Natural gas (trillion cubic feet)	6.5	680	44.4	1454	94.5
Coal (million tons)	1400	230	3,300	364	5100
Generation capacity (million kW)	154	1040	1,606	2104	3240
Maize production (million tons)	131	260	342	453	594
Timber production (million tons)	12	830	102	1425	171
Steel production (million tons)	134	350	468	455	580

current situation, Dr. Meadows (et al.) pointed out that the global economy will approach its limits by environmental pollution and consumption of resources, in “The Limits to Growth” which was published in 1972. (D. H. Meadows, 1972). They also published “The Limits to Growth: a 30-Year Update” in 2004. They speculated on multiple scenarios around the world from an environmental stance which is increasingly worse through “desire” and “overkill” by humankind. (D. H. Meadows, 2004) In his report in 2009, Dr. Rockstrom also pointed out how some human activities have already exceeded their limits.

Such high rates of consumption may lead to resource shortages as described in the next chapter by Professor Taniguchi. But it has also exceeded the ability of the planet to provide a range of ecosystem services and natural resources on a sustainable basis (see environmental management tools in the next chapter), while at the same time actually making some of the economic indicators of sustainability worse-as evidenced by the widening gap between the rich and poor (Fig. 2.3). Indeed the widening inequality only serves to exacerbate poverty. In turn, poverty is not only one of the biggest problems in our society, but it is also has a deep relationship with

Fig. 2.3 World income distribution (Source: Data from Dikhanov, Y. (2005). Trends in global income distribution, 1970–2000, and scenarios for 2015. New York, NY: United Nations Development Programme.)



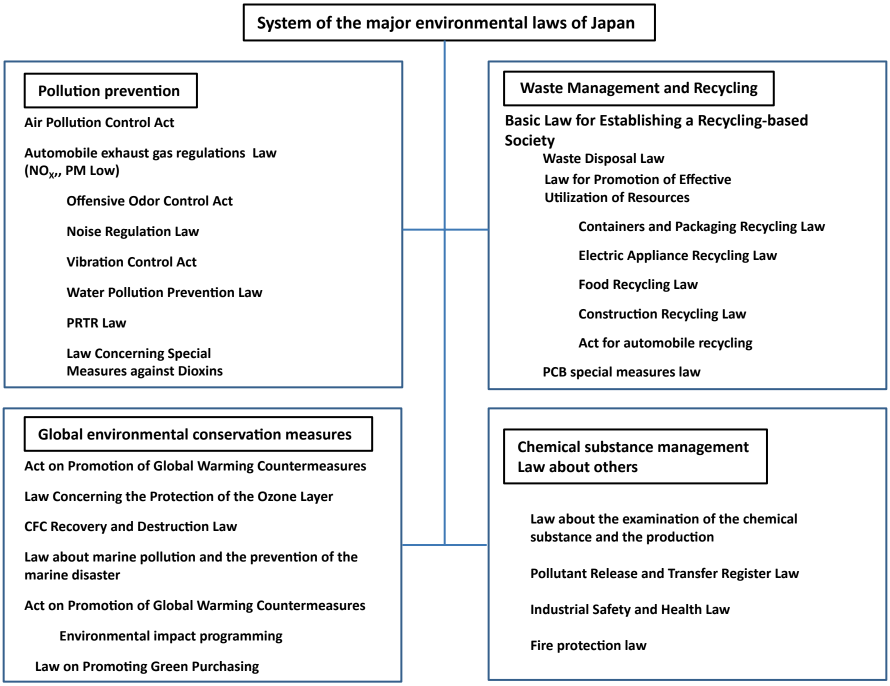


Fig. 2.4 Japan's legal framework for the Environment and Recycling Society. (Translated from http://www.logistics.or.jp/green/map.html. Accessed 26 June 2014)

environmental issues such as deforestation, expansion of desertification, and environmental issues in developing countries. As recognised in the original Brundtland report (WCED 1987), when there is no food today, who will think about the future? When there is no firewood today, who will protect the forest of tomorrow? At present, the 2 % richest monopolize more than 50 % of world income. In contrast, the poorest 20 % of people only have 1–2 % of global income.

What has been happening in businesses and companies during this period? There have certainly been changes in corporate environmental management, starting with the growth in environmental reporting in the 1980s and 1990s and the first international environmental standard (ISO 14001) from 1996. In recent years, the term 'Eco' has become widespread (eco-points, eco-car, etc.) together with advances in energy-saving appliances, technological advances in energy conservation and pollution control technology, and other contributions to reducing environment impact. A comprehensive range of laws has emerged on various public nuisances and also one of the world's leading legal frameworks for a 'recycle based society' has emerged in Japan (see Fig. 2.4). Japan is not alone in this and the EU has also introduced a range of environmental directives on *W*aste *E*lectrical and *E*lectronic *E*quipment (WEEE directive), the use of certain hazardous substances in electrical and electronic equipment (RoHS: *R*estriction *o*f *H*azardous *S*ubstances) and the regulation on *R*egistration, *E*valuation *A*uthorisation and *R*estriction of *CH*emicals (REACH).

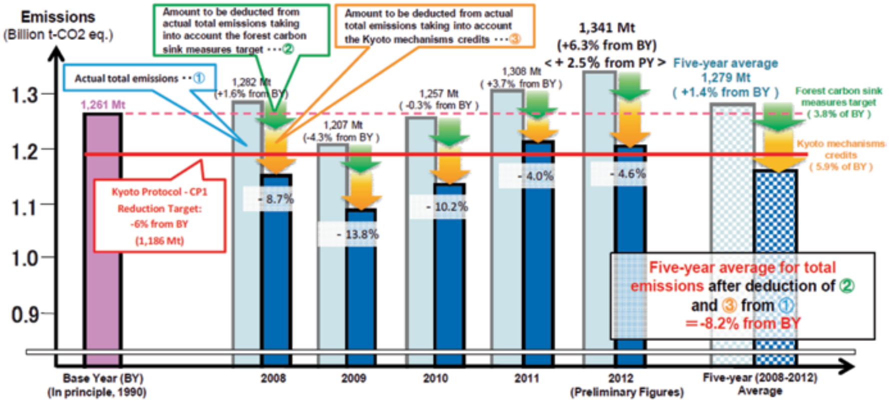


Fig. 2.5 Japan's CO_2 emissions to 2012. (Source: Ministry of the Environment; http://www.env.go.jp/en/headline/file_view.php?serial=547&hou_id=2031. Accessed 26 June 2014)

Despite these positive trends however, when the overall scale of environmental impact is measured in terms of CO_2 emissions, Japan along with other countries, has still made little progress. Japan agreed to reduce total emissions under the Kyoto protocol by 6% relative to 1990. By 2009, Japan's emissions had declined slightly, but the switch from nuclear power to fossil fuels following the 2011 Fukushima nuclear disaster reversed this, and Japan has shown the largest increase in CO_2 emissions of any of developed country in the last year, with a rise in emissions of 4% in 2011 and a further rise of 2.7% in 2012 (Fig. 2.5). Nevertheless with the help of absorption of CO_2 through forest carbon sinks, and purchases of carbon credits through the Kyoto mechanisms, Japan was at least one of the original Annex 1 countries who did meet their original commitment (in contrast to countries such as USA which did not join the Protocol and Canada which reneged on its original commitments). However the Abe government announced in November 2013 that it would abandon the further reduction target of 25% by 2020 adopted by the previous government. Instead, it adopted a target of an *increase* (of 3–4%) relative to the 1990 baseline.

The effects of the 2011 disaster on household energy can be seen in Fig. 2.6. Emissions of CO_2 from the average household in Japan were 4758 kg in fiscal 2010. Supply of electricity was interrupted by the earthquake and following this, nuclear power generation was stopped due to local opposition to restarts after routine maintenance and due to increased regulatory standards and approval procedures. As a result, the supply of electricity has shifted from nuclear generation to fossil fuel-using thermal power generation. Despite many additional measures for saving energy, CO_2 emissions rose to 5060 kg/household in fiscal 2011. This is an increase of about 300 [kgCO_2/ household], or about 6% (Fig. 2.6). And this is 5,270kg/household in FY 2012. Basically, the average Japanese household is emitting higher levels of CO_2 because of the loss of CO_2 emission-free nuclear power from the electricity supply side. However, at present we cannot pronounce the reactivation of nuclear power plants as something "good or bad." This is because the cause of accident of Fukushima nuclear plant is not yet clear and no one can guarantee the safety of nuclear

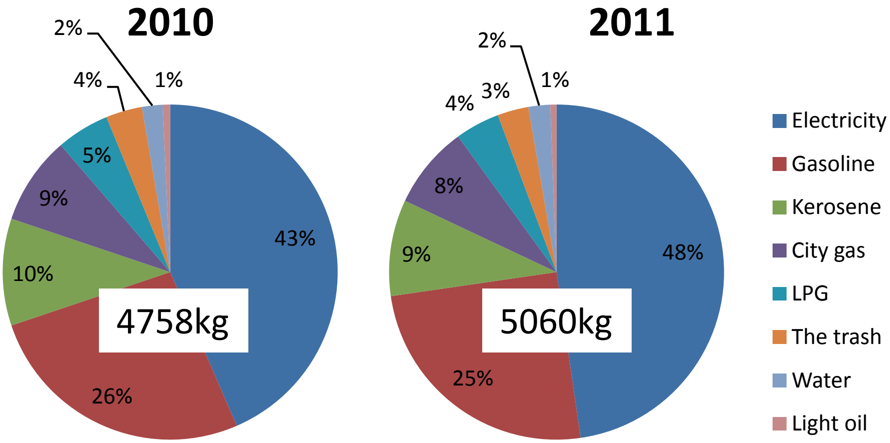


Fig. 2.6 Household emissions before and after the 2011 Disaster. (Source: Japan GHG Inventory Office; https://www.env.go.jp/policy/hakusyo/h25/html/hj13020201.html. Accessed 26 June 2014)

Table 2.5 CO_2 emissions by country ranking trends—2012 (million tons). (Data from Netherlands Environment Assessment Agency)

1.	China 9860
2.	United States 5190
3.	India 1970
4.	Russian Federation 1770
5.	*Japan 1320*
6.	Germany 810
7.	Korea Rep. 640
8.	Canada 560
9.	United Kingdom 490
10.	Mexico 490
11.	Indonesia 490
12.	Saudi Arabia 460
13.	Brazil 460
14.	Australia 430
15.	Iran Islamic Rep. 410
16.	Italy 390

power generation at the moment. Furthermore, we have not resolved the treatment methods to dispose of highly radioactive either technologically or socially.

The growth in emissions from other countries however means that Japan remains in fifth position in the amount of CO_2 emitted (Table 2.5). These global emissions continue to increase the CO_2 concentration in the atmosphere, which passed 400 ppm in 2013—a level not reached for almost 1 million years.

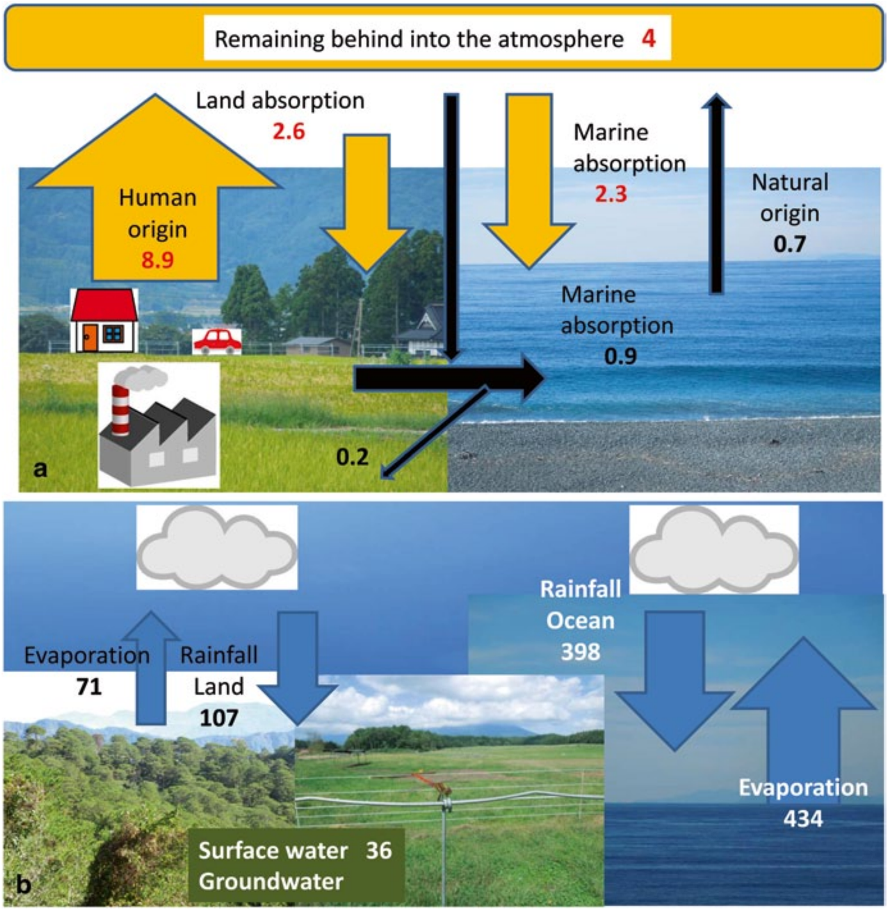


Fig. 2.7 Natural cycles being disturbed by humanactivities–carbon cycle, water cycle, atmosphere circulation, ocean circulation. **a** Schematic diagram of anthropogenic carbon balance (Unit: Giga ton) Yellow: Amount by industrial activity Black: Before Industrial Revolution (Source: Adapted from Japan Meteorological Agency: http://www.data.jma.go.jp/kaiyou/db/mar_env/knowledge/global_co2_flux/carbon_cycle. **b** 2.7.2 Average Movement of water peryear [×103km3/y] (Note: By the law of conservation of mass) (Source: Adapted from JGL, Vol. 3, No.3 2007. Oki and Kanae (2006) revised)

2.2.4 Sustainability, Limits and Balances

Moving to the broader system aspects of sustainability, increasingly we must think of the earth as a dynamic system under increasingly severe disturbance from human activity. Whether it is the carbon cycle, the water cycle, the climate system or the ocean circulation system, human activities are now on a scale capable of disrupting these essential systematic life-support systems for humankind (Fig. 2.7 illustrates carbon and water cycles). Hollywood movies enjoy dramatising future catastrophes arising from our planetary limits being exceeded, but the science is telling us that this is not science fiction- the future life-support system for humankind really are in jeopardy. Rockstrom et al.'s paper in Nature in 2009 starts to quantify this and identifies essential limits which together provide a "Safe operating space for Humanity". Sustainability basically signifies that we have to keep and maintain a safe and satisfactory life for our descendants, and thus **balance** is becoming an important key word. For example, the balance between the earth's capacity and human activity, the balance between nature and human, between living creatures and humans, between the environment and the economy, between hope and desire. It may be necessary to suppress our own numbers or activities to maintain these critical balances. Indeed, I believe that it is increasingly necessary to establish a balance between the earth and human activity in order to maintain the sustainability of both nature and humanity. This in turn requires us to be better in our selection of which technology to use, to limit the appetite (greed) in our mind and to also care about other people. It is necessary to ask a number of key questions if we are to consider true happiness in a sustainable world. "What is our happiness and satisfaction?" "Which is more important, philosophical satisfaction and family especially children and grandchildren, or materials/money/power?" "What is our true purpose?"

2.2.5 Biodiversity

In this short introduction, we also need to point to the drastic reduction in planetary biodiversity which is underway. This is not necessarily a pollution issue but really a symptom of how the increasing population of the planet needs yet more and more land to provide the resources needed for food, timber, fish and other biological resources. I can just point to the explosive growth in the coverage of Southeast Asia (Malaysian and Indonesia in particular) in producing Palm oil (see Fig. 2.8). The destruction of the forest to replace with palm oil plantation is one of the biggest causes of biodiversity loss, and also periodically leads to extremely poor air quality in the region, as well as destroying the hitherto sustainable forest-based life styles of

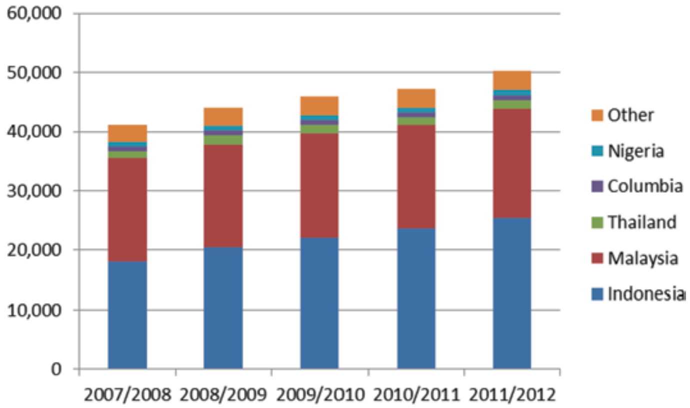


Fig. 2.8 Palm oil production trends. (USDA data). (Unit: 1000 tons)(Source:USDA "World Markets and Trade"August-July)

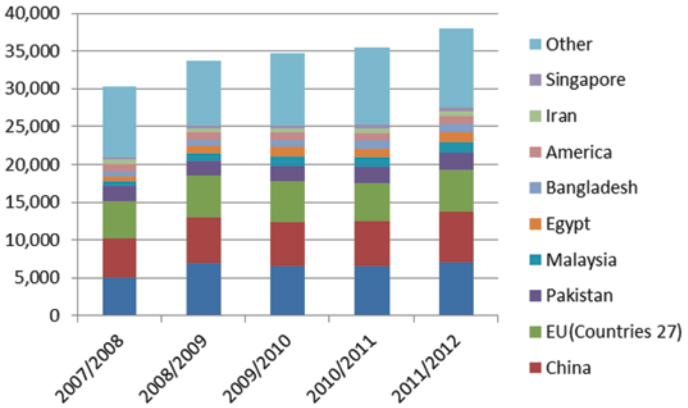


Fig. 2.9 World imports of palm oil. (USDA data). (Unit: 1000 tons) (Source: USDA"World Markets and Trade"August-July)

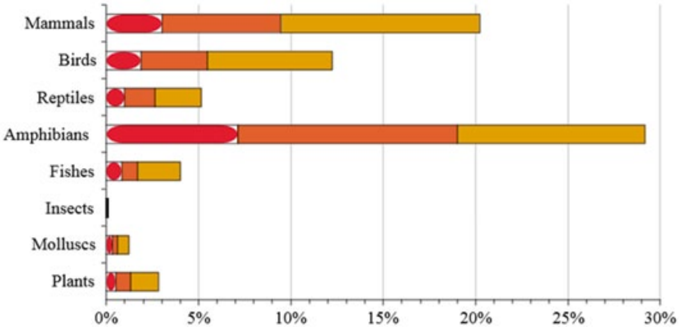


Fig. 2.10 Threatened species of the world. (IUCN 2007 data from http://en.wikipedia.org/wiki/File:IUCN_Red_List_2007.svg. Accessed 26 June 2014)

indigenous people. The driving forces here are not just in the producing countries—as can be seen from Fig. 2.9, the real driving force is the demand in the importing countries such as China, EU, Pakistan, Egypt, and so on.

Biodiversity and the associated ecosystem services are becoming important issues for global sustainability. For a sustainable world, maintaining biodiversity is recognised as very important. In fact, we humans do not even know how many creatures inhabit the earth. Currently, it is said that about 1.4–1.8 million species are recognized scientifically, but some scholars say the numbers of species, including yet unknown organisms, may be much greater. Scientists are now warning that 0.1–0.01 % are becoming extinct every year. The biggest contribution to the accelerating modern rates of extinction (loss of biological diversity) is human activity- especially loss of habitat through habitat destruction or land use change. The Millennium Ecosystem Assessment (MEA 2005) said that the rate of extinction of species is 1000–10,000 times that which would occur in the absence of human involvement, and numbers of threatened species globally are shown in Fig. 2.10. Natural ecosystems exist in complex and subtle balances, which if destroyed may

Fig. 2.11 Japanese mammals and birds already extinct and those currently endangered. (MOE http://www.env.go.jp/en/nature/biodiv/reddata.html. Accessed 26 June 2014)

Mammals	Japanese wolf
	Ezo wolf
	Japanese sea lion
	Okinawa flying fox
	Bonin pipistrelle
Birds	Rufous night heron (Ogasawara island subspecies)
	Crested shelduck
	White-browed crake (Iwo islands sub-species)
	Ryukyu wood pigeon
	Bonin wood pigeon
	Miyako kingfisher
	White-bellied black woodpecker
	Wren(Daito island subspecies)
	Bonin island thrush
	Borodino bush warbler
	Varied tit(Daito islands subspecies)
	Bonin islands honeyeater (Mukoshima islands subspecies)
	Bonin islands grosbeak

not be capable of being restored through human intervention. Biodiversity loss involving the extinction of many organisms raises ethical questions and the question of whether it is any different to allowing the extinction of humans. Japan has its own list of species already extinct and those endangered as in Fig. 2.11. It is important to emphasise that current rates of species extinction have occurred in the past only as a result of catastrophic events such as volcanoes, asteroid impacts, but now are due to human activity.

2.2.6 Energy, Water, Food and its Security

There are two sides to many of the major challenges facing a sustainable world. For instance, with energy there is the environmental impact- the increase in carbon dioxide and harmful substances due to the use of fossil fuels (problems of air pollution and global warming). On the other hand, there are concerns over depletion of energy in general and the specific problem of energy security in Japan. In the latter case, the energy self-sufficiency rate in Japan is about 20 %, even when there is nuclear power. If there is no nuclear power, self-sufficiency is about 4 % or lower. It is thus important to increase renewable energy usage substantially as soon as possible. We will explain one of the examples of such a new energy system in a later chapter (Chap. 7).

Fig. 2.11 continued

Mammals	Japanese river otter
	Tsushima cat
	Iriomote cat
Birds	Short-tailed albatross
	Red-faced cormorant
	White stork(East Asiatic subspecies)
	Japanese crested ibis
	White-tailed sea-eagle
	Buzzard(Ogasawara islands subspecies)
	Buzzard(Daito islands subspecies)
	Hodgson's hawk eagle(Japanese sub-species)
	Golden eagle(Japanese subspecies)
	Crested serpent eagle(Ryukyu islands subspecies)
	Ptarmigan(Japanese subspecies)
	Japanese crane(Red-crowned crane)
	Okinawa rail
	Amami woodcock
	Guillemot, Common murre(Japanese sub-species)
	Tufted puffin
	Japanese wood pigeon(Yaeyama islands subspecies)
	Japanese wood pigeon(Ogasawara and Iwo islands subspecies)
	Emerald dove (Ryukyu islands subspecies)
	Blakiston's fish owl(Japanese sub-species)
	Pryer's woodpecker
	White-backed woodpecker(Amami-oshimasubuspecies)
	Three-toed woodpecker(Japanese sub-species)
	Fairy pitta(East Asiatic subspecies)
	White's ground thrush(Amami-oshima subspecies)
	Bonin islands honeyeater(Hahajima islands subspecies)
	Oriental greenfinch(Ogasawara and Iwo island subspecies)

Water pollution is a serious issue in many areas, but water supply is an even more important issue than energy in many parts of the world. The water which humanity can use easily is about 0.01–0.02 % of the water on the planet—the freshwater existing in the rivers and lakes, and stored in glaciers and underground aquifers (Fig. 2.12). According to the UNDP (United Nations Development Programme), one in five developing countries' population (about 1.1 billion people) cannot be assured of the water needed for farming. These water shortages become more severe with population growth. Currently 884 million people do not have access to 'safe' drinking water in the world. The water environment is thus threatened not just in quality but also quantity.

Food is also an important issue. Malnourished people in the world now are estimated at 925 million, of which 563 million (corresponding to two thirds) are living in the Asia-Pacific Ocean region. The food self-sufficiency rate in Japan has fallen to 40 % in a calorie basis. Since the environment for food production may worsen due to global warming, the countries that are not able to be self-sufficient in food and the associated risks of food shortages are growing. These problems have to be considered in parallel with environmental issues.

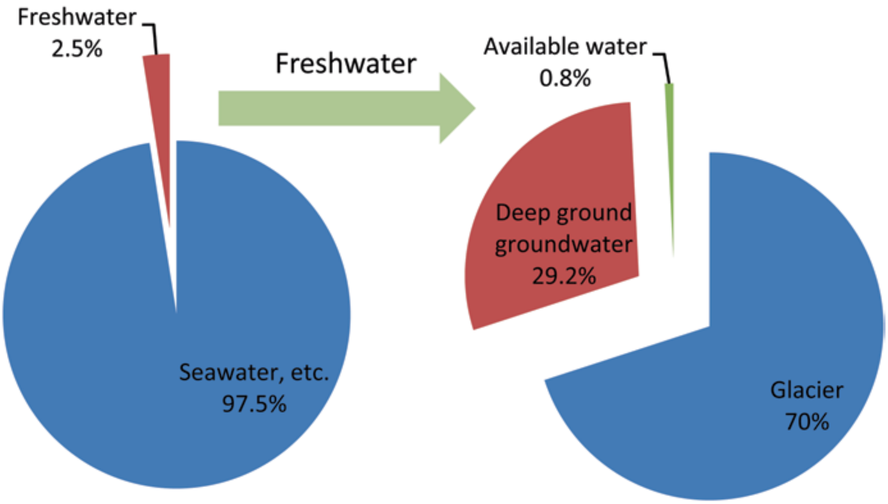


Fig. 2.12 Water available for human use. (Source: UNEP and Japan Water Guard) http://npo-jwg.com/studypl.html

Table 2.6 Three principles of Herman E. Daly

Use rate of renewable resources should not exceed the rate of renewal
Use rate of non-renewable resources should not exceed the speed of conversion to renewable resources
The emission rate of pollutants may not exceed the speed or absorption or degradation in the environment

Table 2.7 Four principles for sustainable development

Concentrations of matter extracted from the Earth should not increase
Chemicals produced by Society should not increase in nature
Nature should not be weakened by physical processes
Society must not create obstacles which deny people the opportunity to meet their needs

2.2.7 Guidelines to Achieving Sustainability

Looking for guidelines to maintain sustainability, three principles were proposed by Herman Daly in 1972, and four Natural Step rules were also proposed by Karl Heinrike Robert in 1989. These are summarized in Tables 2.6 and 2.7 respectively.

I translate these in a more personal way as in Table 2.8, and link them to the fundamental human motives, actions and consequences in Fig. 2.13.

This is what I believe to be necessary to resolve current global environmental problems. To do this, we need the power of young people like the “Environmental Leaders” we are attempting to train in the Environmental Leader program.

Table 2.8 Guidelines made on behalf of the resolution of global environmental problems and sustainable society

Resources that are currently thought not to be depleted should be used in a manner which does not disturb that balance
Resources that are being depleted; we should establish alternative sources or ways of avoiding their use *before* the resource is lost
In the areas of the earth we must use, we do so without destroying the balance. Should not discharge wastes above the limit of natural degradative processes and avoid discharging those that do not decompose naturally
The objective should be personal happiness in peace and fairness

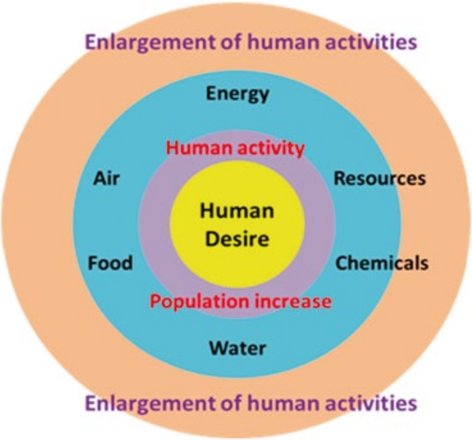


Fig. 2.13 Environmental issues and their root causes

In summary, I have pointed out that global environmental issues of today are occurring as a result of human activities which are beyond the tolerance of the earth. The reasons for this include the trends shown in Fig. 2.13:

1. Overpopulation by explosive population growth.
2. Excessive use of energy, resources chemicals, and water through the growth in human activities.
3. Diffusion of chemicals and increase of waste beyond levels that can be handled.
4. Changes which humans are causing are too fast.
5. In other words, people have caused radical changes in both quality and quantity over a very short period of time (almost instantly in terms of Earth's geological history).

In this series of lectures I ask the students to ask the following questions, and do the same to the readers of this book.

1. What is the essence of environmental issues?
2. What is the cause of environmental problems?
3. How do you solve these problems? What are our best actions?

These are just some of the issues that will be addressed in more detailed during the rest of this course and which are the focus of later chapters in this book.

A Postscript

While this course on energy and resources strategy was being given (October 2013–March 2014), there were many abnormal weather phenomena around the world such as the heavy rain on the Indochina Peninsula in September 2013, Typhoon No. 30 (HAIYAN) in the Philippines in November 2013, and extremely cold weather in North America from December 2013 to January 2014. Furthermore, PM 2.5 warnings (air pollution) have been issued in various regions because of air pollution blowing from China to Japan, resulting in days when children are forbidden to play outside in the Kyushu and Kansai Regions in Japan. In Paris, the atmosphere has become contaminated by exhaust gases, and the Eiffel Tower appears hazy in the smog. In response, car use has been limited to even or odd-numbered days according to license plate numbers.

This reminds us that pollution is not a problem of only one country or region. It exists on a global scale with cross-border pollution from country to country. Water pollution, desertification, and other severe, pressing issues are also continuing. According to the latest information, the average temperature of the world in 2014 was 0.27℃ over that of an average year. In other words, the average temperature of the world in 2014 will have been the highest since the start of statistical records in 1891. It is thus important for Japan to consider how it can contribute to the world through new technology in such fields as introducing renewable energy, energy saving, the prevention of air/water pollution and their purification—especially for developing countries in Asia, Africa, and South and Central America.

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Chapter 3
Limits to Resources, Economic Growth and Happiness

Shoji Taniguchi

Abstract The concept of limits to growth is introduced and the future scenarios involving collapse due to pollution or resource depletion explained. These illustrate the basic problem that we confront on natural resources and the environment within a finite planet. The expanding demand for resources is not only causing the reserve/production ratio to fall below 10 years by 2040 for many metals but aggressive mining causes immense damage to the environment and ecosystems and to the people living there. Methods of measuring impact are introduced—for instance the ecological foot print which shows that 5.3 globes would be needed if all people in the world attained the same affluent lifestyle as the USA. To avoid this future requires reducing consumption and dependence on growth and to focus instead on happiness as our ultimate purpose. This chapter introduces models and ways of thinking which treat economy and industry as intermediates to that overall purpose and ensure natural resources are maintained to provide the essential basic support for humanity. The example of Cuba which is applying some of these principles is also introduced.

Keywords Economic growth · Natural resources · Happiness · Environmental load assessment · Cuba sustainability

3.1 Introduction

This chapter introduces one of the most fundamental issues relating to sustainability- the recognition that the Earth has limits and therefore that to be sustainable, human activities need to be managed so as not to exceed those limits. In this chapter I will look at some of the history of the debate in the calculation of possible limits and the consequences of exceeding those limits, look at some of the measurement tools being developed to monitor trends against certain limits, and also lay the foundation for asking questions about what kind of sustainable world we plan to create and what are the objectives we should be considering for humankind and society.

S. Taniguchi (✉)
Graduate School of Environmental Studies, Tohoku University, Sendai, Japan
e-mail: shoji.taniguchi@gmail.com

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The question whether our world has limits which may at some point constrain human growth or human behaviour is not a recent question. Many people are aware of the calculations of Robert Malthus in 1798; he observed that human population was starting to grow at an exponential rate whereas food production tended to grow at a linear pace, so that population would encounter a limit at some point in the future on food supply. Of course those projections were too simplistic at the time since they failed to foresee the dramatic increase in agricultural productivity and in the areas of land devoted to agriculture which have, up to now, allowed food production to keep pace. Nevertheless, even now around 1 billion people remain short of food and concerns remain whether food supply can be increased to accommodate the growing global population as it exceeds 7 billion. We have also had to sacrifice large parts of the earth's biological systems and biodiversity, as large tracts of forest are converted from their natural state to the agricultural monocultures required to provide the food needed for increasing populations.

Food is one of the most basic of human needs, and may have been the first 'limit' to be widely discussed but, as population and economies grew during the twentieth century, other types of limits started to appear. The ability of local environments to absorb the wastes produced by local populations became overwhelmed giving rise to dead and putrid rivers, smogs, local poisonings by toxic chemicals, culminating in the 1970s and 1980s by the discovery that man-made chemicals (whether they be DDT, PCBs or chlorofluorocarbons) were indeed capable of spreading across the whole planet and exceeding the limits of the global environment to absorb or degrade them. The annual increase in atmospheric concentrations of carbon dioxide and other greenhouse gases also shows that the environment's limit for coping with human emissions of greenhouse gases has been exceeded by a large margin. Recent work is pointing to a range of critical limits which may be fundamental to supporting human society; Rockstrom et al. (2009) list 9 critical limits which define what they call "a safe operating space for humanity"- climate change, chemical pollution, ocean acidification, stratospheric ozone depletion, atmospheric aerosols, biodiversity loss, land use change, nitrogen and phosphorus cycles, and global freshwater use. Of these, three (climate, biodiversity and nitrogen) have already substantially been exceeded and others (ocean acidification and freshwater) are close to the 'safe operating space' boundary. Thus now there is little question whether there are limits, the question is more how society will respond to such limits and to what extent the future of humankind will be determined by them.

Limits were also recognized in the report which brought the concept of sustainable development onto the world stage in 1987, and led to the adoption of the principle of sustainable development in the Rio Earth summit in 1992. As stated in the Brundtland report (WCED 1987) sustainable development is not just about "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" but also has to recognize the "*limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs*". Global warming or climate change is an example of the results of our economic activities exceeding such limits. Human activities, at the same time, lead to the depletion of energy and a range of natural resources, which will prevent the sustainability of human society. Limits and sustainability are often related to environmental limits, but even the market economy itself seems to be unsustainable after the world economic crisis in 2008. While such concerns about the sustainability of current development paths continue, we also see evidence that peoples' life satisfaction and happiness has not improved in spite of the large increases in the gross domestic product (GDP) of many countries.

In this chapter therefore, I will introduce some of work related to calculating limits to resources, economic growth and society, with particular reference to previous work on economics and ethics. I will also introduce some of the analyses which suggest that the genuine purpose of technology and economy should be happiness as an ultimate purpose, with natural capital as our ultimate means. I will introduce limits, and four environmental indicators (ecological rucksacks, ecological footprint, factor X and Life Cycle Assessment) will be described to assist in quantifying the environmental load of our society. The relation between economics and happiness will then be discussed, and intermediate technology proposed by Schumacher will be presented. Finally, I would like to introduce Cuba as an example of sustainability.

3.2 Assessing Current and Future Environment and Resource Loads

3.2.1 Calculating Limits to Growth

Although discussion of specific limits had appeared before the 1970s (such as that between population and food), the first comprehensive advanced analysis of a broad range of limits was carried out by Meadows and her colleagues at MIT following a request by the United Nations Secretary-General at the time (U Thant) to the Club of Rome to project the future of the world. In the resulting book (Meadows et al. 1972) entitled "The Limits to Growth", they calculated various futures for human society and future changes in population, food production per capita, pollution, and resources based on a parameter set derived from previous trends. As can be seen in Fig. 3.1, this future suggested that up to 2000, population, food and pollution would increase rapidly, and resources decrease slightly, but these changes would not imply any remarkable shift in the state of human society. However, after 2000, the model predictions were that resources would decrease steadily; food would peak in the early twenty-first century; pollution would continue to increase but peak around 2030 because of a contraction in industry caused by resource loss and pollution. Population continues to grow until around mid-century, peaking at around 10 billion after which societal collapse would lead to 3 billion dying of disease or hunger until 2100.

This early model was widely criticized for being too simplistic, but models were updated with better data and computer modeling and updates were published in 1992 and 2004 (Meadows et al. 2004). Despite the notable improvement in methodology and the accuracy of input data, the overall outcome remains a collapse of the key

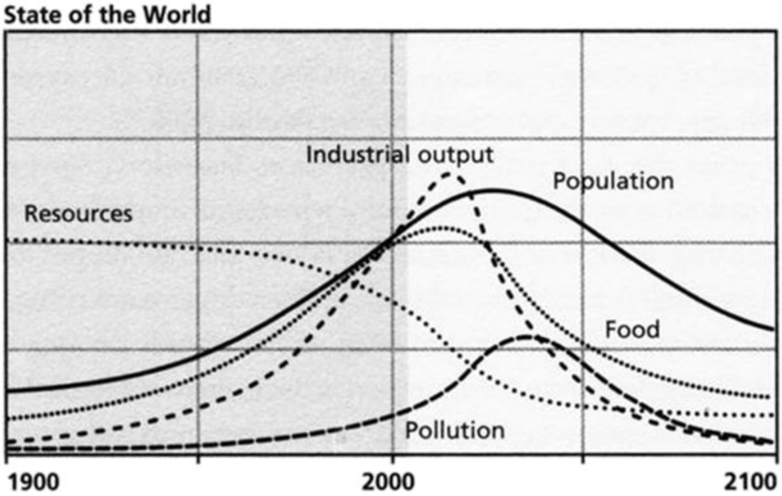


Fig. 3.1 Original “Limits to Growth” projections. (Redrawn from Meadows et al. 1972)

Table 3.1 Growth rate during the last 50 years. (Meadows et al. 2004)

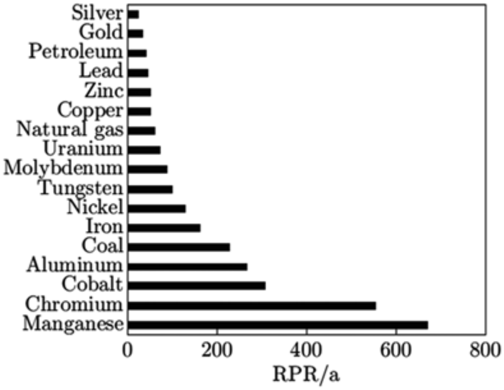
Item	1950	2000	Growth rate (%)
Population × 10^{-6}	2520	6060	240
Vehicles × 10^{-6}	70	723	1029
Oil × 10^{-6}/barrel	380	27600	726
Electricity × 10^{-6} (kW/h)	154	3240	2133
Wheat × 10^{-6}/t	143	584	417
Rice × 10^{-6}/t	150	598	399
Iron × 10^{-6}/t	134	580	446

elements we take for granted in our current society, through the collision of continued exponential growth with finite limits at some point in the future.

The pace of this growth can be demonstrated by Table 3.1 (taken from the 2004 publication), which describes the growth during the last 50 years in various categories. Growth of over 10-fold is observed in vehicle number and over 20-fold in electricity consumption. Such rates of growth raise the question whether we really believe that such high growth is still possible in the next 50 years? Although some researchers argue against the above prediction of clashing against limits, we must eventually all reach some limit as the crew of Spaceship Earth, and this analysis suggests that the limit might fall upon our next generation.

Before the dangerous future envisaged by such models becomes inevitable, we have to act more effectively to realize a more sustainable society. Considering the materials industries on which our whole economy relies, huge amounts of energy and resources are introduced and huge amounts of wastes are discarded to the environment. This ‘one-way’ use of our natural resources would need to change

Fig. 3.2 Resource and production ratio of various resources. (NIMS 2007)



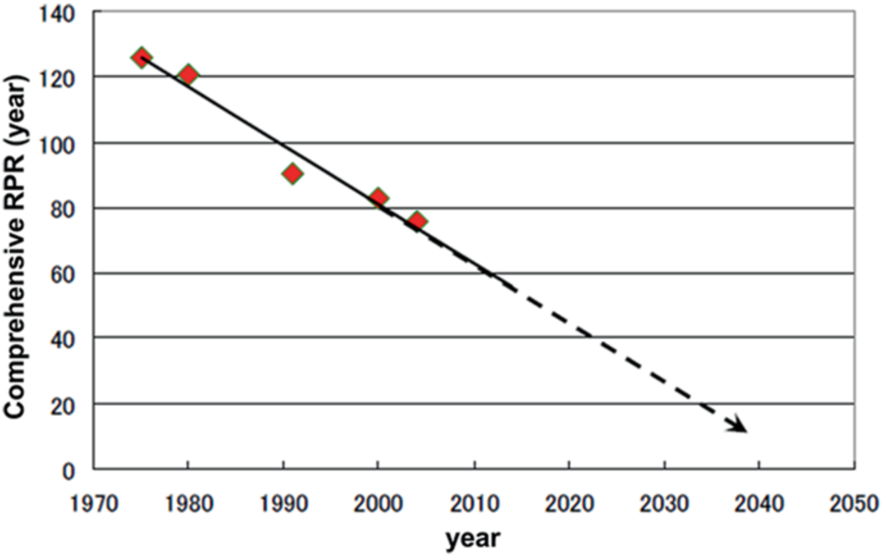


Fig. 3.3 Comprehensive RPR of metal resources. (NIMS 2007)

completely towards a new recycling-based society if our future is to be sustainable. To provide an indicator of the scale of this challenge, Fig. 3.2 shows the reserve/production ratio (RPR) of various metal resources and fossil fuels. It is seen from the figure that the RPR of some important metals and fuels is less than 100 years. From these results, a comprehensive average of RPR of metals can be calculated and plotted against the year as shown in Fig. 3.3. This value of RPR in 1980 was 120 years; however it decreased linearly and became less than 80 years in 2000. If we extrapolate the value it suggests that the comprehensive RPR may fall to 10 years by 2040.

With such rapid changes taking place and predicted, it is important to have appropriate indicators to allow us to assess the environmental burden in society, and

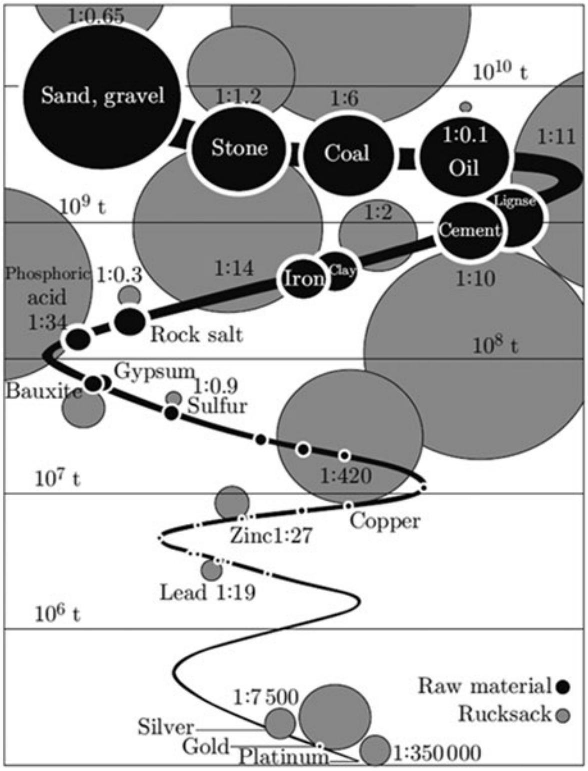


Fig. 3.4 Ecological Rucksack. (Based on production in 1983; Weitzsaecker 1998)

the implications of current growth on limits and sustainability. I will briefly describe some of these;

- **Ecological rucksack** describes the total quantity of materials removed from nature to create a product or service, minus the actual weight of the product; in other words, the amount of waste thrown away in order to obtain a product.
- **Ecological footprint** indicates the amount of biologically productive land and sea area necessary to supply the resources a human population consumes and to mitigate associated waste.
- **Factor X** indicates the reduction rate of mass-throughput required in order to achieve a sustainable society; this corresponds to the environmental efficiency that is the ratio of service to matter.
- **LCA, life cycle assessment,** is a method for measuring the entire environmental load of an industrial product throughout its production, use and disposal.

The Ecological Rucksack is a way of measuring the hidden material flows associated with producing raw materials. As can be seen in Fig. 3.4, the eco-rucksack of various natural resources supplied to society are shown by grey circles which indicate the amount of materials removed from nature and discarded back into the environment and nature after extracting the target material (Weitzsaecker 1998). The black circles convey the amounts of materials extracted (in 1983). It is easily seen that especially for noble metals like gold and platinum, the eco-rucksack is huge, which means that enormous amounts of residues and wastes are discharged to the environment in extracting and producing them. The environmental impact of mineral extraction can thus also be huge; as one example, a nickel mine in New Caledonia takes nickel from an ore containing only ~2% nickel, which is also unevenly distributed beneath the ground surface. Obtaining nickel thus requires destruction of the previous forest ecosystems, in which 95% of the plants were endemic species. This ecosystem is destroyed in the mining operations, and soil washed away from the mine causes severe damage to the ecological system of the adjoining Coral Sea. Such mining developments thus seriously conflict with the environment and the people living there. Similar effects are seen around the world as demand for minerals grows; one of the most recent being the destruction of hundreds of square kilometers of Canadian forest to extract bitumen from the tar sands underground. With the continued rapid growth in demand for metals and rare earth elements, the importance of recovering the elements after use and 'urban mining' thus takes on a greater significance and urgency than ever before.

The Ecological Footprint represents the amount of biologically productive land and sea area necessary to supply the resources that a human population consumes, and to absorb or mitigate the associated waste (Wackernagel and Rees 1995). It is expressed by the area (hectare) needed to support a sustainable life for one person, and in 1995 the average across the world was 1.8 ha/person. If the total area currently demanded by the global population and its lifestyles is calculated, the sum now exceeds 150% of the total surface area of the earth. This means that our world has already overshot a sustainable level for society. For example, the USA is the largest, with the average American requiring 9.70 ha to support their lifestyle. In contrast, the lowest per person is Mozambique with a demand which is just 1/10 of the average Japanese footprint. It can be easily seen that 5.3 earths are needed if all the people living in the world attained the affluent lifestyle of the USA.

The relation between eco-footprint and the human development index (HDI) is shown in Fig. 3.5 for various developing and developed countries. HDI is used by the United Nations and indicates the average of life expectancy, education and GDP, which may describe the development level of countries more accurately than GDP alone. In Fig. 3.5, there is a general trend to increase the ecological footprint as the HDI increases. However, there are exceptions and Cuba appears to be a remarkable country that achieves low eco-footprint and simultaneously a high HDI. I will return to this towards the end of this chapter.

Factor X refers to the possibility of reducing the rate of mass-throughput in society by increasing the efficiency with which society uses resources and energy. If Factor X = 10, then society needs only 10% of the current resources to support its activities which can make a considerable contribution to its sustainability. We can calculate what might be the conditions for a sustainable world if we make certain assumptions (Yamamoto 2001):

A is the consumption of resource/energy per billion people/year for 4.8 billion in developing countries

B is the consumption of resource/energy per billion people/year for 1.2 billion in developed countries

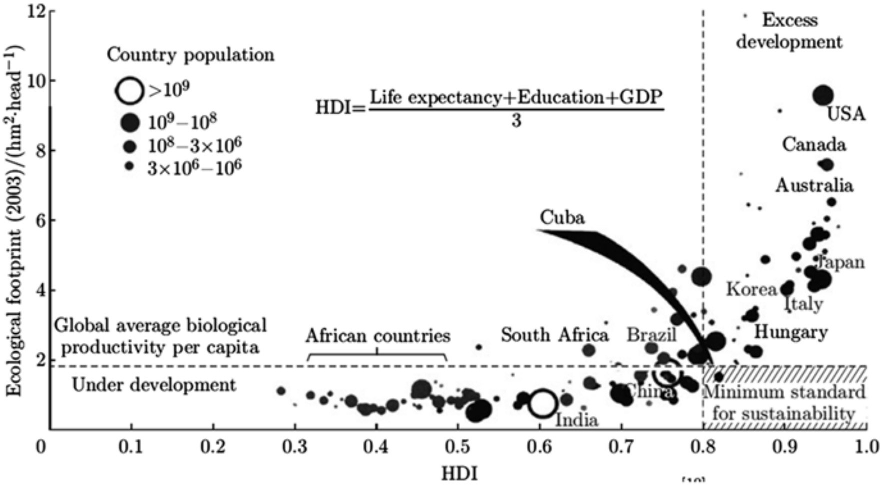


Fig. 3.5 Relation between eco-footprint per capita and the Human Development Index (HDI). (From Yoshida 2009)

C is the level of consumption which is sustainable.

S is the level of consumption in 1 year which is sustainable.

We can assume that the level of consumption in 2000 exceeded the sustainable level by 40 % and that the average ratio of consumption levels between developed and developing countries was 100. If there is an increase in the population of developing countries of 3 billion by 2050, and developed country population stabilizes, we can calculate the level in standard of living which could be the same for all and still be sustainable by 2050. On these assumptions, two equations can be derived.

For 2000, $4.8 \times A + 1.2 \times B = 1.4 \times S$

For 2050 with each consuming a sustainable level of C, $7.8 \times C + 1.2 \times C = S$.

By using these equations, $C/A = 10$ and $C/B = 0.1$ provides a solution. This suggests that developing countries can increase their consumption 10 times, but at the same time developed countries must reduce their consumption by 90 % to 1/10 of the 2000 level by 2050. This is 'Factor 10'. To achieve Factor 10, developed countries can reduce consumption to one tenth; alternatively, if they can achieve a 5-fold increase in the environmental efficiency of industrial products, a reduction of only half would be sufficient.

Life Cycle Assessment Based on the previous analyses, a recycling-based society seems to be the only option to solve the resource problem. However, we have to take into account the fact that recycling is not always the optimum if it needs more resources or energy than producing new products. As one example let us consider an issue raised (Takeda 2000) concerning recycling of polyethylene terephthalate (PET) bottles; he asserted that recycling should not be conducted because it involves higher costs than producing directly from petroleum. On his analysis, a new bottle costs 7.4 ¥, but the recycled bottle costs 27.4 ¥ when the costs of collection and transportation are included. His analysis would mean that recycling may

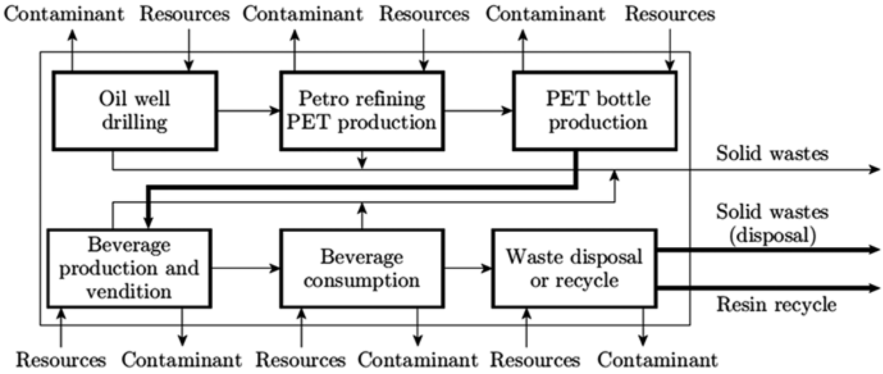


Fig. 3.6 LCA for PET bottle recycling. (From Nakanishi 2003)

Table 3.2 Environmental load of PET bottle production with and without recycling (1000 1.5 l bottles) from Nakanishi (2003)

Process	Stage	Solid waste (kg)	CO_2 (kg)	NOx (kg)	SOx (kg)
Recycle	Collection	0	1.13	2.03	0.644
	Transport	0	0.889	5.86	0.506
	Flake production	7.7	14.6	35	18.7
	Re-pellet	0.858	4.2	3.49	2.78
	Total	8.56	20.8	46.4	22.6
Landfill	Collection	0	1.08	1.93	0.614
	Shredding	0	1.22	1.01	0.81
	Transport	0	0.446	2.94	0.254
	Non-burnable waste	55.21	2.75	5.88	1.68

consume more resources and provide a bigger environmental load than producing new bottles.

LCA however allows us to examine this issue on the basis of more rigorous methods than the cost comparison. Nakanishi (2003) followed the procedure in Fig. 3.6 for the LCA on PET bottle recycling, which indicates the life cycle of a PET bottle from the stage of crude oil production to that of waste-disposal or recycling. As seen in the figure, inputs of resources and outputs of contaminant are counted for each stage and summed up to obtain the final amount of solid waste or recycle resin. Nakanishi carried out the LCA for the recycling of 1000 PET bottles of 1.5 l and compared the amount of atmospheric emissions between recycle and landfill of solid wastes. In this comparison, the amount of contaminant emission from the new PET resin is included as well as from landfill for the disposal of the old bottles. Table 3.2 shows the results of LCA of the emission of CO_2, NOx and SOx. It is clearly seen from Table 3.2 that the amount of solid waste and contaminant emitted from recycle is much smaller than that from landfill.

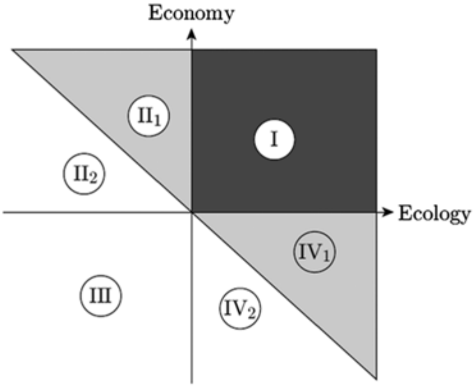


Fig. 3.7 Four phases of technology. (Nakanishi 1994)

Additionally, Nakanishi carried out a cost comparison between these two cases which indicated a cost of 9092 ¥ for recycle and 6373 ¥ for landfill. Landfill was cheaper than recycle, but the cost difference vanishes if the cost of landfill increases by at least 3 times relative to the cost at that time of 25,000 ¥/t. Based on this estimate, recycling of PET bottle was more expensive than landfill, but was considerably more effective in protecting the environment. This is a typical example of conflict between economy and environment.

Nakanishi (1994) developed this relationship between environment and economy to a general guidance involving a simple graph describing four phases of technologies as shown in Fig. 3.7 which can be used to decide priorities in both developing and developed countries. This graph is composed of an economy axis and an ecology axis dividing into four phases designated as I, II, III, and IV. Phase I is the most desirable phase whose technologies are good for both ecology and economy. Unfortunately however, most technologies still fail to meet this ideal criterion and economies are faced with using technologies with various degrees of environmental harm. Nakanishi suggests that developed countries should be expected to move towards phase 1 faster than developing countries. Thus, developing countries are permitted to use technology which is economically effective even if there is ecological weakness (Phase II_1); whereas developed countries should put a higher priority on ecological factors and be limited to Phase IV_1 as well as Phase I. Phases other than I, II_1 and IV_1 are not permitted at all, because those are bad for ecology and also lack economy effectiveness.

While some leading technologies belong to Phase I such as low-energy, clean production or in-process technologies, most technologies in use today were established in the twentieth century and are thought to be located outside Phase I. For example, subsidized recycling technologies and antipollution technologies (end-of-pipe technologies) may belong to Phase IV_1. To shift these technologies to Phase I and also to create new technologies in Phase I is important to establish a sustainable society.

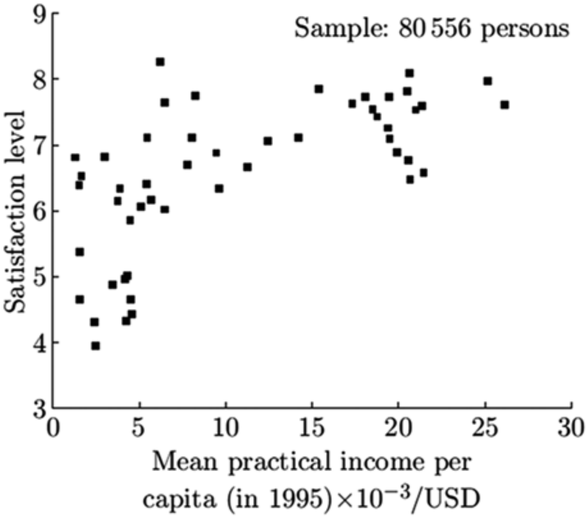


Fig. 3.8 Relation between satisfaction and income per capita. (Frey and Stutzer 2001)

3.3 Relationships Between Economic Growth and Happiness

If there are limits in the extent to which we can grow within a sustainable future, we need to think again about the economic models which drive our increasing demands for raw materials and energy. At present, the aim of most economists and politicians is to increase the GDP of the national economy which leads to ever-increasing energy and material consumption which is not compatible with a sustainable society. Thus some researchers have started to ask the question of what are society's real aims. Frey and Stutzer (2001) investigated the relation between economic growth and happiness and obtained the interesting results on this relationship which are shown in Fig. 3.8 which expresses the relationship between satisfaction level and income per capita. Although considerable scattering is observed in the results, there can be seen two relationships between satisfaction level and income: one is a linear relationship at low income levels; the other is weak or zero dependence at higher income levels.

Looking at just the USA, the annual change in GDP per capita and mean personal happiness are plotted in Fig. 3.9; this shows that while GDP per capita increases 2.5 times since 1946, happiness does not increase at all. A similar tendency can be seen in the case of Japan as seen in Fig. 3.10; which is consistent with the lack of correlation between happiness and income at the higher income levels in Fig. 3.8. The reasons for such tendencies need to be understood because it rather undermines much of the rationale for economic growth; moreover the role of science and engineering is often described as to enrich the life of people, and GDP increase is commonly used as the measure of the extent to which peoples' lives have been improved.

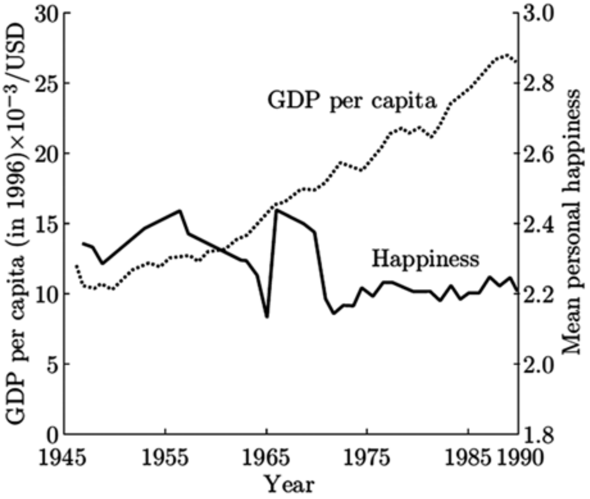


Fig. 3.9 Annual change in GDP per capita and mean personal happiness in the USA. (From Frey and Stutzer 2001)

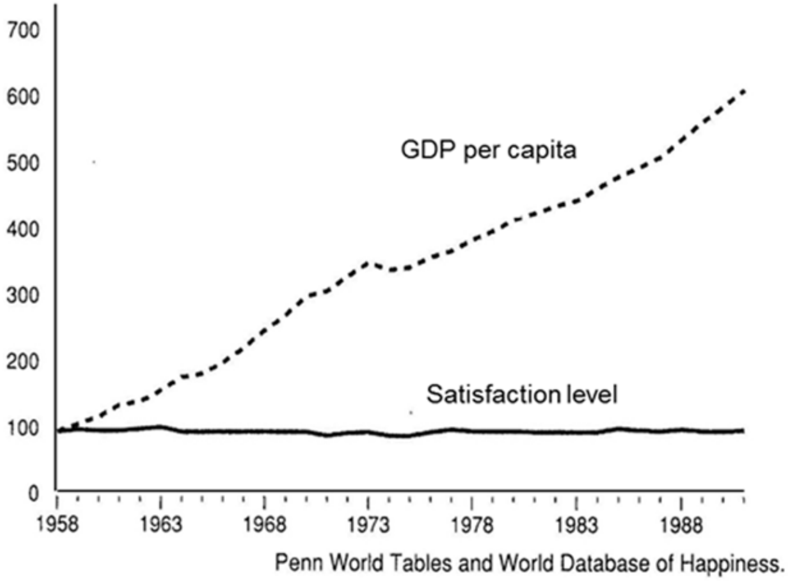


Fig. 3.10 Changes in satisfaction level and GDP per capita in Japan. (1958–1991)

To gain some insight into this conundrum, we can refer to the work of American psychologist, Abraham Maslow, who investigated human needs, and derived his theory of needs hierarchy (Maslow 1943). Based on his theory, there are five levels of human needs: the basic level is the physiological need- what is needed to maintain life (food, water, sleep, procreation); the second can be seen as related to

Fig. 3.11 Layard (2011) and the "Big Seven" of happiness

safety (security, job, health); the third relates to love/belonging needs; the fourth relates to self-esteem, confidence and respect needs; while the fifth and top need is classified as self-actualization where the individual can achieve his or her higher order needs and life satisfaction. The first two needs are basic to survival and only when they are met, may the remaining three needs be realized. By applying this theory, the result of the previous graphs may be explained. Increasing income may well contribute to meeting the first two needs, which is why at the lower levels of income there may be a relationship between increased income and life satisfaction. The higher level needs however cannot be achieved just by income which is why satisfaction level may not increase with increasing income.

Economists use measures of peoples' financial situation as the index of human happiness because it is easy to count and thought to be proportional to happiness. However, Layard (2011) in his book "Happiness" suggests that there are seven components of happiness (he calls these the "big seven" as shown in Fig. 3.11). These components are family relationship, community and friends, work, health, personal freedom, personal values, and financial situation. Moreover, the financial situation is not always in proportion to the other six components. Nowadays, the top priority is unfairly given to the financial situation and as a result many people are chasing after wealth as if the remainder of the life factors were dependent on that single index. We saw a reflection of this in the extraordinary disaster which struck the eastern area of Japan in 2011. Through this disaster, we could learn the importance of family relationships and community and friends. People of Tohoku area didn't complain about their bad luck, but they were deeply thankful for the help extended from others. We, Japanese, were moved strongly by such strong and calm people and learned about the importance of these non-economic aspects of happiness.

Meadows (1999) also built on the hierarchy to propose a theory for the ultimate purpose of development. Figure 3.12 indicates the hierarchy of development and its purpose and means. Towards the higher levels it becomes qualitative and unphysical, while at the lower levels, the parameters are quantitative and physical. Well-being is the ultimate purpose located on the top of the hierarchy, of which the first component is happiness. Human capital and social capital are the intermediate purposes occupying the second step, and composed of health, wealth, goods, etc. Artificial capital comprised of labor, tools, factories and materials makes the intermediate means on the third step. All of these purposes and means are supported

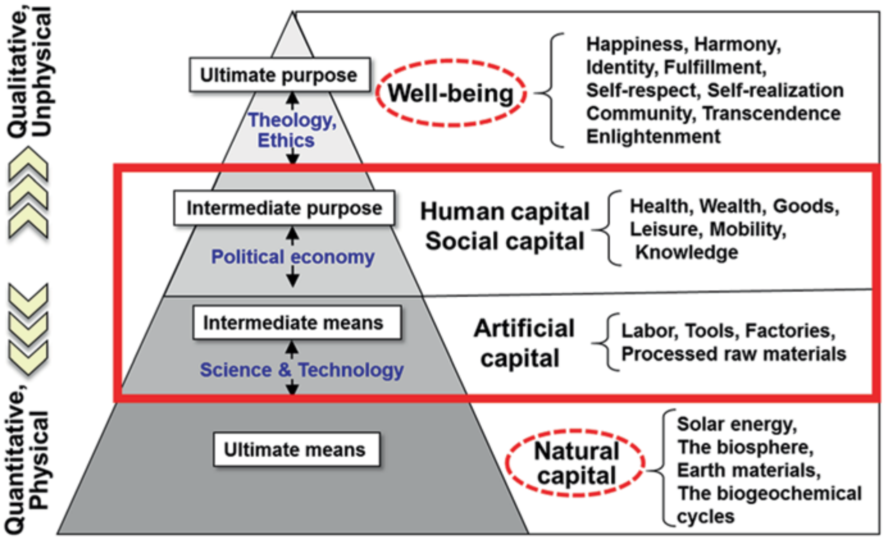


Fig. 3.12 Ultimate means and ultimate purposes of development. (Meadows 1999, Redrawn by Taniguchi 2012)

from the base by the natural capital like solar energy, the biosphere, etc. Each step is based on its own learning such as theology and ethics for the ultimate purpose, political economy for the intermediate purpose, and science and technology for the intermediate means. We are always aware of intermediate purpose and intermediate means when we consider development, and sometime forget the existence of the ultimate purpose and ultimate means. I think these intermediate steps appeared after the industrial revolution and became enormous thanks to science and technology operating in the economy. However, it is essential to pursue well-being and to treasure the natural capital, without getting stuck at the intermediate steps as is happening with the focus on indicators such as GDP.

This issue was also examined by Ernst Schumacher who proposed the thought of “Buddhist Economics” and “Intermediate Technology” in a book entitled “Small is Beautiful”. During his stay in Burma (now Myanmar), Schumacher (1973) noticed that people looked happier than English people in spite of their poor situation. His explanation was that whereas the ordinary rule is that “utility is equal to the amount of goods”, the rule in Burma appeared to be that “utility is equal to the amount of goods divided by the scale of desire”. Thus, increased desire and increased goods do not change utility; as we find when increased desire fuelled by skilful advertising does not lead to lasting satisfaction even when temporarily sated by a purchase. Equally, the people of Burma in Schumacher’s day had constrained their desire so that even small amounts of goods still provided utility (happiness). Similar effects may be seen in other not so rich countries such as Cuba.

Schumacher also pointed out systematic problems in modern economics and technology. The first is: technology does not possess the virtues of self-balancing, self-adjusting and self-cleansing; modern technology includes problems of inhumanity, environmental disruption, and resource wasting. The second is: from the view point of the employer, work is in any case simply an item of cost, to be reduced by automation. From the view point of the workman, work is a disutility and wages are a compensation for the sacrifice. The third is: modern economics does not distinguish between renewable and non-renewable materials, as its very method is to equalize and quantify everything by means of a money price. And the fourth is: the ideal of industry is to eliminate the living factors, even including the human factor, and to turn the productivity process over to machines.

In addition, Schumacher proposed an "Intermediate Technology", later called "Appropriate Technology", which is defined as being cheap enough so that they are accessible to everyone; suitable for small-scale application; and compatible with man's need for creativity. What might such intermediate technologies be? I would like to point to some technologies which may be included in the intermediate technology category. The first example is Rome concrete which has long-term durability of more than 2000 years. It is composed of volcanic ash, hydrated lime and water, and its strength is preserved by a geo-polymer reaction. Modern concrete made of Portland cement has only 60 years of a durable period due to carbonation, and it needs huge energy and emits large amounts of CO_2 in its production process. In Cuba, Rome concrete is applied to building materials because of its low environmental load as well as low cost. In Japan also, a kind of Rome concrete was applied to the breakwater of Otaru Bay. This concrete includes volcanic ash for corrosion resistance against sea water. When this breakwater was designed and constructed 100-years ago, 60,000 test pieces of concrete were prepared in order to evaluate the change in their strength due to aging.

A second example is a straw-bale house made of rice straw compressed into blocks which are light weight, good insulation of heat and sound, and even fire-resistant. Straw-bale houses are attracting the attention of people interested in reducing the environmental load and costs in house building. There is a straw-bale house in Akiu near Sendai city. The wall with 50-cm thick straw-bale coated by clay mortar attains not only high thermal insulation but also fire resistance. This house is a Japanese noodle restaurant (Fig. 3.13).

A third example is the hydraulic ram pump invented in 1796. This pump works only by the kinetic energy of water flow and there is no need for the electric energy necessary for an ordinary pump. A long water pipe through which water flows connects to a chamber having two valves; one is at the exit and the other is at the entrance of an air chamber. Initially, water is flowing out through the exit valve. Once the exit valve is closed suddenly, moving water in the long pipe generates a high pressure in the valve chamber due to the water hammer principle. This high pressure pushes water into the air chamber and then the exit valve opens again. Repeating this cycle, compressed water is lifted to higher places and utilized for various purposes.

A further example is the $ 100 personal computer which was developed in an educational project for IT popularization. This PC plays a central role for children's education in developing countries. The PC can be connected to the internet and charged manually by a rotating handle.

Fig. 3.13 Straw-bale house in Akiu Sendai

Thus in this chapter I point to some of the fundamental problems faced by current generations as we consider the future and its sustainability, and also point to some of the existing theories and technical approaches which exist. Sustainability is the most important issue for human society, and so it would be useful to have examples of how this can be achieved. In this context, much attention has been given to Bhutan and the measures of Gross National Happiness index which is used instead of GDP (Fig. 3.14).

Another example might be Cuba which has also attracted attention for its success in achieving a high level of sustainability under a difficult situation. Cuba's population is 1/10 of Japan, its area is half of the Japanese mainland, its GDP per head is 1/10 of Japan, but as indicated in Fig. 3.5, Cuba succeeds in combining a high HDI with low environmental impact, and can thus be seen as one of the most sustainable countries in the world. In particular, Cuba stands out from other countries in Latin America in education standards, which is attributed to the priority afforded by the Cuban government to education even when Cuba was in severe economic difficulties. Infant mortality is also low, with Cuba achieving levels normally associated with advanced countries such as Japan or USA even though per capita income is one tenth or less.

These desirable outcomes are despite the crises in energy and industry due to the breakup of the Soviet Union and economic embargoes by the USA. The collapse of oil imports and electricity failures caused unemployment to rise as far as 40 %; and GDP was reduced to 48 % of its former level. A food crisis due to agricultural damage was also severe; for example, caloric intake of citizens decreased by 40 %. Cuba thus had to turn to intermediate technologies and social priorities to achieve high levels of sustainability, education and medical care.

Three examples of the measures to support this transition are:

Urban organic agriculture: in difficult periods, people helped feed themselves by urban organic agriculture. Vegetables and fruits were raised in "Organopónicos" set up in urban areas using partitions made of waste materials. The ways of farming

Fig. 3.14 The 9 domains and 33 indicators of the Gross National Happiness index. (http://www.grossnationalhappiness.com/wp-content/uploads/2012/04/Short-GNH-Index-edited.pdf accessed 10 June 2014)

were diffused through TV programs, and worm compost as well as natural enemy insects was applied as alternatives to chemicals.

Free medical service: the number of citizens per doctor is 169 (compared with 520 in Japan). Medical expense is free and medicines are very cheap. A Latin American School of Medicine was established in 1999 and has accepted even foreign students without tuition fees. Several 10,000 patients from Chernobyl were treated. Vaccines are produced by biotechnology and alternative medical systems are developed.

Effort on education: after the Revolution, 23 % of the national budget (10 % of GDP) was applied to education. Tuition fee is completely free from elementary to graduate school. No school was closed during difficult periods. Subjects are practical and students construct their knowledge by themselves (constructionism). For adults, a TV program, ‘College for All’, started to air in 2000 and improved the literacy rate.

While we may not wish to follow the Cuban example, this can remind us that there are alternatives to continuing the current unsustainable economic model and encourage us to think creatively about the future we wish to leave to our children.

The next chapters will describe a range of potential ways of thinking and technological approaches. We have to notice that happiness is our ultimate purpose, economy and industry are intermediate, and natural resources are ultimate means which support all our actions.

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Chapter 4
Fuel Cells for Efficient Use of Energy

Tatsuya Kawada

Abstract This chapter reviews the basic technology and potential application of fuel cells in the provision of energy, and the fundamental principles which would underpin the wider use of hydrogen as an energy source for fuel cells (‘Hydrogen Economy’). Hydrogen’s strengths and weaknesses as an energy carrier are examined, and the current development and commercialization of PEFC and SOFC type fuel cells in transport and domestic combined heat and power systems reviewed.

Keywords Fuel cells · Hydrogen economy · PEFC · SOFC · Combined heat and power

4.1 Background to Fuel Cell Technologies

Currently, most energy sources are derived from the sun since, excluding energy of the Earth itself (such as nuclear, geothermal, and tidal), all are the direct or indirect effects of sunlight now or in the past. Life on earth depends on the solar energy-driven carbon cycle through photosynthesis which stores part of the energy of sunlight as chemical energy in a living body. Humanity has mastered how to manipulate fire and now can use the energy stored in the ground as fossil fuels laid down in past eras—firstly coal and subsequently the more user-friendly, oil, natural gas, etc. Such fossil fuels have supported the modern life of humanity but have changed the atmosphere’s composition and the associated energy balance, leading to the rapid warming and climate change which are currently underway.

The key issue now is thus how to reduce the use of fossil resources and introduce alternative ‘renewable’ or ‘sustainable’ energies. Modern technologies, such as solar cell and wind turbines can already convert the energy from sunlight to electricity with higher efficiencies than plant photosynthesis. Electricity is a useful form of

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T. Kawada (✉)
Graduate School of Environmental Studies, Tohoku University, Sendai, Japan
e-mail: kawada@mail.kankyo.tohoku.ac.jp

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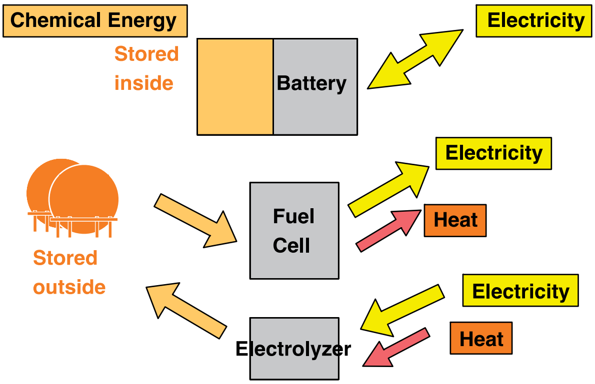


Fig. 4.1 Secondary battery vs. fuel cell in the hydrogen energy system

energy which, in theory, may be converted to work with an efficiency of 100 %. Also, unlike the direct use of solar energy itself, electricity can be transported by transmission lines. However, electricity is not suitable for demands varying over time. When supply and demand are different, some means of storing excess supply or providing at times of shortage is also required.

As one means for compensating for the fluctuation of electrical energy obtained from sources such as wind power and solar cells, development of secondary (or rechargeable) batteries is thriving. In addition to the classical lead-sulfur batteries, sodium-sulfur batteries have entered practical use for the purpose of leveling large power fluctuations. In recent years, lithium-ion batteries have started to be used as a power source for electric vehicles or hybrid cars, which can also contribute to averaging energy demand. Several new types of batteries have been proposed to achieve larger capacity per volume or per weight and shorter charge/discharge time.

In the large scale wind and solar power renewable energy future, it will be necessary to store a greater proportion of the power. However, battery function is provided by the electrode active material in the battery cell, so to accumulate a larger amount of electricity over longer periods, it is necessary to use a larger battery cell body. From the point of initial investment and resource consumption footprint, to increase capacity and size endlessly is impossible, which creates the demand for more effective means of storing renewable energies on a large scale. The concept of a hydrogen energy system or ‘hydrogen society’ may provide a solution to these problems (Fig. 4.1). Hydrogen can be produced from water via electrolysis or other methods, and directly or indirectly from renewable energy resources. It can be stored in a tank as a pressurized gas or as a liquid, or in a form of hydride compound. When used, it emits only water. Hydrogen thus can be regarded as a potentially ideal energy carrier and storage medium.

The essential device to complete the hydrogen energy system, by converting the chemical energy of hydrogen to electricity, is the fuel cell. A fuel cell consists of electrochemical cells as the secondary battery, but without having active materials inside. Since the fuel and oxidant (air) can be continuously supplied from the outside, the size of the fuel cell is not limited by the stored energy but only by the power, i.e. energy per second. The hydrogen fuel cell vehicle has been under development for many years and is planned to be commercialized soon, opening the way to a hydrogen society in the future.

Wider use of renewable energies also requires an appropriate backup energy source that can compensate for periodic shortages in the renewable energy supply. Such backup electricity may be generated using fossil fuels, but for localized or distributed energy systems, fuel cell CHP (cogeneration of heat and power) technology (which was proposed decades ago) is now emerging as a high-efficiency new technology using fuel cells. Fuel cells may also be used as a larger-scale centralized energy system as a part of a 'combined cycle' system with gas and/or steam turbines, which can achieve the highest ever efficiency of any generator using fossil fuels.

In the following sections, the theoretical background and the technologies of fuel cells will be described in further detail.

4.2 The Principle of Fuel Cell Power Generation

4.2.1 Comparison of 'Normal' Combustion with Fuel Cells

As the historical means for extracting the chemical energy from fuel, mankind has taken advantage of combustion whereby the chemical bond changes associated with the reaction of the fuel with oxygen emit heat (heat of reaction), as a result of differences in binding energies. In thermal power generation, the heat produced is used to drive a turbine and generate electricity.

In contrast, in the fuel cell, the fuel and oxygen are separated by a membrane with ionic conductivity and they react through ions passing through the membrane. However, with this passage, electrons are accumulated on one electrode so if the electrodes are not connected to an external circuit, the reaction stops. In order for the reaction to continue, there is a need for electrons to flow between the electrodes through an external circuit. The force to proceed with the reaction is translated into the electrical force (voltage) which drives the discharge of electricity to the external circuit; thus as the reaction proceeds, energy can be taken out as electric power (Fig. 4.2).

This situation can be compared with a system used for lifting luggage by connecting to a pulley weight (Fig. 4.3). Due to gravity, the weight tries to descend (it tries to cause a reaction just as in the fuel cell), and gravity is converted to a force to lift the luggage (equivalent to the fuel cell voltage). In theory, the weight can lift luggage up to the same weight. Therefore, the energy of the weight can be converted most effectively when the luggage is just as heavy as the weight. In reality there is a frictional resistance, so if the weight is only a little heavier than the luggage, the pulley does not move. When the weight is much heavier than the luggage however, it is lifted quickly, but, the energy conversion efficiency is small and excess energy is released as heat.

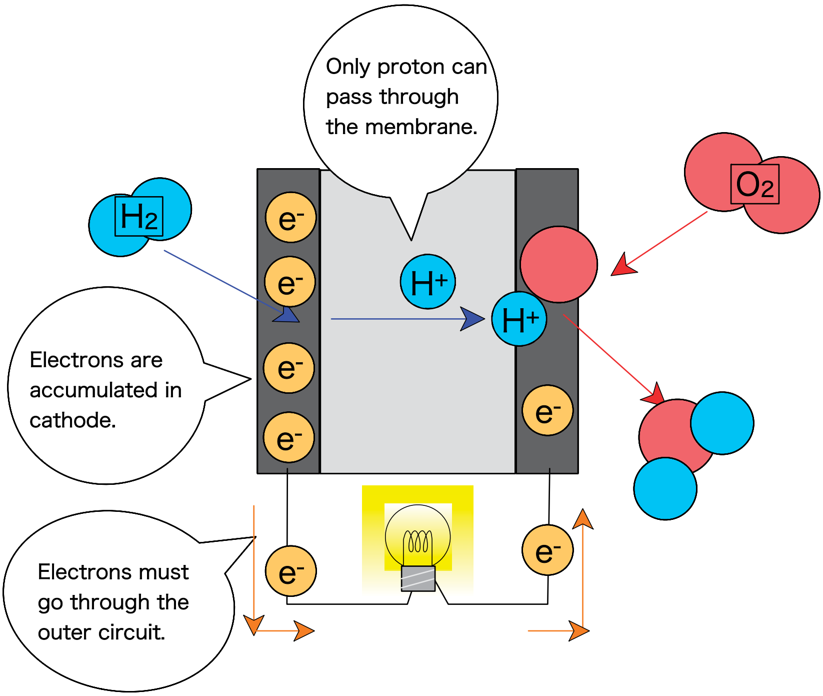
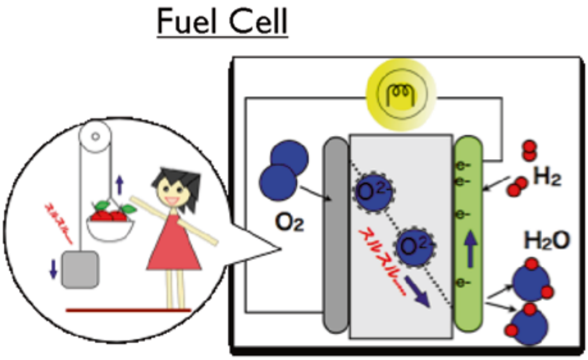


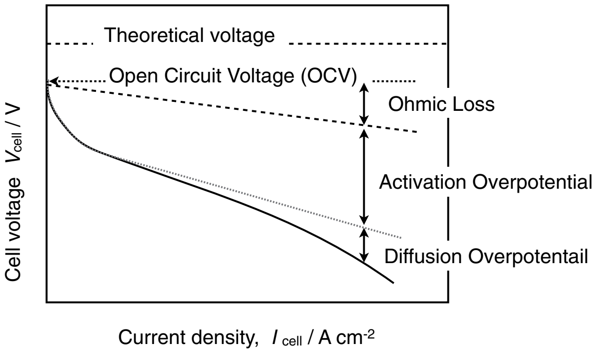
Fig. 4.2 Schematic view of fuel cells with proton conductor membrane

Fig. 4.3 Schematic illustration of electrochemical reaction



In a similar way, fuel cell efficiency is highest at close to the equilibrium state. When the current increases, the fuel cell moves away from its equilibrium state and the voltage or efficiency is reduced (Fig. 4.4). The degree of this reduction is determined by the resistance of the fuel cell which is described by terms such as electrolyte resistance, electrode reaction resistance, current collector resistance. An efficient fuel cell has small resistance, and the reduction in voltage is small even when taking out a large current. In our analogy it can also be noted that when the luggage

Fig. 4.4 Schematic voltage-current relationship of a fuel cell



is heavier than the weight, it lifts the weight in reverse. This corresponds to the electrical process of breaking down the water in electrolysis to produce hydrogen.

4.2.2 Concept of Efficiency

With any energy conversion device using limited resources, energy conversion efficiency is an important factor. However, efficiency data as issued in performance specifications for various energy conversion devices are often based on different assumptions, and may be misleading when such assumptions are not appreciated. We thus first consider the knowledge required to assess the efficiency of conversion of chemical energy to and from electrical energy.

Thermodynamic Aspects In conversion from chemical energy, it is necessary to know how much energy is released in the chemical reactions involved. Also to know the driving force under which the chemical reaction proceeds. These values are available from thermodynamic databases established by our scientific predecessors. For example, Table 4.1 is an example of the output of a personal computer-based thermodynamic database MALT, showing the change of energy when the H_2O molecule is formed by the reaction of H_2 with O_2 at around 1 atmosphere (10^5 Pa).

In Table 4.1a, the column headed by $\Delta_r H$ is the heat of reaction at each temperature (H is the enthalpy. Δ_r shows it is the amount that changes as a result of the reaction). The negative sign shows that the energy of the system is reduced- in other words, heat is released. The column headed by $\Delta_r G$ (G is the Gibbs energy) is the driving force to promote the reaction. A negative sign means that the reaction shown here will proceed spontaneously, and the value is the maximum amount of energy that can be converted into electrical (work) in the fuel cell.

If we look at the change in values in Table 4.1a with temperature, the temperature dependence of $\Delta_r H$ is seen to be small. It can also be seen that the absolute value of $\Delta_r G$ becomes smaller as the temperature rises. In general, as the temperature is increased, the discrete state becomes more stable than forming a large molecule. So, at higher temperatures, the state of $H_2 + 1/2O_2$ is more stable than the

Table 4.1 An example of output of the thermodynamic database MALT. (http://www.kagaku.com/malt/)

T	$\Delta_r S°$	$\Delta_r H°$	$\Delta_r G°$
K	J/K·mol	kJ/mol	kJ/mol
a) H_2 *and* $1/2O_2$ *to* H_2O *as vapour*			
298.15	−44.366	−241.826	−228.600
373.15	−46.585	−242.567	−225.186
473.15	−48.869	−243.529	−220.408
573.15	−50.652	−244.458	−215.428
673.15	−52.068	−245.338	−210.290
773.15	−53.205	−246.158	−205.024
873.15	−54.126	−246.914	−199.656
973.15	−54.872	−247.601	−194.205
1073.15	−55.479	−248.222	−188.686
1173.15	−55.973	−248.776	−183.113
1273.15	−56.374	−249.267	−177.495
b) H_2 *and* $1/2O_2$ *to* H_2O *as liquid*			
298.15	−163.179	−285.830	−237.178
373.00	−156.047	−283.439	−225.240
373.00		(H2O:bp)	

originating water molecules (H_2O). At ultra-high temperatures, where the value of $\Delta_r G$ becomes positive, H_2O will spontaneously decompose to $1/2O_2$ and H_2.

Definition of Efficiency The efficiency η of the fuel cell or thermal power system is defined as the ratio of the extracted electric power (work = W) to the heat available from the combustion of the fuel ($\Delta_r H$) at the standard temperature; $\eta = W/\Delta_r H$.

Here, care should be taken in the choice of the reference value $\Delta_r H$. In this case, the value at the temperature of 298.15 K in Table 4.1a is a virtual value because at 1 atm, H_2O vapor becomes liquid water at room temperature; the latent heat of condensation is thus included in $\Delta_r H$ (Table 4.1b) which thus has a higher value than the figure for the vapour phase in Table 4.1a.

The nominal efficiency of the system depends on which reference value is used. To avoid confusion, the value of $\Delta_r H$ which is free of the heat of condensation is referred to as the Lower Heating Value (LHV); and the Higher Heating Value (HHV) includes the heat of condensation. The efficiency which defines the basis on which it was calculated then becomes η_{LHV} or η_{HHV}. When not distinguished, efficiency values are in many cases calculated using the LHV to give the appearance of higher efficiency so it is necessary to be careful when comparing different systems.

Efficiency of a Heat Engine Heat engines produce mechanical work by repeatedly absorbing high-temperature heat obtained from the combustion of the fuel, discharging a part of the heat at low temperatures, and returning to the original state. Considering the balance of heat supply and use, the work (W) obtained from the heat engine is the difference between the heat charged (Q_1) and the heat discharged (Q_2); $W = Q_1 - Q_2$. Therefore, the efficiency of the heat engine is equal to $(Q_1 - Q_2)/Q_1$. The maximum value of the thermal energy that can be taken in and out during the operation of the heat engine is proportional to the temperature at each stage, so the maximum value of efficiency (η) can also be written as $\eta_{max} = (T_1 - T_2)/T_1$

This is called the Carnot efficiency, and the efficiency of any heat engine cannot in principle exceed the Carnot efficiency.

Efficiency of a Fuel Cell In contrast to the heat engine, the fuel in a fuel cell is converted, without burning, directly into electricity, so the power generation in a fuel cell is not restricted by the Carnot efficiency. The maximum value of the efficiency of the fuel cell is $\Delta_r G/\Delta_r H$ as shown above, but in reality (Fig. 4.4), when taking out electrical current, this causes a voltage loss due to internal resistance, and the efficiency decreases. Accordingly, the real fuel cell efficiency is best considered with reference to the operating voltage. If the fuel cell is operated at V_{out}, and as a result of the reaction of 1 mol oxygen atom, an electric current of $2F$[1] coulomb flows in the external circuit, an energy of $4FV_{out}$ joule is retrieved. If the ratio of the fuel flow used for the electrochemical reaction is f, then we can express the efficiency of a cell or a stack by the following formula.

$$\eta = 2FfV_{out}/\Delta_r H$$

When a fuel cell is integrated into a system, further sources of efficiency loss should be taken into consideration. Since the fuel cell generates direct current (DC), it may be converted to alternating current (AC) using an inverter, which causes an efficiency loss of 5–10 %. The auxiliary equipment for water circulation and air blower etc. will also consume power. The system efficiency is thus calculated as an overall efficiency of the fuel to the electricity output.

Comparing the Efficiency of Actual Systems Heat engines can range from a relatively small gas engine system of just a few kW to a few MW class, to a large-scale power station where gas and/or steam turbines are used. Given the aforementioned Carnot efficiency, the efficiency increases as the operating temperature T_1 becomes higher. Modern gas turbines burn the fuel at high temperatures exceeding 1500 °C. In addition, some combine with a steam turbine using the exhaust heat to make a ‘combined cycle’, which can reach a 60 % LHV efficiency. However, with the heat engine, as shown in Fig. 4.5, obtaining a high efficiency is difficult for small systems.

On the other hand, the fuel cell, unlike the heat engine, has less of a size-effect on power generation efficiency. An efficiency of ~50 % LHV can be achieved not only with 100 kW class systems but also with 1 kW class residential fuel cell systems. Some recently announced systems show efficiencies exceeding 60 % LHV. In contrast to heat engines, the larger the system becomes, the more fluid and thermal management becomes difficult. Development is underway for fuel cell-gas turbine-

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[1] F is the Faraday Constant, 96485 C/mol.

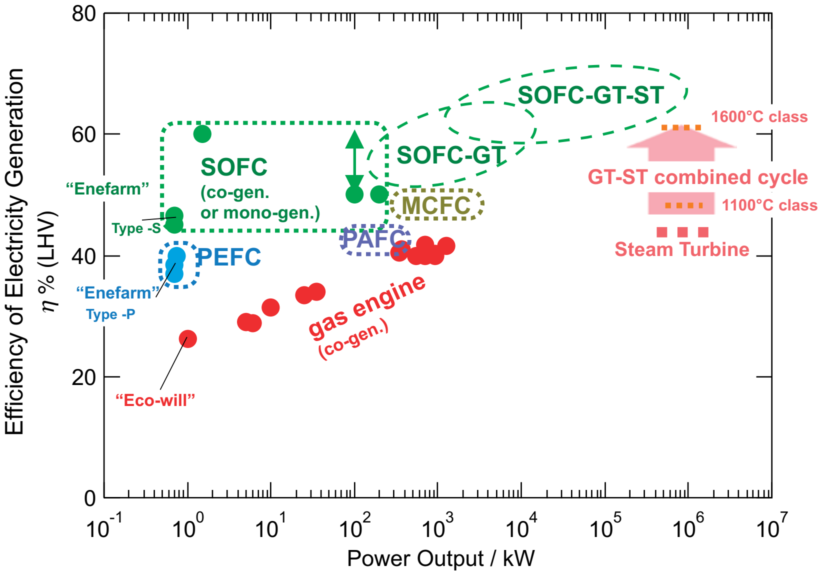

Fig. 4.5 Efficiency versus scale for heat engines and fuel cells. (SOFC: solid oxide fuel cell, PEFC: polymer electrolyte fuel cell, PAFC: phosphoric acid fuel cell, MCFC: molten carbonate fuel cell, GT: gas turbine and ST: steam turbine)

steam turbine triple combined systems which are expected to achieve an efficiency of 70 % LHV.

4.3 Type, History, and Mechanism of Fuel Cells

As previously noted, fuel cell reactions proceed through a membrane which transmits ions involved in the combustion reaction of the fuel. The basic electrochemistry of the fuel cell can be traced back to Sir William Grove in 1838 who was first to demonstrate how to generate electricity from the reaction of hydrogen and oxygen (although prior to this, Sir Humphrey Davy proposed a carbon -air battery in 1802 which is sometimes regarded as the beginning of the fuel cell).

The earliest commercial fuel cell used phosphoric acid as the electrolyte (phosphoric acid fuel cell: PAFC). In this fuel cell, the electrolyte diaphragm is soaked with phosphoric acid, and is operated at approximately 200 °C. Porous carbon material supporting platinum as a catalyst is used as the electrodes. Systems are available for sale with an output of 100 kW ~ 200 kW with an efficiency of ~ 40–42 % (LHV). However, as will be mentioned below, for equipment of this class a gas engine can achieve a relatively high power generation efficiency at lower cost. Therefore to take full advantage of the fuel cell's future potential, we need to further improve the performance.

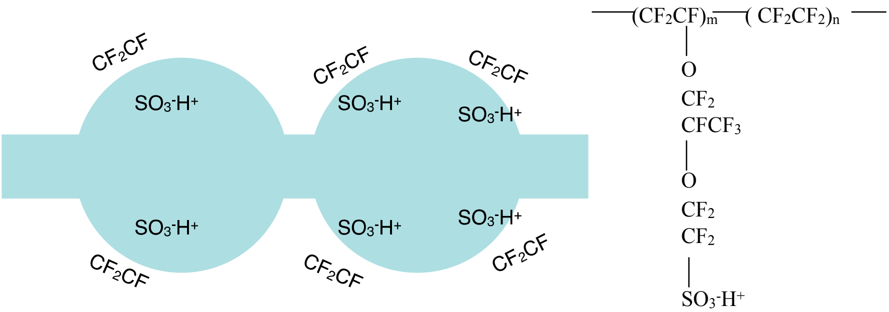

Fig. 4.6 Structure of a proton exchange membrane

More recently, a fuel cell made of ceramic materials (solid oxide fuel cell: SOFC) offering an efficiency of more than 50 % has entered practical use. An SOFC-gas turbine combined system with even higher efficiency is under development. SOFC is also applied to smaller systems as a household fuel cell and for a mobile system.

A further type, the polymer based fuel cell (polymer electrolyte fuel cell: PEFC) has made rapid progress in recent decades for fuel cell vehicles as well as for household applications. Developments in fuel cell vehicles and their associated infrastructure are now at a turning point for widespread installation into society and the start of mass production. In the following sections, we introduce the PEFC and SOFC and consider their detailed mechanisms, technology status, and challenges.

4.4 Mechanism and Characteristics of the Polymer Electrolyte Fuel Cell (PEFC)

Currently under development as a power source for automobiles is the fuel cell which uses a polymer electrolyte membrane which passes hydrogen ions (protons). This type is referred to as a polymer electrolyte fuel cell (PEFC) or proton exchange membrane fuel cell (PEMFC). Nafion® (developed by Dupont Company) or a similar polymer is generally used as the electrolyte membrane.

Figure 4.6 is a schematic diagram of the electrolyte membrane in the PEFC. The polymer has a backbone of a chemically stable fluorocarbon polymer structure in which there are branches with $SO_3^-H^+$ (sulfo group) attached. These parts gather together to form a local structure (inverse micelle structure), take in water easily, making proton-conducting channels. Proton conductivity becomes higher as humidity increases. Protons are known to transport by 'hopping' along the framework of hydrogen bonds in the absorbed water (Grötthus mechanism), or migrate as H_3O^+ together with a water molecule (vehicle mechanism). Recent reports of molecular dynamics simulation suggest the former mechanism is dominant in a Nafion® membrane.

The electrodes used in the PEFC are made of porous carbon material encrusted with fine particles of platinum. They are attached to both sides of the electrolyte

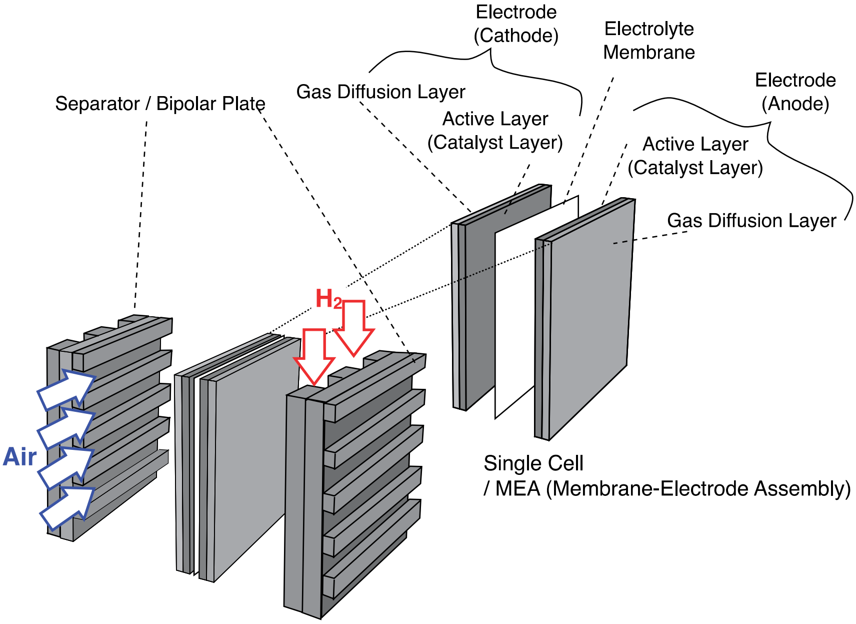

Fig. 4.7 Schematic illustration of a single cell of PEFC

membrane. The negative electrode on which a hydrogen molecule is oxidized (two electrons are extracted) to form protons is called the 'fuel electrode' or 'anode'. The opposite electrode is called the 'air electrode' or 'cathode' which reduces protons to a hydrogen molecule. The tri-layer of anode-electrolyte-cathode is referred to as a 'single cell' or 'MEA' (membrane-electrode assembly) especially for PEFC. The single cells are laminated via a current collecting plate (called a 'separator') made from materials such as carbon, to build a 'stack' to generate a practical high voltage. Cooling water is often circulated inside the separators to remove heat generated by thermodynamic and kinetic losses. (Fig. 4.7)

The energy conversion efficiency in a PEFC is limited by the activation resistance at the electrodes, especially at the cathode. Although the theoretical equilibrium potential of a single cell is above 1.2 V, the output voltage is generally below 0.8 V when a practical current is extracted though, with a PEFC, further voltage loss is small when a large current per area is extracted. The high current density, together with the simple structure of the cell stack, thus enables PEFC to achieve a high power density per unit of volume, which makes it suitable for fuel cell vehicles. It is a common feature of PEFC to operate at ambient temperatures, and this low operating temperature relative to other major types of fuel cells enabling quick start-up and shutdown, is also advantageous for vehicles and other mobile applications (Fig. 4.8).

Technical problems which relate to PEFCs can be summarized as follows:

- Poisoning of catalyst. When hydrogen fuel is contaminated with CO at 10 ppm or above, this strongly adsorbs on the Pt catalyst in the electrode, and reduces its

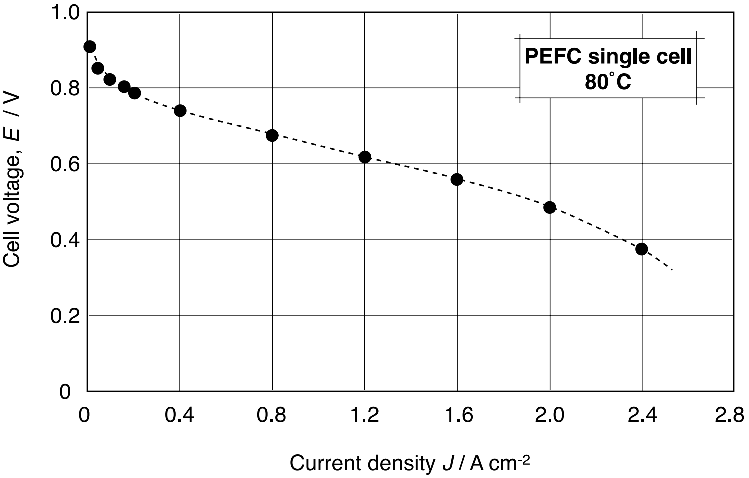

Fig. 4.8 Example of current-voltage characteristics in a PEFC. (Figure reproduced from data in Antoni et al. 2009. Characterization of single cell PEFC performances using US/Japan/EU procedures and hardwares. Fuel Cell Seminar and Exposition, Nov. 16–19, 2009, Palm Springs, CA, USA)

catalytic activity. A purification process is thus necessary for a hydrogen station, and for a stationary fuel cell system that uses town gas as the fuel.

- Water management. The electrolyte membrane requires high humidity to have enough proton conductivity. However, too much humidity causes condensation of water which blocks the gas channels. A system for precise humidity control is required.
- Durability. Several sources of degradation have been pointed out for PEFC. Dissolution of the Pt catalyst and damage to the electrolyte membrane can cause severe problems. Operating conditions have been optimized for stationary and mobile systems to avoid severe degradation.
- Cost. The use of Pt catalyst contributes to the high cost of PEFC. The limited platinum resources will also become a significant problem if fuel cell vehicles are widely commercialized. Reduction in the amount of Pt is still a major focus of research and development for PEFC.

4.5 Mechanism and Features of SOFC

In contrast to the PEFC, a SOFC operates at temperatures higher than 600 °C. The electrolyte of the SOFC is a ceramic membrane that conducts oxide ion, O^{2-}. Figure 4.9 shows a schematic view of the crystal structure of a typical electrolyte material, yttria stabilized zirconia, YSZ, which is zirconium oxide in its high temperature phase (cubic fluorite phase) stabilized by replacing a part of Zr^{4+} ions with

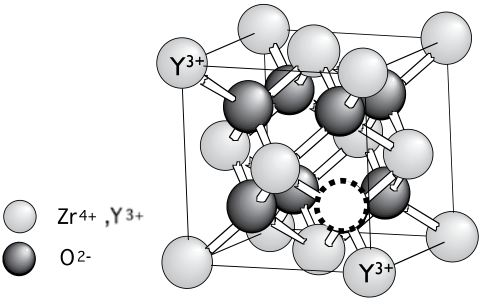

Fig. 4.9 Crystal structure of yttria stabilized zirconia, YSZ used as the electrolyte material of SOFC

Y^{3+} ions. Introduction of 3 + cations in a 4 + cation site violates the charge neutrality in the crystal, resulting in the formation of vacancies on the oxide ion site. When an oxide ion jumps into the vacancy from a neighbouring site leaving a vacancy behind, a charge 2 + is transported by the vacancy. Oxide ion is thus transported by this vacancy mechanism.

It is not therefore necessary for a SOFC to use platinum or other precious metals for the electrode catalyst. This is due to the high operation temperature, and is regarded as an advantage for SOFC over PEFC or PAFC. The most popular anode material is nickel-YSZ 'cermet' (a *cer*amics and *met*al composite). The YSZ particles prevent the nickel particles from agglomerating, and form three-dimensional paths for oxide ion in the electrode layer. For the cathode, electronically conductive ceramics are utilized. In the early stage of the development of SOFCs, (La, Sr)MnO_3 was regarded as the best candidate due to its stability and compatibility with the YSZ electrolyte. Recent development of reduced temperature SOFCs, requires a cathode with a better performance, and the use of (La, Sr)(Co, Fe)O_3 has become popular. Since this material reacts to YSZ to form an insulating layer, a thin interlayer is inserted between the cathode and the electrolyte.

As with other types of fuel cells, SOFC is also used as a 'stack', piling up multiple single cells. The shape of the stack however can differ- planar stacks, tubular stacks, flat tubular stacks, or segment-in-series stacks are possible (Fig. 4.10). Planar stacking has an advantage in energy density, while tubular stacks have higher stability against thermo-mechanical stresses. Segment-in-series type stacks can be cost-effective since the structure is sustained by a low cost ceramic substrate. The component connecting single cells is called a separator in a PEFC, but is generally called an 'interconnect' in a SOFC. Metal or ceramic interconnects are used depending on the stack design.

The most distinctive feature of the SOFC configuration is its high operating temperature. This causes various advantages and disadvantages for a SOFC relative to other types of fuel cells as listed below.

- High energy conversion efficiency. High temperature operation is advantageous for achieving high energy-conversion efficiency, especially when hydrocarbon

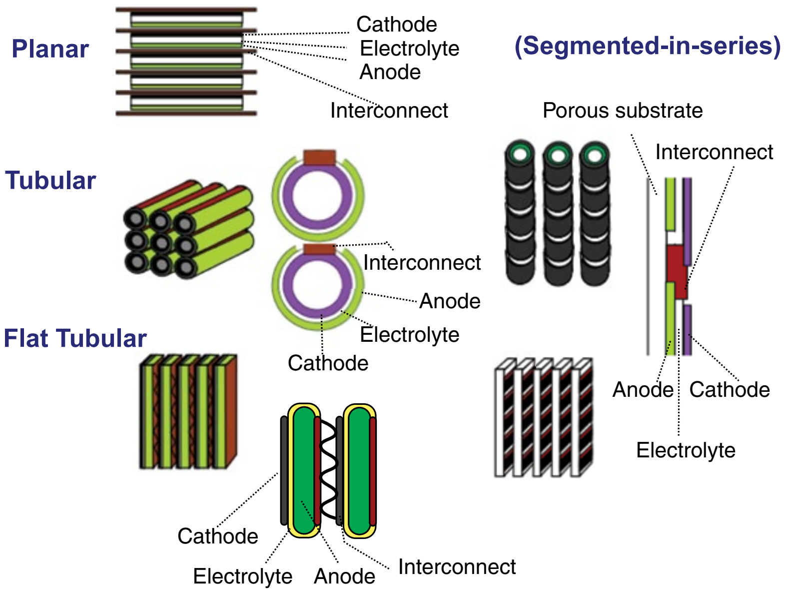

Fig. 4.10 Various types of SOFC stack

fuels are used[2]. So far, SOFC systems with energy conversion efficiencies ranging from 40 to 60 % LHV have been developed. Even higher efficiency may be possible when the exhaust heat is utilized for other types of generators, like a fuel cell-gas turbine combined cycle, a triple combined cycle with an additional steam turbine, or any other co-generation systems.

- Flexible fuel selection. SOFC can use a variety of fuels including H_2 and CO (a reformer may not completely reform the hydrocarbon fuels, thus CO can be accommodated, provided that carbon deposition is avoided).
- Difficulty in start/shutdown. Since SOFC is made of layered ceramics, fast heat up and cooling down may cause mechanical damage, which would be a fatal failure.
- Cost. The use of rather large amounts of nickel and rare earth metals contributes to a high material cost for SOFC even though it does not use precious metals.

Further developments are under study to achieve lower costs and longer durability.

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[2] This may be confusing for a reader who has learned that the theoretical efficiency of a fuel cell, $\Delta_r G/\Delta_r H$, decreases with increasing temperature. There are two reasons for the high efficiency of SOFC. One is the small activation polarization in the electrode processes at high temperatures. Another reason is related to the thermodynamics of hydrocarbon fuels. When methane is used, for example, it is first reformed to hydrogen using water as $CH_4+H_2O=CO+3H_2$. Since this reaction is endothermic, heat must be obtained by using a part of fuel in the PEFC, but with a SOFC, high temperature waste heat can be used for the reforming reaction, increasing overall efficiency.

4.6 Hydrogen Energy Society and Fuel Cells

The major application of fuel cells, especially of the PEFC, is anticipated to be in fuel cell vehicles. However, demand for fuel cell cars will be dependent on the availability of a hydrogen station near to the fuel cell car owner. From the reverse perspective, who would be willing to build a hydrogen station without a sufficient number of fuel cell vehicles coming to the station? Solving this dilemma requires political action and in Japan, related companies made an agreement under the support of the government to promote the development of hydrogen vehicles and hydrogen stations simultaneously, and much effort is going into bringing the technology to commercialization. However, a vision of a future energy system necessary for achieving reductions in energy use and CO_2 emissions, is still unclear and awaits new technologies or concepts to emerge.

With present technology, the hydrogen for hydrogen filling stations is mainly produced from natural gas or petroleum resources. The efficiency of fuel cell vehicles thus should be discussed on a complete system ('well-to-wheel') basis, and any energy losses in production and reformation of the fuel included with those in conversion of the chemical energy to electrical energy and propulsion systems in the car. Although different groups use different calculations on well to wheel efficiencies, a common conclusion is that the hydrogen fuel cell vehicle does not have a big advantage over a popular technology such as a gasoline hybrid vehicle when the hydrogen is supplied from fossil fuel resources.

Efforts on building hydrogen stations and on commercializing fuel cell vehicles are not however meaningless if the hydrogen-supply infrastructure is built up and becomes an integral part of society. This would support the introduction of any renewable energy technology since hydrogen can be produced through other renewable routes such as solar or wind electricity. Thus, development of fuel cells should be discussed not only from the fuel cell technology and economy but also from the viewpoint of future energy strategy.

4.7 Fuel Cells in Cogeneration Systems

In a power plant of efficiency η, $1-\eta$ of the energy in the fuel is released into the environment as heat. This waste heat is difficult to re-use in large-scale centralized power generation facilities, but in localized relatively small power generation equipment using gas engines or stationary fuel cells, the heat discharged may be used to meet local demand through providing a hot water supply or steam. We called these Cogeneration of Heat and Power (CHP) systems—a cogeneration system of electricity and heat. This is considered as effective means for the efficient use of chemical energy.

The efficiency of a CHP system is often discussed in terms of overall efficiency; simply summing up the amount of electricity generation and heat recovered. For

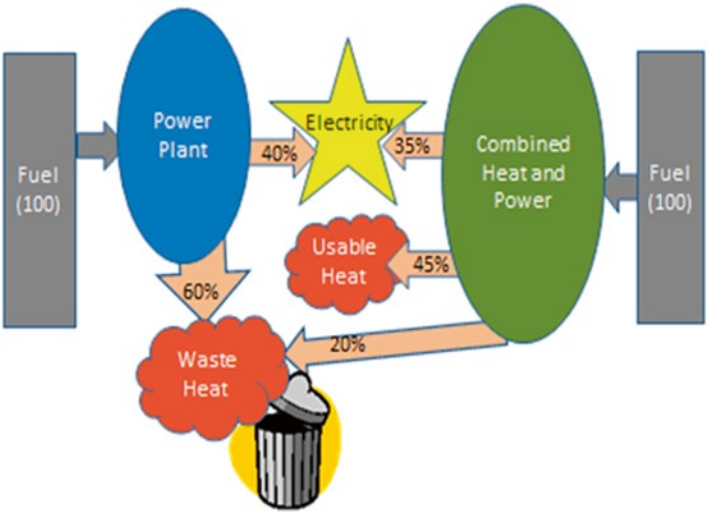

Fig. 4.11 Traditional concept of cogeneration efficiency

instance, Fig. 4.11 is typical illustration of the advantages of cogeneration, showing how in a large-scale thermal power station with a generation efficiency of 40 %, 60 % of the energy in the fuel is wasted. In contrast, cogeneration can achieve a thermal output of 45 % and an electrical conversion efficiency of 35 %, so the overall efficiency is said to be 80 %.

Such claims are very 'Eco' and imply that the main benefit of cogeneration is that its overall efficiency is high. Taking at face value this implies that the power generation efficiency is not so important even if it is low or, to take to extremes, that an 80 % 'overall efficiency' is satisfactory even with just a boiler that does not generate electricity! This comparison shows that it is not just the *amount* of energy that should be considered but also its *quality*.

As mentioned above, Carnot efficiency teaches that low temperature heat is only able to produce very limited work. We can say this is a *low-quality energy*. On the other hand, electricity can do work with an efficiency of 100 %. In evaluation of cogeneration systems therefore, those two types of energies must not be simply added. The effectiveness of cogeneration also varies with the conditions of the site; the demand ratio of electricity to heat, and how they change with time. Residential CHP, which is sold in Japan as "Ene-farm", is a suitable application for fuel cells, especially for SOFC, since an average family uses electricity and hot water in similar amounts. The problem is however, that the everyday life of each family is not always in the 'average' pattern. When CHP is operated just to meet the electricity demand, the hot water may be surplus or inadequate.

More effective utilization of fuel cell CHP would be possible if local society has networks of electricity and heat supply between nearby houses, offices, shops, restaurants, etc. Fuel cells of an appropriate size for the local network would make it possible to compensate for fluctuations in solar cells or wind turbine supplies before connection to the grid, and would promote the introduction of renewable energies. In addition, having a redundancy of energy supply would be beneficial to make the society more resilient against disasters.

4.8 In Conclusion: Future Energy Technologies and Society

We have looked at the theory, the technology and the application of fuel cells, with special emphasis on PEFC and SOFC types. Even though they are both fuel cells working under the same theory of energy conversion, they are quite different in their materials and merits/demerits and thus in their optimum applications. The same can be said for any other energy technology, so knowing every detail is important in appropriate selection and introduction of a technology. On the other hand, effective utilization of an energy technology may require a change in society and the lifestyle of the people. Decision makers should consider not only the technology and economics at the present moment, but should develop a plan or vision for an ideal future society. For that, again, correct understanding of technologies is essential.

Chapter 5
Energy and Supercritical Fluids

Richard L. Smith

Abstract Global energy demand is expected to increase from 12.4 gigatons oil equivalent (Gtoe) in 2010 to 16.7 Gtoe by 2035. Energy systems will need to be redesigned or rethought to achieve the high efficiencies required to meet such energy demands. Energy systems that take advantage of the favorable thermo-physical properties of supercritical fluids can help raise efficiency and this chapter introduces several applications of energy systems that use supercritical fluids. These include (i) transcritical cycles for heating (ii) cryogenic exergy recovery for liquefied natural gas transport, (iii) geothermal and waste heat energy, (iv) refrigeration, (v) ultra-supercritical steam generators, (vi) biofuel synthesis, (vii) hydrothermal conversion of biomass and (viii) solvo-thermal processing of biomass with ionic liquids. Supercritical fluids offer unique technological advantages in their use for energy systems and increase cycle efficiencies and simplify chemical processing.

Keywords Energy systems · Transcritical · Biomass · Ionic liquids · Supercritical · Hydrogenation

5.1 Energy Poverty and Global Energy Trends

The availability of energy directly affects the quality of life in the world as more than 1.3 billion people live without electricity and more than 2.6 billion people live without clean cooking facilities (IEA 2014). The lack of electricity and clean cooking facilities is referred to as energy poverty (Fig. 5.1). Presently, there is widespread energy poverty in sub-Saharan Africa, India, developing Asia, China and Latin America. Energy poverty can be expected to increase as both the world population and global energy demand increase.

R. L. Smith (✉)
Research Center of Supercritical Fluid Technology, Graduate School of Environmental Studies, Tohoku University, Sendai, Japan
e-mail: smith@scf.che.tohoku.ac.jp

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Global energy demand was 12.38 Gtoe (16.5 TW) in 2010 and is expected to rise to 16.73 Gtoe (22.2 TW) by 2035 (IEA 2014). While the energy demand for countries in the Organization for Economic Co-operation and Development (OECD) is expected to decrease during the 2010–2035 period, rising living standards in China, India, the Middle East, and non-OECD countries will cause the global energy demand to increase by more than one-third by 2035.

There will also be several new energy trends that are likely to occur over the 2014–2035 period. For instance:

- The US and Brazil will become major energy exporters due to the use of hydraulic fracturing commonly referred to in the US and Europe as "fracking", while deep-water drilling technologies off countries such as Brazil will also obtain unconventional gas and oil. Such trends will increase the supply of liquefied natural gas (LNG).
- The expansion of the Panama Canal, which is scheduled to be completed in 2015, will give larger liquefied natural gas (LNG) transport vessels access to Asia. The prospect of being able to readily transport LNG from South and North America means that LNG will become a globalized market in the period 2015–2035.
- Coal as an energy source will shift to Asia with coal consumption by India in 2035 being roughly that of China, Japan and the European Union (IEA 2014). This means that many new power plants that use coal will need to be built and that it will be very important to develop cleaner and more efficient combustion technologies for coal.
- As much as 90 % of Middle East oil will be exported to Asia by 2035 so that combustion processes will need attention to their design.

As such trends develop, it is essential that the new energy systems being built have high efficiencies so that catastrophic damage to the environment does not occur.

Energy systems that use fluids in their supercritical state have the potential to reduce energy consumption, reduce pollution and emissions to the environment and improve the global environment and living standards. Fluids in their supercritical state especially when used as working fluids in heat pumps can make highly efficient energy systems because there is no phase change for a fluid in its supercritical state.

5.2 The Supercritical State of Substances

The critical point of a substance is defined as the highest temperature and pressure for which vapor and liquid can co-exist in equilibrium (Fig. 5.2). The supercritical state occurs when a fluid is at conditions above its critical temperature and critical pressure. Many small molecules (H_2O, CO_2) have well-defined critical points whereas large molecules (polymers, waxes) decompose at conditions below their critical temperature.

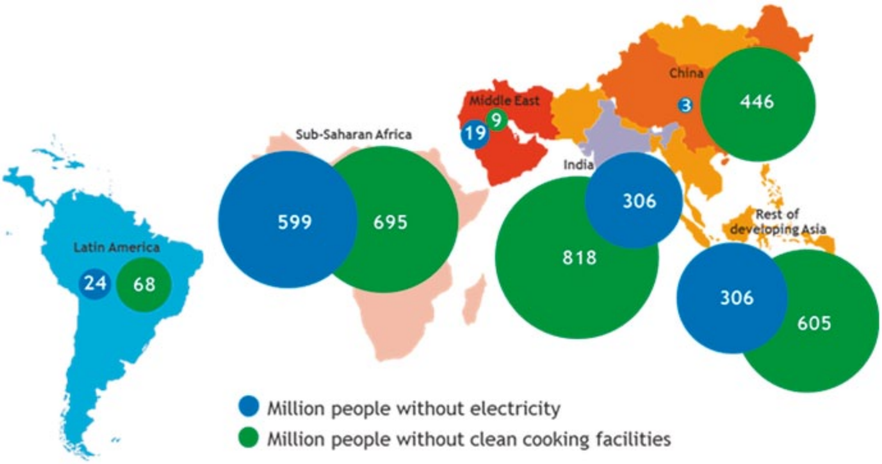


Fig. 5.1 Number of people without modern energy access by selected regions in 2011. (© OECD/IEA (IEA 2014))

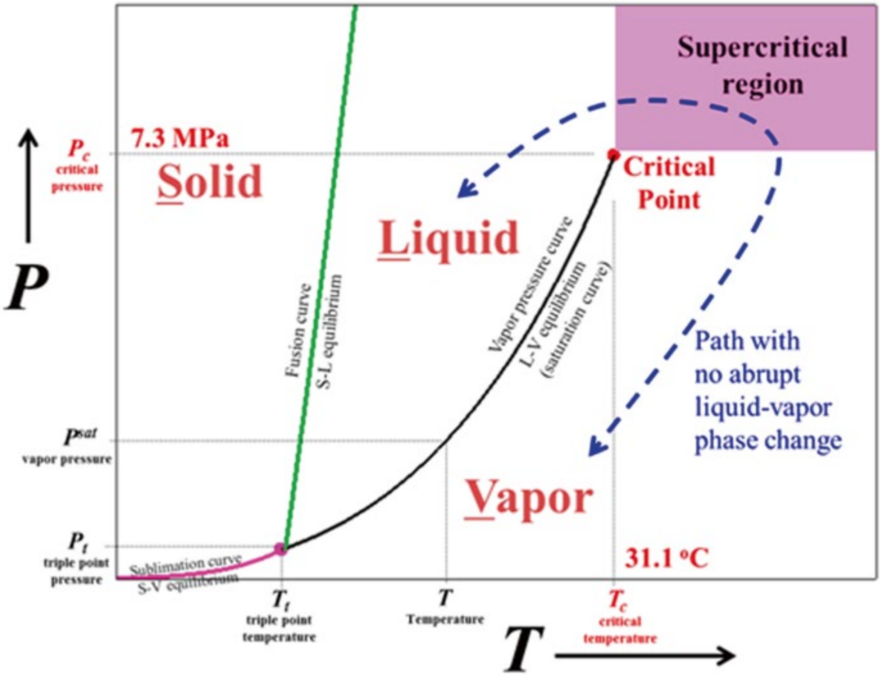


Fig. 5.2 Schematic pressure-temperature phase diagram of carbon dioxide (CO_2) showing the location of its three states of aggregation, *solid* (*S*), *liquid* (*L*) and *vapor* (*V*) and the location of the *supercritical region*. CO_2 is in its supercritical states when temperature is greater than the T_c and pressure is greater than the P_c

In Fig. 5.2, CO_2 is in its supercritical state when conditions of temperature and pressure are greater than T_c and P_c—shown as the supercritical region. Through variation of temperature and pressure, it is possible to change the state of a fluid from liquid to vapor and vice versa without abrupt phase change by letting the fluid pass through the supercritical region as also shown in Fig. 5.2. During the change of conditions of a fluid through the critical region, the fluid phase remains homogeneous and the path is referred to as *transcritical*. The lack of an abrupt phase change for fluids in their supercritical state is highly-advantageous in heat and mass transport and it is a key concept in developing highly-efficient energy systems.

5.3 Supercritical Fluids and Their Use in Energy Systems

Supercritical fluids are being studied for use in heating, cryogenic exergy recovery, geothermal and waste heat energy, refrigeration, ultra-supercritical steam generators, biofuel synthesis and biomass conversion types of energy systems (Smith et.al. 2013; Machida et.al. 2011). In some of these applications, the supercritical fluid is used as a *working fluid*, which means that the substance acts to transport energy in a cycle through various devices and only undergoes heat and work exchange with the environment. The homogeneous phase conditions of the supercritical region give highly-efficient energy transport. Energy systems that use a working fluid in its supercritical state are referred to as transcritical cycles since conditions traverse the critical region. In other applications, the supercritical fluid is used as a reaction solvent or as a solvent to enhance mass and heat transport to efficiently transform raw materials into chemicals or products. The next sections provide some basic definitions used to evaluate the efficiency of a device and provide an overview of some of the applications of supercritical fluids in energy systems.

5.3.1 Thermal Efficiency

Consider an energy system in which the objective is to produce heat, for example, a natural gas burner to produce warm air. The thermal efficiency of the system can be defined as a ratio of energy obtained to that supplied:

$$\eta_{thermal} = \frac{\text{Energy obtained}}{\text{Energy supplied}} \tag{5.1}$$

Not all of the energy value of the fuel (energy supplied) can be obtained so that $\eta_{thermal} < 1$. The thermal efficiency depends on the device and also depends on the type of energy being supplied. Thermal efficiencies for coal and fossil fuel combustion are typically 40–90 %, with the higher values being for natural gas burners- since natural gas can achieve more complete combustion than coal among other practical considerations. Heating by a device that uses electrical resistance, on the other hand, is almost 100 % efficient. However, the electricity used in the device must be generated by power generation processes that are generally only about 40 % efficient.

Although combustion of natural gas might seem to be the most efficient way to generate heat, there are other methods that use the heat contained in the environment in a very clever way such that more heat can be obtained than that of either combustion or electrical resistance. Consider the idea of a heat pump as described next.

5.3.2 *Heat Pump*

A heat pump is an energy system that uses electricity to move heat from a low temperature source to a high temperature source. Since the heat pump uses electrical energy to *move* heat from the environment to the desired location, it can obtain thermal efficiencies defined by Eq. (5.1) much greater than 1. Because it is not usual to have an efficiency greater than 1 (or 100 %), the efficiency of a heat pump is defined in terms of a coefficient of performance:

$$\text{Coefficient of Performance (COP)} = \frac{\text{Energy obtained}}{\text{Electrical energy supplied}} \tag{5.2}$$

For a device that uses electrical resistance as the heat source, Eq. (5.2) would give a COP value of one. For a heat pump however, COP values of 3, 4 or even 5 are not uncommon. A COP value of 4 means that 1 kW of electrical energy supplied will generate 4 kW of heat. Remarkably, this would be four times that of a device that uses electrical resistance heating and much more than would be possible by burning fossil fuels!

Before explaining the components of a heat pump, it is helpful to compare the heating that can be supplied by combustion, electrical resistance and a heat pump. Consider the conversion of 100 units of fuel to heat as shown in Fig. 5.3. In combustion, some amount of the heat is lost to the environment, so that from 100 units of fuel, 80 units of heat can be obtained. In electrical resistance heating, the thermal efficiency given by Eq. (5.1) is close to 1 and this would give a COP value of 1 if Eq. (5.2) were used. However, electricity must be generated and power plants are generally only about 40 % efficient. Thus, for electrical resistance heating, 100 units of the original fossil fuel provide 40 units of electricity which gives only 40 units of heat.

As also shown in Fig. 5.3, a heat pump uses the electricity in a device to move heat from one place to another rather than supplying heat directly. From 100 units of fuel, 40 units of electricity are produced from a power plant as in the case for electrical resistance heating; however, a heat pump with a COP of 4 moves 120 units of heat from the environment to give a total of 160 units of total heat. Thus, a heat pump is a device that allows highly efficient use of energy resources.

5.3.3 *Working Fluid*

To move heat from the environment to a target, a heat pump uses a working fluid that flows through various devices in a cycle (Fig. 5.4). Electricity is used to supply the work (W) required to move the fluid through the various devices in the cycle.

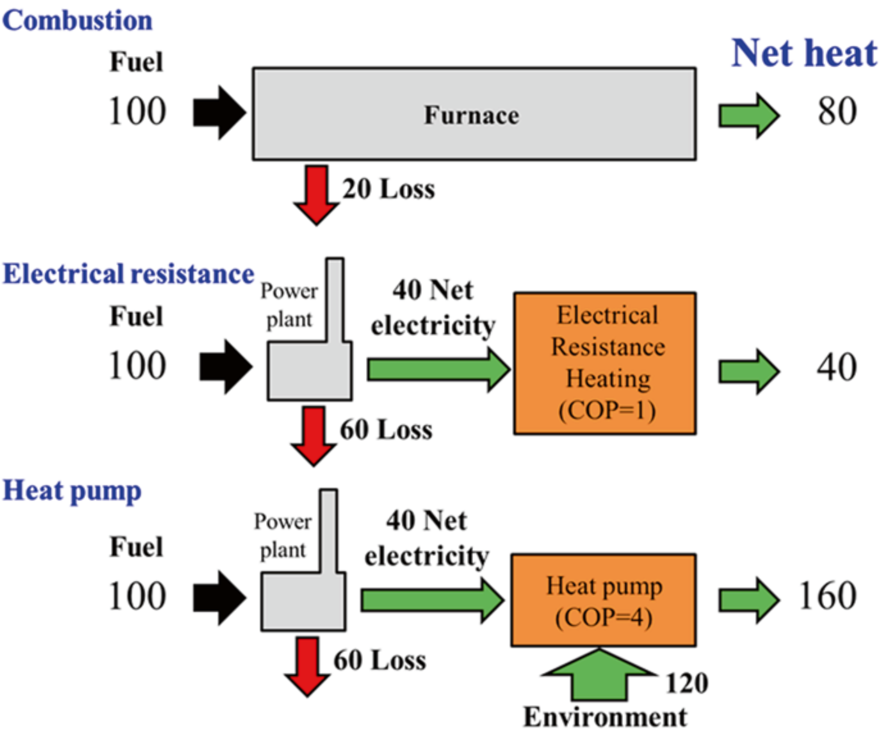


Fig. 5.3 Heat that can be obtained from combustion, electrical resistance heating and a heat pump from 100 units of fuel. Losses shown are typical for the devices

One device (evaporator) is at a much colder temperature than the environment so that heat transfers from the environment to the evaporator. Another device (heat exchanger) is at a temperature that is much hotter than the environment so that heat transfers from the heat exchanger to the target area or fluid. In Fig. 5.4, the environment supplies heat (Q_C) to the evaporator to vaporize liquid CO_2 so that it can be compressed and the hot CO_2 supplies heat (Q_H) through the heat exchanger so that it can be used for making hot water. The heat pump achieves its high efficiency by using heat available in the environment to recycle the CO_2. The choice of the working fluid and the specification of the conditions of the devices are important for achieving the desired results in any heat pump system. Once the concept of the heat pump is understood, it can be seen that there are many applications.

5.3.4 Eco-Cute Hot Water Heater

The Eco-Cute hot water heater shown in Fig. 5.4 is a special case of a heat pump system that uses CO_2 as the working fluid for making hot water. In Fig. 5.4, electrical work is input to a compressor that pressurizes the CO_2. Pressurization of the CO_2

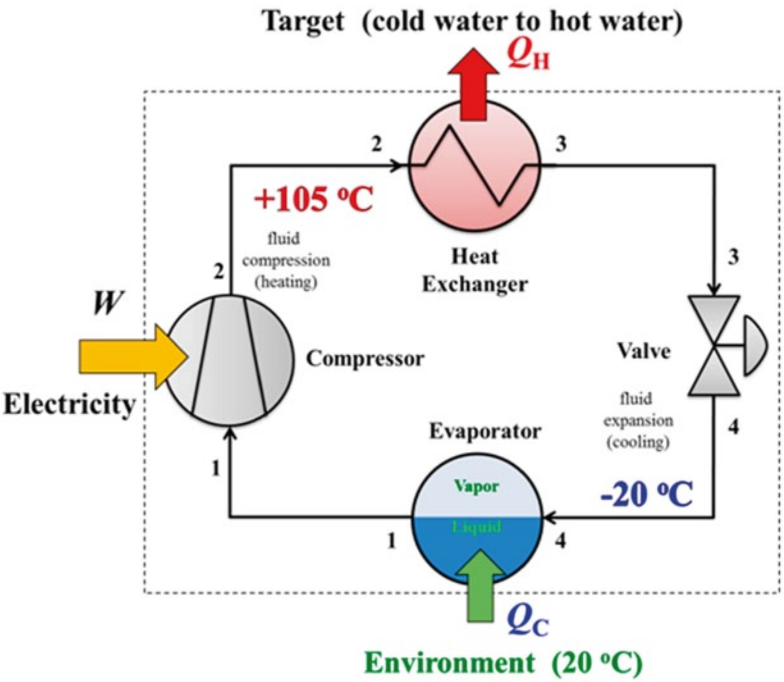


Fig. 5.4 Heat pump system that uses CO_2 as the working fluid for heating hot water. The compressor pressurizes vapor CO_2 that increases its temperature. The heat exchanger allows the hot CO_2 to transfers its heat to make hot water. The valve expands the CO_2 that causes cooling and makes a vapor-liquid mixture form. The evaporator draws heat from the environment to vaporize the liquid. Since the temperature of the CO_2 (−20 °C) is much lower than that of the environment (+20 °C), the heat pump can extract heat from the environment. The heat from the environment is used to vaporize liquid CO_2 in the evaporator so that it can be compressed again in the cycle. (Figure adapted from Smith et al. 2013)

causes it to heat up. Then, after heat is transferred from CO_2 to water with a heat exchanger, the CO_2 is depressurized through a valve to form a vapor-liquid mixture. The depressurization of the CO_2 causes it to cool and is called a *Joule-Thomson expansion*. Heat from the environment is used to vaporize the liquid formed so the vapour can be recompressed for another cycle. The flow diagram shown in Fig. 5.4 is the basis for the Eco-Cute hot water heating system developed and marketed by more than 20 different companies in Japan. As of 2013, more than 4 million units have been installed.

The Eco-Cute system is a heat pump system that can be represented on a thermodynamic temperature-entropy (*T-S*) diagram (Fig. 5.5). For the case of pressurization from 2 to 10 MPa shown by the path from **Point 1** to **Point 2**, the temperature of CO_2 increases from −20 °C (vapor) to 105 °C (supercritical). In Fig. 5.5, the compression of CO_2 is simplified as an ideal reversible process with no friction so that ΔS of compression is taken to be zero. In actual compressors, some amount of energy is lost by friction in the device and viscous losses by the fluid flow. Heat

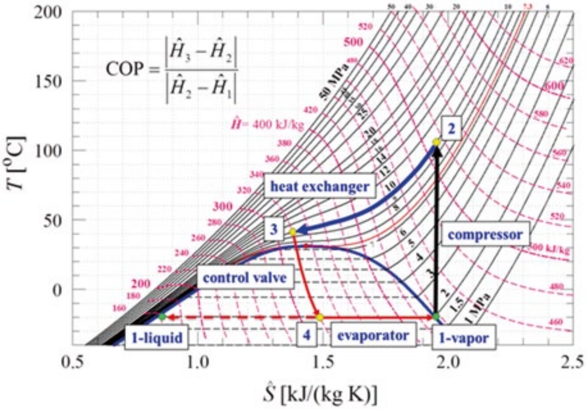


Fig. 5.5 Temperature-Entropy (*T*-*S*) diagram for CO_2 showing a typical set of conditions for a heat pump system. The COP of the heat pump is given by the ratio of enthalpy changes of the fluid, namely, the enthalpy change of the fluid in the heat exchanger (*2 to 3*) divided by the enthalpy change of the fluid in the compressor (*1 to 2*)

exchange between CO_2 in its supercritical state and water at ambient conditions takes place from **Point 2** to **Point 3** in a heat exchanger. The heat exchanger allows the heat of a hot fluid to be transferred to that of a cold fluid without direct contact between the two fluids. For the case of making hot water, CO_2 transfers its heat (105–40 °C) according to its decrease in enthalpy (510–320 kJ/kg) to heat water (20–90 °C).

In Fig. 5.5, the CO_2 remains in a single phase (supercritical) condition during the heat transfer process from **Point 2** to **Point 3**. After the CO_2 transfers its heat, it is expanded through a valve from **Point 3** to **Point 4** which causes both liquid and vapor to form. The pressure chosen for **Point 4** controls the final temperature according to the phase behavior of CO_2. At **Point 4**, the temperature of the CO_2 is at − 20 °C, which is considerably colder than the environmental temperature of + 20 °C so that the environment can supply heat to the evaporator. Heat transfer from the environmental allows the CO_2 to be recycled so that the process can be continuous. Since one of the paths shown (**Point 2** to **Point 3**) uses the working fluid (CO_2) in the supercritical region, the energy system shown in the figure is called a *transcritical cycle*.

5.3.5 Cryogenic Exergy Recovery Energy Systems

Natural gas, which is primarily methane (CH_4) is shipped worldwide as a liquid at − 160 °C and atmospheric pressure. This liquefied natural gas is referred to as LNG and in this form, its volume is reduced by about 1/630 compared with its gas form. After the LNG reaches its destination at a terminal, it is typically heated with sea water to convert it to vapor so that it can be transported through pipelines. The availability of a large cold temperature source is referred to as *cold energy* or *cryogenic exergy* since its temperature differs substantially from that of the environment.

Natural gas requires about 850 kWh of electrical energy per ton to produce the liquid that is necessary for its transport (Angelino and Invernizzi 2009). The use of heat pump cycles in the conversion of LNG to gas at receiving terminals has

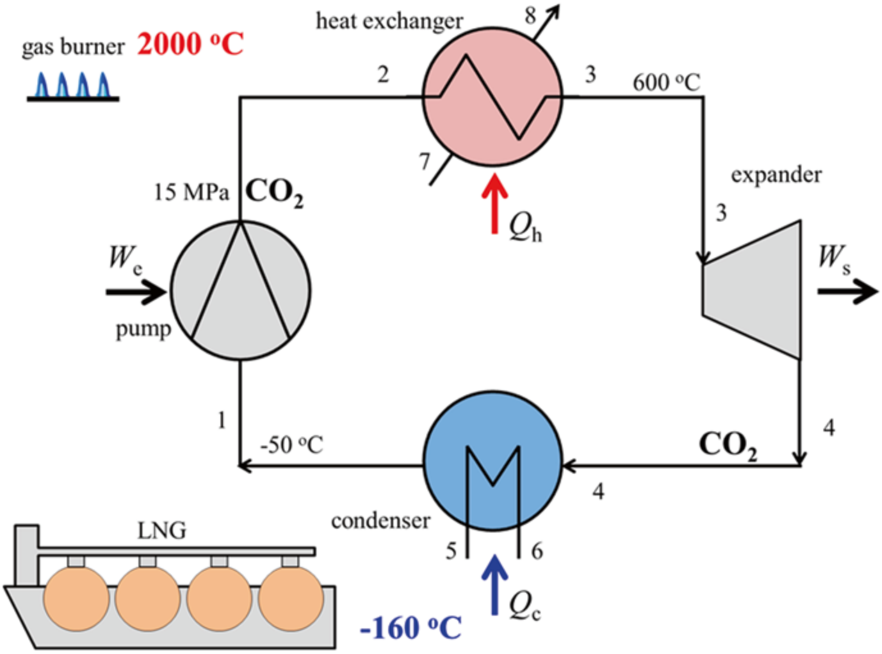


Fig. 5.6 Carbon dioxide energy system for recovering the cryogenic exergy from liquefied natural gas (LNG) transport vessels with a transcritical carbon dioxide cycle. From *Point 1* to *2*, liquid CO_2 at −50 °C is feed into a pump where it is compressed to 15 MPa. It is heated to 600 °C in the heat exchanger. The CO_2 is then expanded to generate electrical energy from *Point 3* to *4*. Then, the CO_2 is liquefied from *Point 4* to *1* by using the cold energy source of the LNG that is at −60 °C. As the LNG is warmed to the desired conditions, the CO_2 cycle produces electrical energy. Besides the electrical energy of the pump (W_e), some amount of fuel must be burned to heat the CO_2 in the heat exchanger

the potential to recover much of the energy required in LNG liquefaction. Many cryogenic energy recovery systems have been proposed based on nitrogen, organic compounds or steam (Angelino and Invernizzi 2009). However, carbon dioxide is favored as a working fluid not only for its wide operating range (−50 to 800 °C) that allows for simple process systems, but also because CO_2 is noncorrosive, nonflammable, safe and inexpensive.

Figure 5.6 shows an example of a carbon dioxide energy system for using cryogenic exergy of LNG transport ships. In the cycle, CO_2 begins from its liquid state at Point 1 where it is pressurized. Then, the compressed liquid is heated to a high temperature (ca. 600 °C). Because the pressure of the compressed CO_2 liquid is greater than the critical pressure of CO_2 ($P_c = 7.3$ MPa), there is no phase change during the heating. The supercritical CO_2 is expanded in an expander, where it creates electricity through shaft work. The expanded CO_2 is in a gas phase at **Point 4**. The LNG provides the necessary energy to cool and liquefy the gaseous CO_2 at **Point 4**.

In the energy system of Fig. 5.6, the LNG is warmed to the desired conditions while the CO_2 is cycled in the loop to create electrical energy. Some amount of fuel

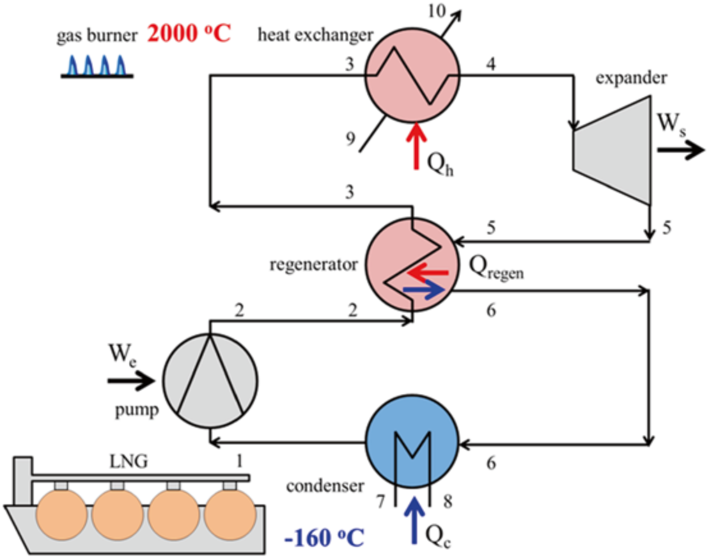


Fig. 5.7 Carbon dioxide energy system for recovering the cryogenic exergy from liquefied natural gas (LNG) transport vessels with a transcritical carbon dioxide cycle with regeneration. The cycle operating conditions are similar to those shown in Fig. 5.6. However, the hot gas exiting from the expander is used to pre-heat the compressed liquid so that heating requirements for the heat exchanger are reduced

must be combusted to generate the high temperature required in the heat exchanger and some amount of electricity must be supplied to the pump for compressing the liquid CO_2. Nevertheless, the overall efficiency of the cycle in Fig. 5.6 is close to 46 % and the efficiency can be improved further by using a technique such as regeneration that is outlined in Fig. 5.7.

Regeneration usually refers to the collection of heat available in a gas stream for reuse in the process. In Fig. 5.7, CO_2 gas exiting from the expander is still very hot (ca. 250 °C) and so this heat can be used to pre-heat the feed to the heat exchanger. By using the available heat, the fuel burned in the gas burner can be reduced so that the efficiency of the process can be increased. Typically by using one or more regenerators, process efficiency can be improved by 5–10 %. For an optimized case that uses high and low pressure expanders with regenerators, a compressor and sea water, efficiencies as high as 59.0 % have been reported for operating conditions at 700 °C (Angelino and Invernizzi 2009).

5.3.6 *Refrigeration*

In refrigeration systems, the cold source of the heat pump is used instead of the hot source. Equation (5.2) can still be used to evaluate the performance of a heat pump refrigerator. However, heat generated by compression of the vapor must now be rejected to the environment. Thus, the heat pump used as a refrigerator has lower performance than when used as a heater. For the most efficient use of energy resources, both the hot and cold sources of the heat pump should be used. For example, the hot source for heating water as in the Eco-Cute hot water heater and the cold source for refrigeration or cooling should be used simultaneously to maximize the efficiency of the input energy.

5.3.7 Geothermal Energy Systems

In geothermal energy systems, heat from the Earth serves as the hot source (Q_h) and the environment serves as the cold source (Q_c). A working fluid is used in a Rankine cycle to generate electricity from geothermal and waste heat (ca. 100 °C) heat. In principle, the process systems look similar to those in Fig. 5.6 with Q_h being the geothermal or waste heat hot source and Q_c being the environmental temperature (this could be that of the air, earth, river or sea). The working fluid can be CO_2 in cases where domestic electrical energy is required, or the working fluid can be an organic solvent for cases where industrial electrical energy is required, sometimes in conjunction with petroleum production.

5.3.8 Ultra-supercritical Steam Generators

Ultra-supercritical (USC) steam cycles operate at much higher temperatures (ca. 700 °C) and pressures (ca. 30 MPa) than those of boiling-water Rankine cycles. The advantage of USC steam cycles compared with boiling-water steam cycles is that USC steam cycles can achieve much higher efficiencies (ca. 50 %) compared with low-pressure Rankine cycles (ca. 30 %). Due to their higher efficiencies, USC steam cycles have lower fuel (coal, biomass) requirements and generate lower amounts of CO_2 compared with low-pressure Rankine cycles. In principle, the process system for a USC steam cycle appears as Fig. 5.6 with Q_h being supplied by coal, fuel oil or biomass and Q_c being supplied by river water or the sea. On a temperature-entropy diagram, the process steps would be represented as shown in Fig. 5.8.

In Fig. 5.8, liquid water at 100 °C (**Point 1**) is compressed to 30 MPa (Point 2). Heating of the compressed liquid from **Point 2** to **3** is by heat exchange with combustion gases from a fuel source such as coal, petroleum or biomass. During the heat exchange process, there is no phase change. Then from **Point 3** to **4**, the stream produces work through a high-pressure expander. The effluent stream is regenerated by contact with exit gases from the supercritical steam generator from **Point 4** to **5**. Then, a low-pressure expander is used to obtain additional work from **Point 5** to **6**. Sea water or river water is used in the condensation step (**Point 6** to **1)** that is necessary to recycle the water. There are some practical considerations for the system regarding materials of construction used at the high-temperature and high-pressure conditions, corrosion, maintenance, and the optimum number of devices. However,

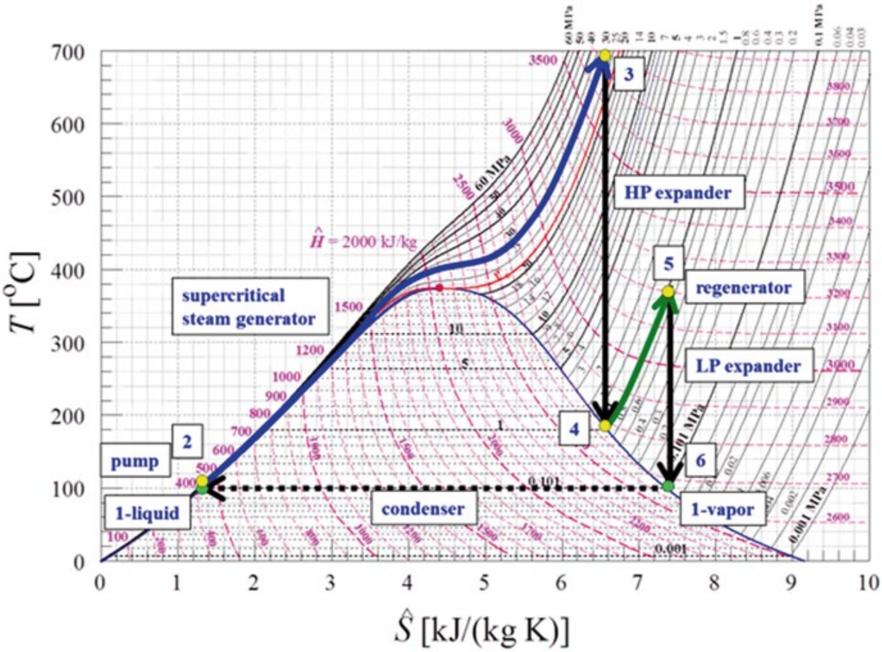
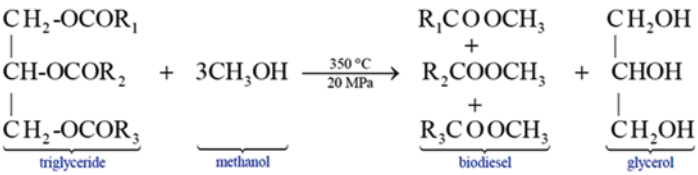


Fig. 5.8 Simplified ultra-supercritical Rankine cycle with regeneration. Components in the system are: *1* pump, *2* steam generator, *3* high-pressure (HP) expander, *4* regenerator, low-pressure (LP) expander and *5* condenser. The expanders and pump are shown as purely isentropic (ΔS=0) expansions and compressions for simplicity

energy systems based on Fig. 5.8. are commercial and are expected to play a major role in the energy picture of Asia in 2035.

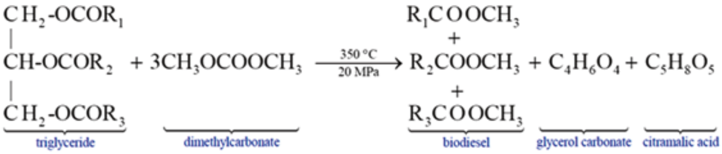
5.3.9 Biofuel Synthesis

Supercritical fluids can be used as reaction solvents for producing biodiesel fuel from oilseed crops. Methanol (Ishikawa and Saka 2001; Minami and Saka 2006), methyl acetate (Saka and Isayama 2009), and dimethyl carbonate (Ilham and Saka 2009), each have distinctive advantages as reaction solvents in their supercritical state. For example, the transesterification of triglycerides with supercritical methanol gives biodiesel and glycerol:



$$\underbrace{\begin{array}{l} CH_2\text{-}OCOR_1 \\ | \\ CH\text{-}OCOR_2 \\ | \\ CH_2\text{-}OCOR_3 \end{array}}_{\text{triglyceride}} + \underbrace{3CH_3OH}_{\text{methanol}} \xrightarrow[20\ \text{MPa}]{350\ °\text{C}} \underbrace{\begin{array}{c} R_1COOCH_3 \\ + \\ R_2COOCH_3 \\ + \\ R_3COOCH_3 \end{array}}_{\text{biodiesel}} + \underbrace{\begin{array}{l} CH_2OH \\ | \\ CHOH \\ | \\ CH_2OH \end{array}}_{\text{glycerol}} \quad (3)$$

In Eq. (5.3), the esters formed from the reaction represent the biodiesel product and the glycerol represents the by-product, which is not always desirable. In the Saka series of methods to synthesize biodiesel, other reaction solvents offer interesting possibilities. For example, when supercritical dimethyl carbonate is used as the solvent, the by-product is glycerol carbonate and citramalic acid, which can be considered to be value-added products:



$$\underbrace{\begin{array}{l} CH_2\text{-}OCOR_1 \\ | \\ CH\text{-}OCOR_2 \\ | \\ CH_2\text{-}OCOR_3 \end{array}}_{\text{triglyceride}} + \underbrace{3CH_3OCOOCH_3}_{\text{dimethylcarbonate}} \xrightarrow[20\,\text{MPa}]{350\,^\circ\text{C}} \underbrace{\begin{array}{c} R_1COOCH_3 \\ + \\ R_2COOCH_3 \\ + \\ R_3COOCH_3 \end{array}}_{\text{biodiesel}} + \underbrace{C_4H_6O_4}_{\text{glycerol carbonate}} + \underbrace{C_5H_8O_5}_{\text{citramalic acid}} \qquad (4)$$

Thus, there are many favorable combinations of supercritical organic solvents that can lead to more desirable chemical products.

Many substances in their supercritical state can act not only as a reaction solvent, but also become part of the product and by-product. Further, in their supercritical state, organic solvents have much more favorable heat and mass transfer characteristics compared with those of a liquid solvent and frequently catalysts are not required.

5.3.10 Biomass Conversion

The Sun is the source of all of our sustainable energy with Earth receiving roughly 100,000 TW (75,320 Gtoe/year) of energy. The Earth's ecosystems only absorb a fraction of this energy with the greatest recoverable amounts being stored in the atmosphere as wind, in terrestrial ecosystems as plants and forests, and in aquatic ecosystems as phytoplankton. Considering our projected energy consumption of 22.2 TW in 2040, harvesting only a small fraction of the available energy would allow the world to eliminate energy poverty and improve human welfare. Developing efficient ways of converting biomass in its various forms are seen as important topics for future sustainable development.

Biomass occurs in many different forms and is diverse, seasonal and unevenly distributed in the world. Biomass has been used extensively throughout history for a multitude of purposes. Most lignocellulosic biomass contains cellulose (ca. 50 %), hemicellulose (ca. 25 %), lignin (ca. 20 %), inorganics (ash, ca. 2 %) and wax (ca. < 1 %). Several strategies exist for converting biomass to chemical products: (i) thermal, (ii) biochemical and (iii) chemical.

Thermal methods use heat to convert biomass to chemical products. *Torrefaction* applies mild heat (ca. 200 °C) to biomass in the absence of oxygen to vaporize light oils and moisture and produces densified material that is suitable for pelleting.

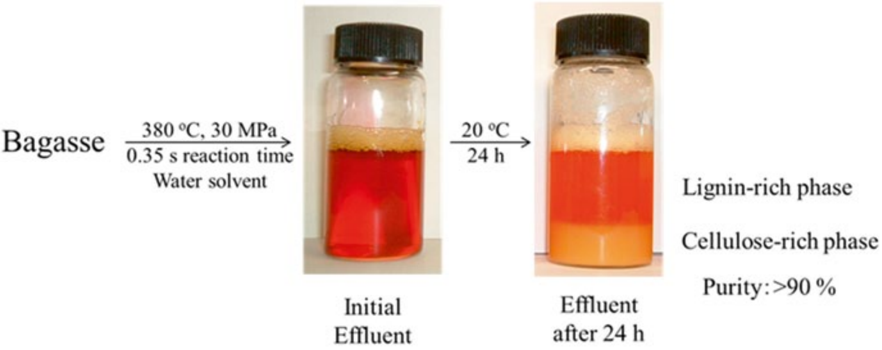


Fig. 5.9 Treatment of bagasse with supercritical water allows separation of the various fractions and and produces a cellulose-rich phase that is high in purity. (Adapted from Arai et al. (2009) with permission Elsevier ©)

Torrefied biomass is also referred to as bio-coal and its pellets are often co-burned with coal to reduce costs and improve environmental aspects. *Pyrolysis* applies moderate heat (300–500 °C) to biomass in the absence of oxygen to produce gases such as hydrogen or methane and solid bio-char. *Gasification* applies high heat (ca. 700 °C) to biomass in the presence of oxygen or water to produce gases such as carbon monoxide, carbon dioxide and hydrogen. The gas mixture, carbon monoxide and hydrogen along with some carbon dioxide is referred to as synthesis gas or *syngas*, since it can be used for synthesis of ammonia or methanol.

Biochemical methods use enzymes or genetic engineering methods to transform biomass into chemical products. For example, fermentation can be used to produce ethanol from grains with yeast. More interestingly, enzymatic transformations of biomass have the possibility of transforming wood into edible starch, which would help solve the world's global food demand (You et al. 2013).

Chemical methods use additional substances and solvents to convert biomass into chemical products. Two methods can be introduced:

(1) water as the solvent with added heat, which is called *hydrothermal;*
(2) ionic liquids with added heat, which is called *solvothermal.*

Hydrothermal methods take advantage of the hydrolytic properties of water with biomass, whereas solvothermal methods take advantage of specific interactions of the solvent with biomass.

In hydrothermal methods, water is heated (100–400 °C) and mixed with biomass to promote reactive separation usually without the addition of other chemicals. When water above its critical point (T_c: 374 °C, P_c: 22.1 MPa) is used and rapidly mixed with biomass, a cellulose-rich phase and a lignin-rich phase (Fig. 5.9.) is formed (Arai et.al. 2009) or if heat is applied in steps then the biomass can be fractionated (Sasaki 2003). Thus, hydrothermal treatment of biomass can provide a method to convert biomass to chemicals or as a pretreatment step in a chemical process.

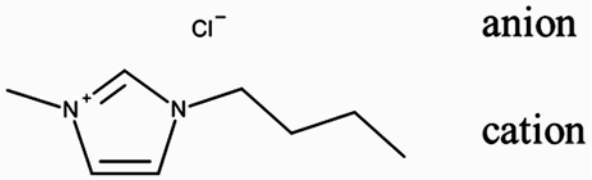


Fig. 5.10 Ionic liquid, 1-butyl-3-methylimidazolium chloride that is referred to as [bmim][Cl]. The *cation* is organic and the *anion* is inorganic. The melting point of [bmim][Cl] is about 69 °C. The chloride anion plays a key role in the ability of the ionic liquid to dissolve biomass

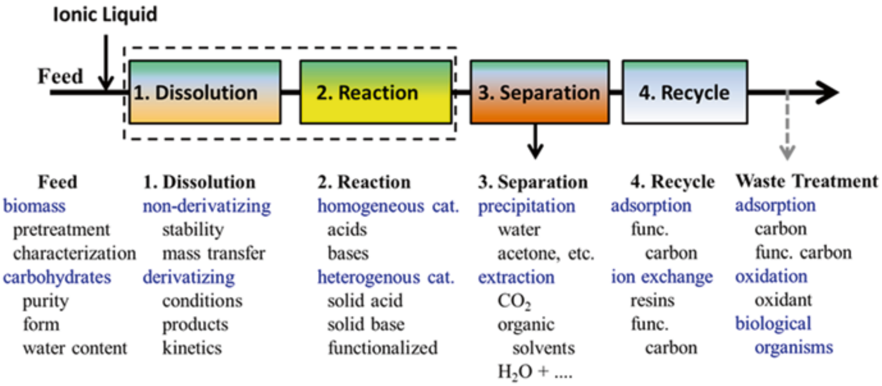


Fig. 5.11 Basic steps for processing biomass with ionic liquids. The feed can be any type of lignocellulosic biomass in practical studies or simple carbohydrates in research studies. The dissolution step and the reaction step (*dashed box*) are sometimes combined. Reaction products can be separated as a precipitate by adding water or an organic solvent

In solvothermal methods that use ionic liquids as solvent, solutions are heated under mild conditions (80–120 °C) to dissolve the biomass, after which there are many possibilities in its processing. In this section, ionic liquids will be introduced as the solvent of interest.

Ionic liquids (ILs) are organic salts that have melting points close to room temperature. Ionic liquids became popular as solvents to study in 2002, when it was discovered that some ionic liquids can dissolve cellulose (Swatloski et al. 2002) and biomass (Fort et al. 2007). An ionic liquid that dissolves both cellulose and biomass is shown in Fig. 5.10.

The basic steps for processing biomass with an ionic liquid are shown in Fig. 5.11. In the dissolution step (1), conditions can be chosen such that the ionic liquid is non-derivatizing or derivatizing. Non-derivatizing conditions are important when it necessary to maintain the polymeric structures of the compounds of the biomass, whereas derivatizing conditions are used when depolymerization is required. In the reaction step (2), homogeneous (liquid) or heterogeneous (solid) catalysts are used to promote formation of the desired products (Guo et al. 2012); these can be carbohydrates such as glucose or commodity chemicals such as biofuels (Fang et al.

2014). In the separation step (3), products are separated from the ionic liquid by adding an additional substance that acts as an anti-solvent. Adding water or acetone to the biomass and ionic liquid solution causes the cellulose fraction to precipitate as amorphous cellulose. In the recycle step, the ionic liquid is purified by washing and extraction. Recovery of the ionic liquid from aqueous streams is a research topic but it can be accomplished by ion exchange resin (Anthony et al. 2001), by adsorption onto activated carbon (Lemus et.al. 2013a, b) or the adsorption of the ionic liquid onto functionalized carbon materials (Qi et al. 2013).

Supercritical fluids play several important roles in the processing of biomass with ionic liquids. Firstly, the viscosity of many ionic liquids that dissolve biomass is high, with viscosity values being 50–300 times higher than water. Dissolution of biomass into the ionic liquid causes the viscosity of the solution to greatly increase. Carbon dioxide, which has low viscosity, has good solubility in many ionic liquids while ionic liquids, do not dissolve into the gas or supercritical phase of CO_2. Thus, CO_2 can act as a viscosity reducing agent for the dissolution and reaction steps in Fig. 5.11. Secondly, if reactions are desirable, CO_2 can act as a mass transfer agent to promote reactant solubility in the ionic liquid phase. A good example is the promotion of hydrogenation reactions by using molecular hydrogen in the ionic liquid phase. Thirdly, many small non-polar molecules are soluble in the supercritical CO_2. Thus, supercritical CO_2 can be used in the separation step of Fig. 5.11 to extract products (Brennecke et al. 2002).

5.4 Conclusions

An overview has been given of energy applications with supercritical fluids. Using fluids in their supercritical state can allow the development of energy-efficient cycles, and robust biofuel syntheses. Supercritical fluids used with ionic liquids show great promise in developing biomass as a sustainable energy resource for chemicals and biofuels.

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Chapter 6
Geothermal Energy

Toshiyuki Hashida

Abstract This chapter focuses on a source of renewable energy which could be very significant in Japan and similar geologically active zones. Geothermal energy has the advantage of heat and electricity with minimal environmental impact. Potentially the available energy exceeds human needs but there remain technical barriers to its economic exploitation on a larger scale away from the most intense sources near tectonic plate boundaries. The role of drilling and fracturing to create Enhanced (engineered) Geothermal Systems (EGS) is described together with the relevant factors for the design of geothermal energy extraction systems. The role of modelling to simulate the effects of fracturing to create flow pathways for heated water is also described.

Keywords Geothermal energy · Hot dry rock · EGS · Hydraulic stimulation

6.1 Geothermal Energy: Current and Future

Geothermal energy exploits the heat from the Earth's crust to generate electricity or provide heat directly e.g. for district heating, hot water, horticulture etc. Ground source heat pumps can also be classified as geothermal energy although not the subject of this chapter. According to the International Energy Agency (IEA 2010a), installed capacity of geothermal energy at the end of 2009 was 10.7 gigawatts (GWe) for electricity generation and 50.6 GWth for direct use as heat. Most recent estimates suggest modest growth in supply, with 11,224 GW of electricity generated in 24 countries in 2012 (GEA 2012).

Currently, geothermal energy is exploited most in the countries shown in Table 6.1. A significant proportion of electricity is generated from geothermal in Iceland (25 %), El Salvador (22 %), Kenya and the Philippines (17 % each), and Costa Rica (13 %). In absolute figures, the United States produces the most geothermal electricity: 16,603 GWh from an installed capacity of 3093 MWe. Japan's geothermal usage is in 8th position globally for electricity and 5th for heat.

T. Hashida (✉)
Fracture and Reliability Research Institute, Tohoku University, Sendai, Japan
e-mail: hashida@rift.mech.tohoku.ac.jp

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Table 6.1 Top 10 Countries using geothermal energy. (IEA 2010a)

Country	Geothermal electricity production GWh/yr	Country	Geothermal direct use GWh/yr
United States	16,603	China	20,932
Philippines	10,311	United States	15,710
Indonesia	9600	Sweden	12,585
Mexico	7047	Turkey	10,247
Italy	5520	Japan	7139
Iceland	4597	Norway	7000
New Zealand	4055	Iceland	6768
Japan	3064	France	3592
Kenya	1430	Germany	3546
El Salvador	1422	Netherlands	2972

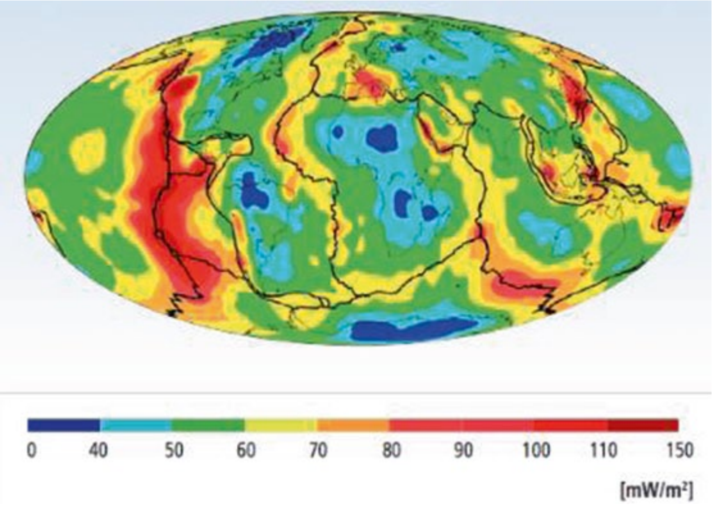

Fig. 6.1 Areas of high geothermal activity due to Tectonic Plate movement. (Source: IPCC 2011)

Geothermal power is potentially cost effective, reliable, sustainable, and environment- friendly but, as can be seen from the location of the main users in Table 6.1, has historically been located at areas near tectonic plate boundaries (Fig. 6.1), where the heat is relatively easy to access—indeed the tradition of hot springs can be traced back thousands of years in some areas.

In recent years, technological advances have dramatically expanded the range and size of potentially viable resources, especially for applications such as home heating, increasing the potential for widespread exploitation. In addition, the technologies of deep drilling and fracturing have improved, and allow the heat present in the crust outside the main plate boundaries to be accessed, thus offering potential

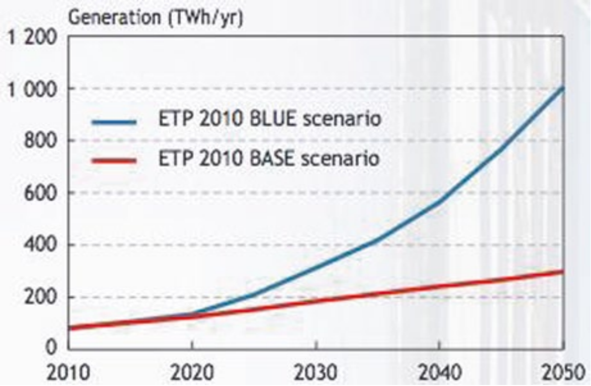

Fig. 6.2 Geothermal energy electricity generation scenarios. (From IEA 2010a)

around the world. These Enhanced (or Engineered) Geothermal Systems (EGS) are the critical foundation for future expansion in geothermal energy.

Regarding future potential, IEA's baseline scenario (IEA 2010b) envisages only modest growth in the role of geothermal energy, suggesting it could provide 1 % (approximately 300 TWh) of global electricity by 2050 (Fig. 6.2). However, if greenhouse gas reduction is afforded the higher priority that would be necessary to meet G8 countries' target of a 50 % reduction in GHG emissions by 2050, geothermal electricity generation could increase up to 1060 TWh/yr by 2050 (the 'blue' scenario in Fig. 6.2). Industry association estimates are that geothermal energy generated electricity and heat will be even higher than the IEA upper estimates.

IEA have compiled a 'Roadmap' for Geothermal (IEA 2011) which indicates a potential to achieve at least a 20-fold increase in global production of heat and electricity from geothermal energy between now and 2050. Through a combination of actions that encourage the development of untapped geothermal resources and new technologies, geothermal energy could then account for around 3.5 % of annual global electricity production and 3.9 % of energy for heat (excluding ground source heat pumps) by 2050.

6.2 Advantages, Disadvantages and Barriers

Some of the pros and cons of geothermal energy are summarized in Table 6.2

A primary advantage is the potential for accessing energy which is currently unused and renewable, since it arises from heat released from the radioactive decay of the Earth's minerals and some residual heat from the original formation of the planet. Contribution to global warming is also low since CO_2 emissions from within geological formations are limited, and most life cycle emissions are those associated with the construction and running of the facility. Life cycle emissions are thus substantially lower than fossil fuels and comparable to solar PV (Table 6.3).

Table 6.2 Advantages and drawbacks in utilizing underground geothermal resources

Advantage	Drawback
Constant and stable	Complexity and heterogeneity
Isolation properties- barriers to gases	Uncertainty and limited information
Renewable and untapped resource	Geological faults (instability, leakage)
Low emissions of greenhouse gases	Cost (construction, maintenance, maintenance of flows)
Safe and secure from threats (terrorism)	Chemical contaminants and scaling

Table 6.3 Life cycle greenhouse gas emissions by electricity source. (Adapted from IPCC 2011)

Electricity generating technology	CO_2 per KWh electricity (mean of available estimates (g))
Hydroelectric	4
Wind (onshore)	12
Nuclear	16
Solar PV	46
Geothermal	45
Natural gas	469
Coal	1001

Further advantages are that geothermal energy provides base load power with no seasonal variation and is not weather dependent. Its resource is also isolated underground which makes it secure and also imparts resilience against earthquakes (as shown in the 2011 Great Eastern Japan earthquake when no geothermal facilities were damaged). In recognition of these advantages, geothermal energy is increasingly included as a desirable renewable energy in some country's renewable energy policies; for instance, it is eligible for Feed-in-tariff (FIT) subsidies in Japan and Germany.

The potential size of the geothermal heat resource can be estimated from the mean temperature depth distribution shown in Fig. 6.3 (Armstead and Tester 1987). The mean surface temperature is 15 ºC, with a thermal gradient of 25 ºC/km near the surface and 11 ºC/km near the 'Moho' where temperature is ~600 ºC at a crustal depth of 35 km (all figures approximate). If we set a maximum depth up to which the underground heat may be extracted (d in Fig. 6.3) as the current depth limit for directional drillings (6 km), the potential geothermal energy resource can then be estimated by calculating the mean crustal temperature up to 6 km, and then calculating the volume that would be required to supply global energy demands. A simple calculation shows that the heat stored in a rock mass of approximately 96 km^2 by 6 km deep is equivalent to the world energy demand forecast for 2030 of 170×10^8 t oil equivalent. We thus see that the potential of geothermal energy is huge and the challenge is to extract it efficiently and economically.

However to realise this large potential, a number of barriers need to be overcome. Those cited by the IEA include public awareness and acceptance, and logistical problems such as insufficient numbers of trained geothermal scientists and engineers. There are also barriers and uncertainties which influence the economics of geothermal energy. In particular these include the rate of failure of drilling to

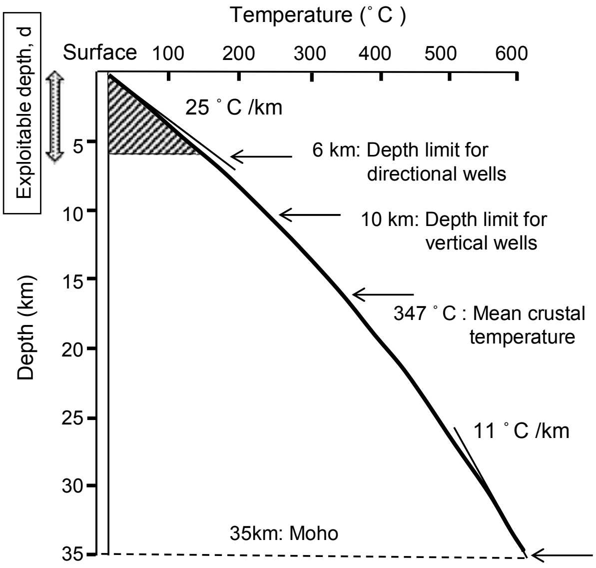

Fig. 6.3 Estimating potential crustal heat resources. (Armstead and Tester 1987)

discover viable reservoirs, which leads to high development costs and risks; another factor is the requirement for deep reservoirs and, even when resources are accessed, insufficient productivity and accessibility in the reservoirs. In addition, maintaining flow rates over time presents many challenges. Moreover, hot water from geothermal sources may hold in solution trace amounts of toxic elements.[1]

A key barrier remains the uncertainty induced by the complex and inhomogeneous nature of rock masses, which imposes a significant challenge to the reliable and extensive use of geothermal resources, and requires the use of EGS, which stimulates subsurface regions where temperatures are high enough to be utilized effectively. A reservoir consisting of a fracture network is created or enhanced to provide well-connected fluid pathways between injection and production wells. Heat is extracted by circulating water through the reservoir in a closed loop (see next section). This chapter thus focuses on potential approaches to reduce this uncertainty and contribute to the development of geothermal energy extraction.

6.3 Exploitation of Geothermal Energy

A general diagram showing the penetration of surface water into zones near hot rocks or magma and its return as hot water is shown in Fig. 6.4 (GEA 2012). Also see the literature (White 1967; White et al. 1971) for detailed discussion regarding the characteristics of geothermal reservoirs. In order to exploit this energy, the three necessary conditions are also shown in the Figure; namely high temperature rock,

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[1] Generally cooled geothermal fluids are re-injected underground which may also stimulate production as a side benefit of reducing this environmental risk.

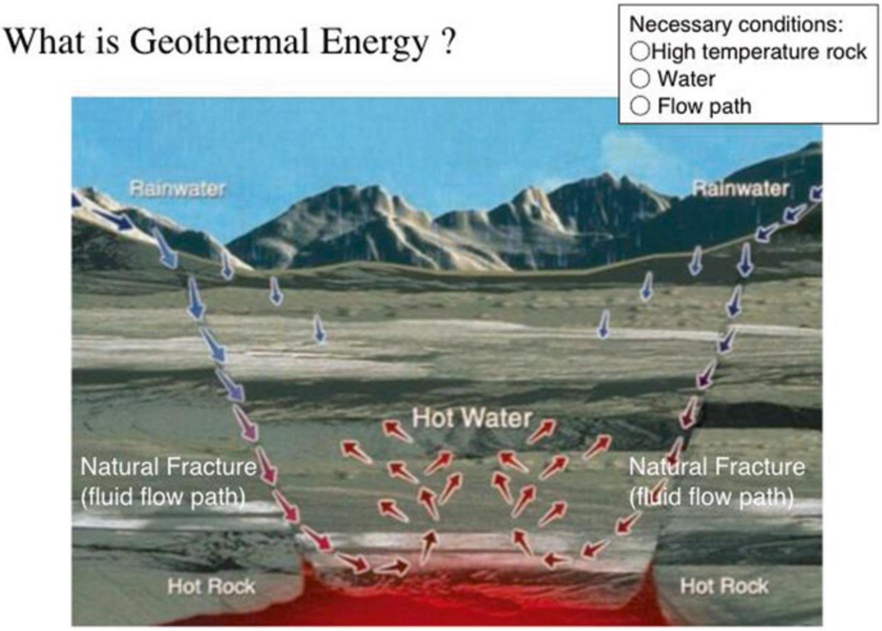


Fig. 6.4 General schematic of geothermal energy reservoir. (Geothermal Energy Association Web site, http://geo-energy.org/basics.aspx)

water which flows from natural sources, and flow paths which allow heated water to flow back through natural fractures.

There are a range of techniques for extracting geothermal energy related to the depths and temperature and nature of the resources involved. Figure 6.5 provides a broad classification of underground heat utilization methods according to their approximate ranges of depth and temperature. The types of underground heat utilized to date include geothermal heat pumps, district heating systems, and steam-based heat and electricity generation systems. Under appropriate conditions, high-, in-

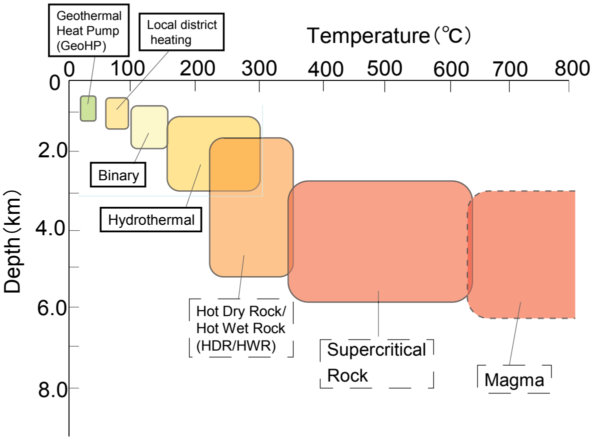


Fig. 6.5 Classification of underground heat utilization methods

termediate- and low-temperature geothermal fields can be utilized for both power generation and the direct use of heat (Tester et al. 2005).

Geothermal heat pumps utilize relatively low and constant temperature ground heat and have been increasingly finding applications as efficient home heating and cooling installations. Hydrothermal power plants are the most typical installation for electricity generation and include two main types: hot water-dominated and steam-dominated systems. The temperature range for the hydrothermal systems is typically 150–300 °C. Binary-cycle power plants may also provide a useful option where low reservoir temperatures (approximately 100–150 °C) are encountered.

Hot dry rocks (HDR) and hot wet rocks (HWR), supercritical rocks and magma energy systems are at the research or development stage. Supercritical rocks refer to high temperature rock masses whose temperature and pressure exceed the critical point of water (374 °C, 22 MPa). In contrast with naturally occurring hydrothermal systems, HDR and HWR refer to geothermal reservoir systems created using artificial methods; these engineered reservoir systems using hydraulic stimulations were first proposed by Tester et al. (1989) and Potter et al. (1974). The aim of geothermal energy extraction using hydraulic stimulations is to mine the heat energy stored in subsurface rocks by creating a system of open, connected fractures through which water can be circulated down injection wells, heated by contact with the rocks, and returned to the surface in production wells to form a closed loop, as illustrated in Fig. 6.6. Following the introduction of HDR, the concept of HWR has been proposed which intends to combine an artificial reservoir system with the existing hydrothermal system (Takahashi and Hashida 1992).

EGS is a newly coined terminology defined as engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources (Fig. 6.6). EGS may refer to geothermal reservoir systems that have been produced by means of artificial and engineering methodologies such as hydraulic stimulation methods in currently non-productive formations and rock masses. In this regard, EGS is an equivalent concept to HWR which aims to improve and enhance the performance of existing reservoirs by use of hydraulic stimulation. HDR may be also included in the EGS concept and in this chapter, the terminology EGS includes both HDR and HWR.

Heat extraction from ultra-high temperature systems such as supercritical rocks and magma may be feasible and attractive in the future, but this chapter focuses on the development of hydrothermal and EGS systems, which are current and near-future heat sources for electricity generation. The reader is referred to Hashida et al. (2000), and Hashida and Takahashi (2003) for the development of supercritical rocks, and Colp (1982), and Teplow et al. (2009) for the exploitation of magma energy.

6.4 EGS Projects

In order to realise the potential of geothermal energy, the 3 pre-requisites already mentioned of high temperature rock, water and flow path are needed. Most current geothermal sources have magma relatively close to the surface and water coming

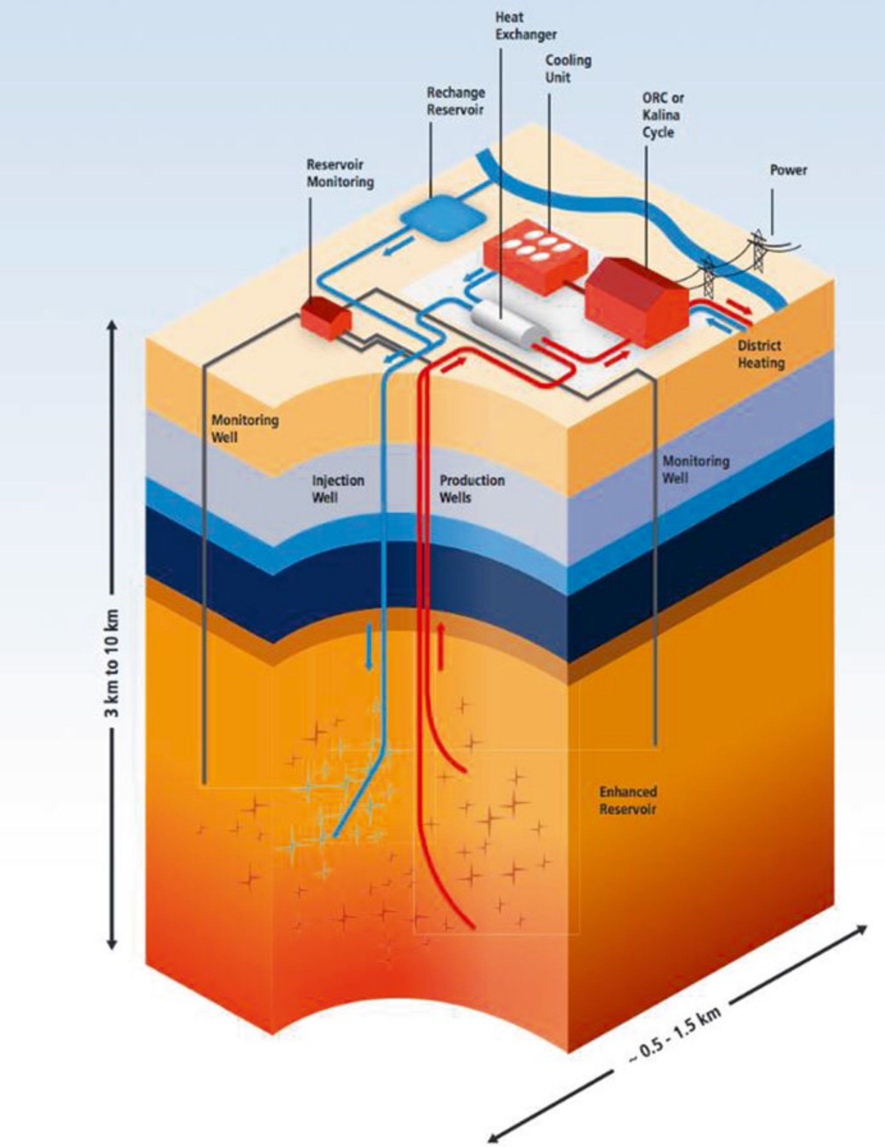


Fig. 6.6 Enhanced or engineered geothermal system (EGS). (Source, IPCC 2011)

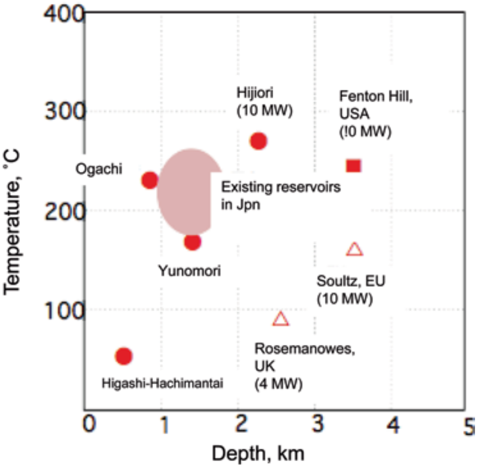
from the surface penetrates to close to the magma area and absorbs the heat. Return flow path is determined by the fractures or faults which exist naturally. When all three conditions are met then a viable extraction is possible, but in many cases all three conditions are not all met at the same time.

Reservoir engineering is designed to determine the volume of geothermal resources and the appropriate plant design for sustainable use and safe and efficient operation. Where flows are inadequate, this may require the creation of an artificial or engineered geothermal energy system of which a critical part is hydraulic fracturing or stimulation. The modern method of estimating reserves and sizing power plants is to apply reservoir simulation technology. A conceptual model is built using available data, it is then translated into a numerical representation, and calibrated to the unexploited, initial thermodynamic state of the reservoir (Grant et al. 1982). Critical parts of the overall reservoir simulation are to model the effects of fracturing in the EGS, to predict the effects of such stimulation and design optimum strategies for the EGS.

Knowledge of temperature at drillable depth is a prerequisite for site selection for any EGS development. The thermo-mechanical signature of the lithosphere and crust are equally important as they provide critical constraints affecting the crustal stress field, heat flow and temperature gradients. Many rocks will already contain natural fractures in the rock mass, and it is imperative to assess their distribution (hole drilling will reveal some of the existing rock characteristics including naturally occurring fractures) which can then inform the design of the fracturing stimulation. Modelling and simulation may play a role and, for the development of mass transport modelling, an artificial geothermal system can be modelled where a reservoir is artificially created by hydraulic stimulation and the fractures connected with two drilled boreholes. Circulation using the reservoir is then performed by injecting cold water into the injection well and recovering it through the production well.

A number of research projects on HDR/HWR have been performed internationally at sites of several countries with various temperatures, depths and locations (Fig. 6.7).

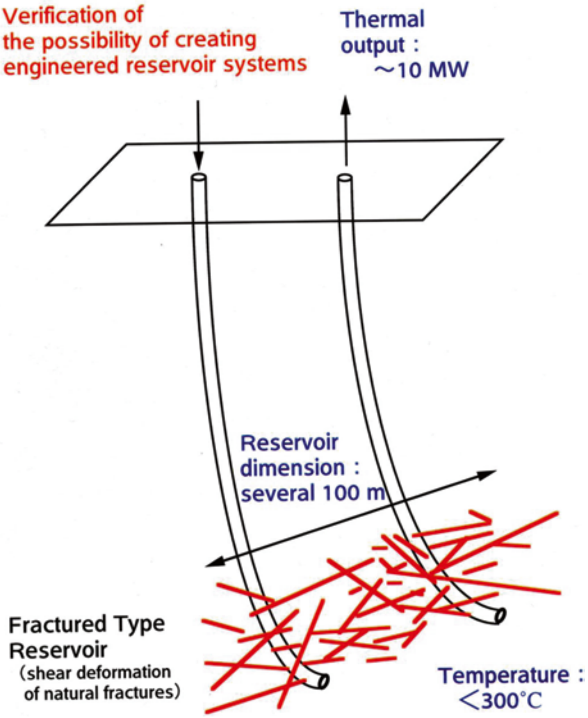
Fig. 6.7 HDR/HWR projects conducted to date



The key challenge for EGS is to stimulate and maintain multiple reservoirs with sufficient volumes to sustain long-term production at acceptable rates and flow impedances, while managing water losses and risk from induced seismicity (Tester et al. 2006). Conventional geothermal resources currently used to produce electricity are either high-temperature systems (>180 ºC), using steam power cycles (either flash or dry steam driving condensing turbines), or low to intermediate temperature (<180 ºC) using binary-cycle power plants. All projects in Fig. 6.7 have succeeded in creating artificial fracturing, and have demonstrated that it is possible to create such an artificial water circulation system in rock masses, with the remaining task to design the reservoir and to predict long-term performance.

Included in these projects is the Hijiori experiment in Japan funded by Japan's New Energy and Development Organization (NEDO). The Japanese work at the Hijiori (10 MW) site has involved EGS using stimulation of subsurface regions where temperatures are high enough for effective utilization. These experiments have successfully generated a reservoir of several 100 m diameter with a thermal output of up to 10 MW. Rock temperatures were generally below 300 and this has allowed the possibility of creating fractured reservoirs to be verified. In these projects, a reservoir consisting of a fracture network is created or enhanced to provide well-connected fluid pathways between injection and production wells (see Fig. 6.8). Heat is ex-

Fig. 6.8 Achievements of the HDR/HWR projects



tracted by circulating water through the reservoir in a closed loop and can be used for power generation with binary-cycle plants and for industrial or residential heating.

These experiments have proved the technical viability of the EGS approach, and confirm that knowledge of temperature at drillable depth is a prerequisite for site selection in any EGS development. The challenge remains to develop methodologies to simulate and design viable economic systems. In this respect, one relevant project being carried out at Tohoku University is the numerical simulator FRACSIM 3-D as one of recently developed analogue and numerical models which provide insights useful for geothermal exploration and production (Watanabe and Takahashi (1995); Willis-Richards et al. (1996); Jing et al. (2000); Jing et al. (2014)). Taking account of fracture distributions, the permeability of the rock before and after fracturing can be simulated. This has been applied to the long-term circulation and heat extraction experiment at Hijori, Japan.

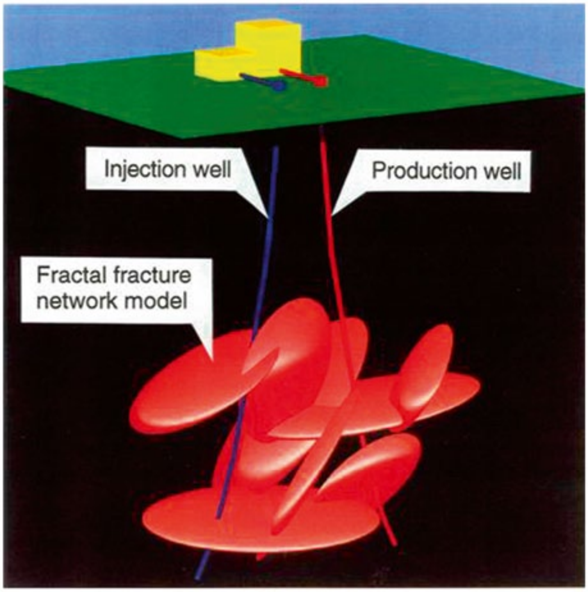
6.5 EGS Modelling

The HDR/HWR projects shown in Fig. 6.7 have confirmed that one of the crucial pre-requisites is to form an extensive fracture network sufficient for sustainable heat extraction. For the formation of EGS, as mentioned previously, it is required to stimulate and maintain multiple reservoirs with sufficient volumes to sustain long-term production at acceptable rates: in other words to establish and maintain the water supply and viable flow paths from the high-temperature rock. A small number of multiple fractures may only result in an early thermal drawdown due to the limited area of heat exchanging surface (hydraulically induced fracture surface). The majority of the rock mass types encountered and/or selected for the sites of the HDR/HWR projects included a number of naturally occurring fractures. Furthermore, hydraulic stimulations conducted have been shown to induce primarily shear dilation (aperture increase due to slip deformation along the natural fracture) rather than formation of new fractures. Thus, based on the experience obtained from the HDR/HWR projects, it appears to be a viable approach to utilize and stimulate a natural fracture system in order to create a water circulation loop with sufficiently high permeability for geothermal energy extraction.

The above-mentioned observation underlines the importance of characterizing and modelling the distribution of natural fractures and their mechanical response for the design of engineered geothermal reservoirs. Figure 6.9 shows a schematic of the fracture network model employed for the development of FRACSIM-3D. FRACSIM 3-D takes into account the complexity of natural fractures, and utilizes the phenomenon of fractal geometry (because most fractures exhibit the characteristics of fractals) to simulate the reservoirs shown in red in Fig. 6.9. In FRACSIM-3D, the reservoir is assumed to consist of a number of circular cracks whose length distribution follows the fractal geometry.

As illustrated in Fig. 6.10, FRACSIM-3D firstly generates a natural fracture network based on the fractal characteristics, which can be obtained from surface observations. Observation of cores and well logs may be used to determine the number

Fig. 6.9 Fundamental design methodology for extraction of geothermal energy



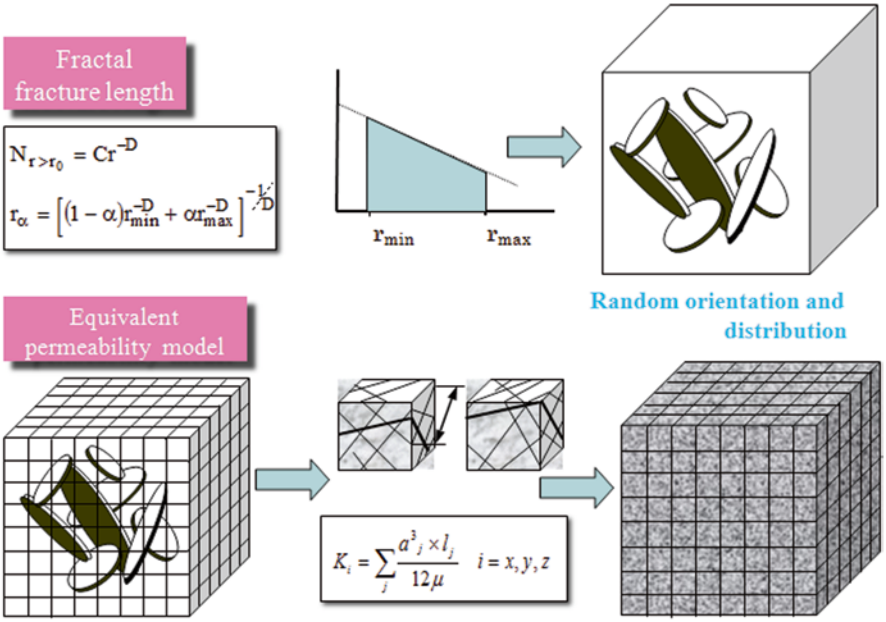


Fig. 6.10 Numerical simulation concept: FRACSIM-3D

of the fractures to be generated in the calculation volume. To conduct fluid flow analysis for hydraulic stimulation and to determine the water pressure within the fractures, the generated fractal fracture network is mapped on a regular cubical grid. Then the equivalent permeability of each block is calculated, based on the sum of the products of the fracture apertures to the 3rd power and length of the intersection of the fracture with the block face. The flow analysis is performed assuming that the calculated permeability controls the fluid flow rate from one block to another block. In FRACSIM-3D, shear dilation mechanism for fracture opening is accounted for, in addition to jacking mechanisms. The fractal nature of the fracture surface roughness is also taken into account in order to predict the shear dilation of fractures. This grid model with a spatial distribution of equivalent permeability is employed to perform numerical computations for mass and heat transfer and to simulate the artificial reservoir formation by hydraulic stimulation and subsequent heat extraction through the man-made water circulation loop in the reservoir. The model can also

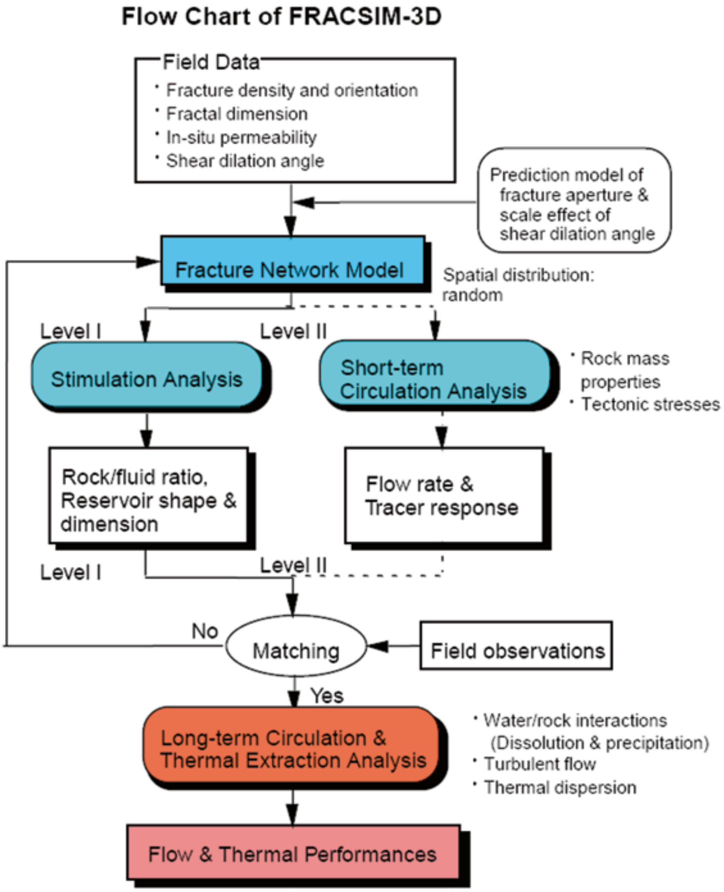


Fig. 6.11 Design methodology for engineered geothermal reservoirs

be utilized to simulate tracer tests. The numerical model for tracer analysis assumes that the migration of tracer species (particles) is dictated by a flow-dependent probability in each grid. The probability of tracer migration for a given orientation is obtained by dividing the flow rate in the direction with the total flow rate for the grid.

Based on the field experience and the development of numerical simulation code, we have elaborated the flow chart for the procedure of FRACSIM-3D shown in Fig. 6.11. Based on field data such as fracture density (number), orientation, and fractal dimension of fracture size, natural fracture networks are generated within a cubic fracture generation volume assuming its spatially random distribution. Field information such as fracture density and orientation can be obtained from the observation of cores and well logs.

It is crucially important to make a good estimate of the initial fracture aperture and shear dilation angle for the fractures having different dimensions in the generated fracture network. A predictive model for fracture aperture and shear dilation angle has been incorporated into FRACSIM-3D. The model predicts the initial fracture aperture based on initial permeability data to be measured in a borehole, and the shear dilation angle of each fracture is estimated numerically on the basis of the fractal nature of the fracture surface.

Because the distribution of natural fractures is a stochastic characteristic, it is not technically feasible to determine *a priori* size and spatial location of each natural fracture in the fracture network generated using the fractal model. Thus, we have proposed a method for determining the natural fracture distribution by comparing numerical predictions with field observations. Specifically, a number of natural fracture networks are generated using random seeds (say 50 realizations in the example to be described below).

First, based on the natural fracture networks generated, we carry out a hydraulic stimulation analysis to compare the numerical outputs with field observations. The field data to be used for this comparison are rock to fluid ratio (RFR), and shape and dimension of the created reservoir. The RFR parameter is a measure of the amount of fracture void space created during hydraulic stimulation, which can be computed from the rock volume stimulated and the injected fluid volume. The stimulated rock volume, and the shape and dimension of the created reservoir may be estimated using field date obtained from microseismic methods. This evaluation step is labeled as Level I. If preliminary and short-term water injection test results such as impedance and tracer responses are available for the site, short-term circulation analyses may be further performed. Flow rates and tracer responses between injection and production wells may be used to compare the numerical outputs with field observations. This assessment stage is denoted as Level II.

This process is repeated for all natural fracture networks prepared, and the fracture model that matches best with the field observations is then selected. An analysis of long-term water circulation is subsequently carried out to predict the thermal extraction performance of the created reservoir, based on the selected best fracture network model for a pair of injection and production wells. Thermal drawdown (time history of water temperature at the production well) can be calculated for the

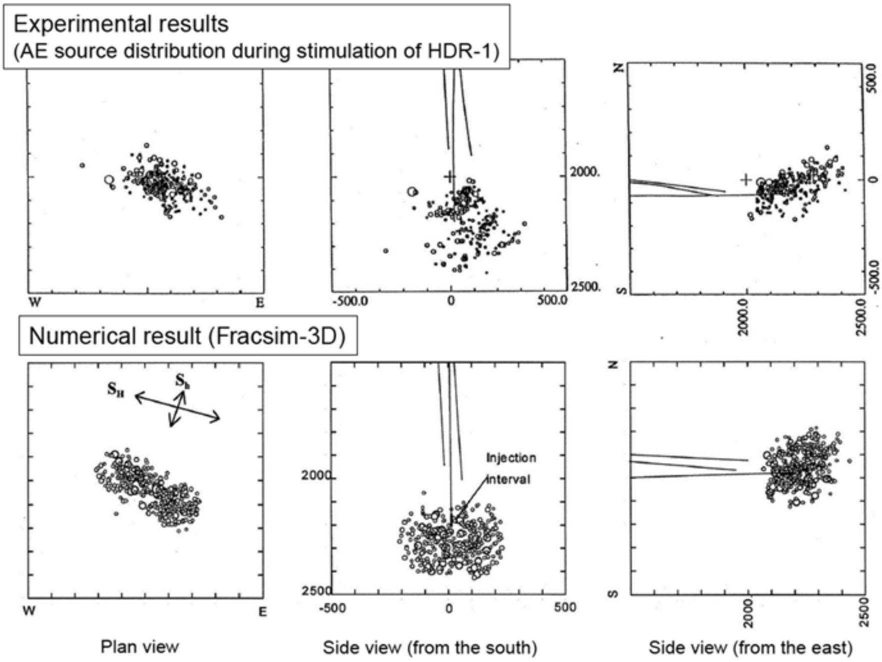


Fig. 6.12 Application of FRACSIM-3D to Hijiori

given circulation conditions such as injection pressure. The numerical result may be utilized to design the operating conditions such as injection rate and pressure for sustainable heat extraction.

The evaluation procedure in Fig. 6.11 has been applied to the Hijiori field experiment (Kuriyagawa and Tenma 1999). The experimental HDR system created at Hijiori comprised an artificial reservoir formed by hydraulic stimulation at a depth of ~2200 m and a water circulation test was performed for 1 year. The results are shown in Fig. 6.12 where the upper row of 3 figures are the experimental results of hydraulic stimulation from 3 directions of view (circles indicate seismic events detected during the hydraulic stimulation process). The lower row of figures gives the simulated results based on the selected best fracture network (circles give the location of the circular fractures whose aperture was increased due to the hydraulic stimulation in the numerical simulation).

In this experiment, 50 natural fracture networks were generated using random seeds and the best fracture network was identified according to the procedure of Level I and II as shown in Fig. 6.11. It appears that the numerical results correspond well with the field data in terms of the shape and dimension of the reservoir created. In particular, the numerical model FRACSIM-3D reproduces the downward migration of the created reservoir as indicated by the experimental results. This comparison may also support the validity of the numerical model.

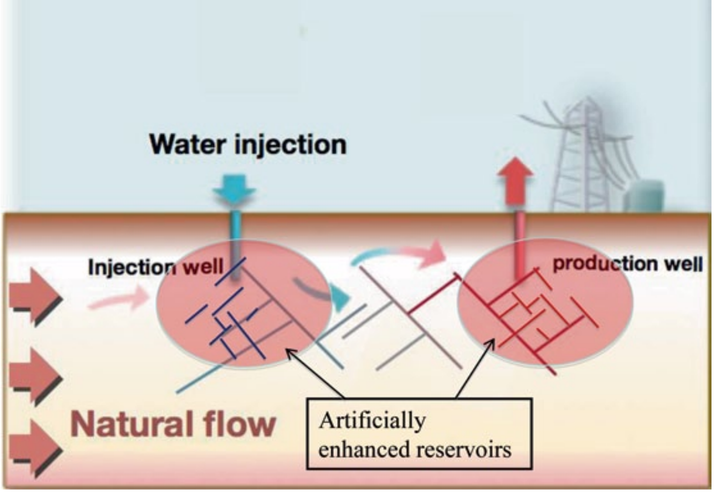


Fig. 6.13 Upstream hydraulic stimulation

Furthermore, it has been demonstrated that the predicted thermal drawdown compared well with the field data from a 1-year circulation test conducted at the Hijiori site.

6.6 Reinjection for Enhancement of Existing Hydrothermal Reservoirs

One remaining area of research is the serious global issue of declining heat production from existing geothermal reservoirs. At the same time, geothermal energy facilities are faced with the challenge of disposing of extractive water after its heat has been used for electricity generation or local heating. Such water can be contaminated with various minerals making their discharge to surface waters an environmental issue. For this reason many administrations have required by law that an injection well must be produced to provide a return path for extracted water, as illustrated in Fig. 6.13.

However there are concerns about the potential cooling effects of re-injected water on the reservoir, since discharged water is generally after passage through the power plant cooling tower, and therefore quite low temperature. For this reason, many geothermal facilities inject the extracted water *downstream* of the reservoir. This avoids the danger of too much cooling in the reservoir but this may lead to inadequate water flows. We thus briefly consider this issue.

The reservoir system with reinjection shown in Fig. 6.13 can be considered as analogous to the artificial water circulation system illustrated in Fig. 6.6. For existing hydrothermal systems, it is thus proposed to utilize the reinjection in order to establish a water circulation loop just like the borehole systems connected with a fractured reservoir created by hydraulic stimulation. The implementation of reinjection should be useful to mitigate and reduce declining heat production in the hydrothermal system provided that the conditions of reinjection (such as temperature and flow rate) and its location are properly designed with respect to the heat extraction rate. The simulation code, FRACSIM-3D as described previously may offer a useful tool for the design of such reinjection strategies.

In addition to numerical simulation code, a mathematical model based on fractional derivatives has been investigated in order to characterize subsurface mass and fluid flow in inhomogeneous and complex rock masses (Fomin et al. 2005, 2011). Numerical flow models which explicitly account for heterogeneities such as natural fractures often require detailed knowledge of the subsurface structure and/or systematic data sets of field flow testing in order to determine the spatial distribution of heterogeneities. Execution of numerical simulations based on such a flow model also requires relatively large computer capacity and long computation times. The fractional derivatives based mathematical model is expected to provide a simple and useful tool to analyze the mass and heat transport in complex reservoir systems.

It is often pointed out that the flow behaviour in the vicinity of wellbores dominates the overall flow impedance of the hydrothermal system because of its concentrated and high flow rate. Mineral depositions and plugging may be anticipated to take place along the flow path at wellbores, reducing permeability. Thus, an improvement in permeability near the wellbore is expected to enhance greatly the fluid conductance of the reservoir. Hydraulic stimulation of wellbores may provide a very effective approach for this purpose. The operation of hydraulic stimulation is expected to increase the aperture of pre-existing fractures intersecting the wellbore and to connect the wellbore with isolated natural fractures, leading to enhanced water permeability in the vicinity of the wellbore. Hydraulic stimulation may be useful not only for the stimulation of production wells, but also in reinjection wells. Thus, the technology developed for creating man-made reservoir systems and relevant numerical simulation models can be utilized to combine the existing reservoir with an artificial fracture system in order to mitigate the decline in the heat production. This strategy would reduce the uncertainty associated with the development of many geothermal energy extraction systems.

6.7 Conclusion

It has been said that the underground (or ‘inner space’) just below us is less studied than the universe. One of the primary reasons for this may be its uncertainty due to the complexity of the subsurface structure including the complicated distribution of natural fractures. Nonetheless the underground provides a safe and resilient space for energy systems which can be truly harmonized with the environment. This chapter describes a methodology for the development of geothermal energy extraction with a special focus on designs for engineered geothermal reservoirs. It is emphasized that the engineering methodology enables artificial reservoir systems to be created in the subsurface structure. A numerical simulation model which expresses the complex distribution of natural fractures on the basis of fractal geometry has been introduced and applied to field experiment with the objective of developing a quantitative basis for designing geothermal reservoirs in the complex natural system. It is also proposed that this engineering methodology could also be applied in order to tackle the common issue of the declining heat production in existing reservoirs.

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Chapter 7
Technology Development Towards Localised Small-scale Electricity Generation and Its Use in Smart Buildings

Yasumitsu Tanaka and Kazuyuki Tohji

Abstract Technological development is required for systems which will allow current centralised energy systems to be replaced by more dispersed and multiple low-energy sources. Such a system poses challenges both in maximising possible sources of small energy and also in developing the batteries necessary to deal with their intermittent supply. This chapter describes development of systems which run on limited sources of DC energy, and the interaction between the supply sources and the batteries to provide systems which are resilient to blackouts from natural disasters. It also describes work at Tohoku University on micro-scale generation from activities in everyday life and the first stages towards harnessing local marine energy and biomass sources. This development was tested by the disaster of the Great East Japan Earthquake and Tsunami on March 11, 2011 after which a black out and complete cessation of utilities lasted from a few days to several weeks, emphasising the critical importance of resilient energy sources.

Keywords DC/AC hybrid · Smart building · Energy management system · Local generation · Small energy · Renewable energy · Secondary battery

7.1 Introduction

Most of the chapters in this book present the results of basic research related to specific environmental or resource-related problems. However, in order to contribute to a more sustainable society, we need to apply this knowledge in a way that society can utilise- in particular to find alternatives to the current dependence on centralised

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Y. Tanaka (✉) · K. Tohji
Graduate School of Environmental Studies, Tohoku University, Sendai, Japan
e-mail: tanaka@mail.kankyo.tohoku.ac.jp

K. Tohji
e-mail: tohjik@mail.kankyo.tohoku.ac.jp

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large-scale fossil fuel electricity generation distributed via a large capacity grid. Not only does this system lock us in to fossil fuels such as coal, oil and gas, but major efficiency losses are also suffered in transmission (Hawken et al. 1999). This chapter focuses on technology demonstration projects carried out at the Graduate School aimed at improving the efficiency with which we can use local and small-scale sources of renewable energy.

There are two main strands to this work. The first is to improve the efficiency with which electricity is used in 'smart houses' where PV solar or other local sources of direct current (DC) electricity are generated. Normally, such DC generation is converted to alternating current (AC) before being included in houses' circuits; this involves a loss of energy in conversion of ~ 10 %. The Graduate School main building and the adjoining 'Ecollab.' (an abbreviation of ecology, collaboration and laboratory. GSES 2011) smart house are testing systems for high voltage DC lighting and other DC services, together with the necessary circuit and battery storage designs. The second strand to this development is to explore possible micro sources of electricity through everyday activities, and local as yet untapped sources of renewable energy in the 'Next Generation Energy for Tohoku Recovery (NET)' project. In this chapter we will provide a brief overview of both projects and their results.

7.2 DC/AC Hybrid Control Systems for a Smart Building

7.2.1 Concept

There are many visions of a more sustainable low-carbon society (e.g. MOE 2007) where domestic electricity is provided, not by large centralised power stations burning fossil fuel, but by local dispersed sources of solar PV, wind or other renewable sources. Such sources are however intermittent and their power density relatively low, so that particular challenges exist in both maximising efficiency of use and in smoothing over the inevitable peaks and troughs in local generation. Provision also needs to be retained for access to the main grid to meet demands when local supplies are insufficient. In addition, following the Great East Japan Earthquake and Tsunami when existing power supplies were lost over wide areas for several days, there has been much interest also in local sources of supply which are more resilient and resistant to disasters.

Current power systems treat renewable energy as load variations on the basic supply grid and do not allow for the large-scale introduction of renewable energy; thus new systems based on applying IT to allow local management of energy supply use and optimisation, and which can operate on their own during times of emergency are required. The Graduate School was thus awarded a grant in 2011 from the Ministry of Economy, Trade and Industry New Industries Creative Technology Development Program (creation of new industries through IT fusion) to work with industry to develop a new system for 'smart' buildings. This has the aim of developing technology that will help realize a smart community network, and to provide various next-generation services, such as visualized portal sites, car sharing services and energy accommodation between buildings (GSES 2012).

The system developed for local production and consumption of renewable energy, uses a combination of solar power and large lithium-ion secondary batteries, and is supported by the standard commercial power supply to meet demand which exceeds the local supply (Fig. 7.1). This is combined with DC-driven LED lighting, which is supplied directly from the PV solar supply, thus improving the power utilization efficiency. Furthermore, in the rooms supplied by DC, we are able to explore the optimum configurations for an energy-saving environment, through combinations of DC and AC power with digital household appliances. By using IT, we have also developed control systems to automatically deal with DC and AC load variations. This system has the additional critical advantage that it can use both accumulated electricity and renewable energy during disasters and emergencies to ensure stability in supply for as long as possible. The system also has resilience because, even after the energy has been completely consumed, the IT system automatically restores each part of the system when renewable energy is restored.

7.2.2 Renewable Energy Supply

The basic renewable supply is a 392 m^2 area of solar panels on the building roof which provides a maximum of 60 kW output providing a DC 300 V supply. The specifications of this solar panel are the followings. This photovoltaic system provides electricity to the main building of the Graduate School through the lithium ion secondary batteries, and reduces the need for commercial power by around at least 10 % on the annual average consumption.

7.2.3 Battery Storage and Management

This is a large-scale power storage system of approximately 50 kWh that efficiently stores power generated in the solar power system. It serves to reuse all outlets (except those used for connecting experimental equipment) by the DC 300 V wiring used in the building. LED lights installed in the main building can be powered without DC/AC and AC/DC conversion losses. The selected battery was an olivine-type iron phosphate lithium ion battery connected with 240 sheets in 30 columns comprising a photovoltaic solar cell with a maximum output of 250 W. Specifications are in Table 7.1 and the system was one of the first mass-produced secondary battery cells and packs for sale to the public. We use 1.2 kWh modules and this stationary power storage system is characterized by its long life and high safety, making it ideal for a large-scale power storage system. It has a quick charge and discharge performance and can charge over 90 % of its capacity in 1 h. It also has the resource efficiency advantage of using iron instead of rare metals for its electrodes.

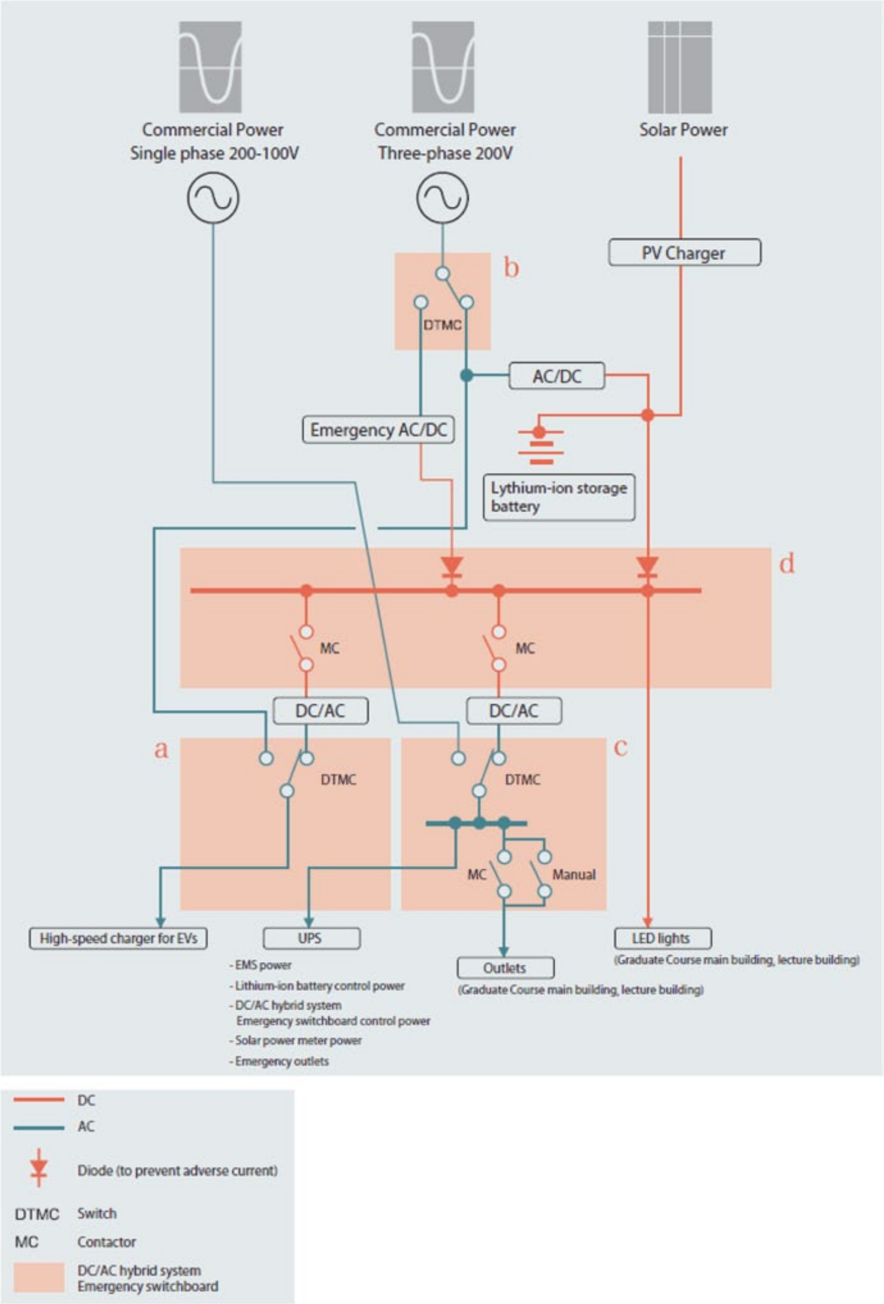


Fig. 7.1 Conceptual diagram of Hybrid DC/AC System. (GSES 2012)

Table 7.1 Battery specifications

Battery type	Lithium ion secondary battery
Storage capacity	57.6 kWh (8 units of 7.2 kWh)
Rated input	PV48 kW, AC48 kW
Rated output	48 kW
Rated voltage	307.2 V

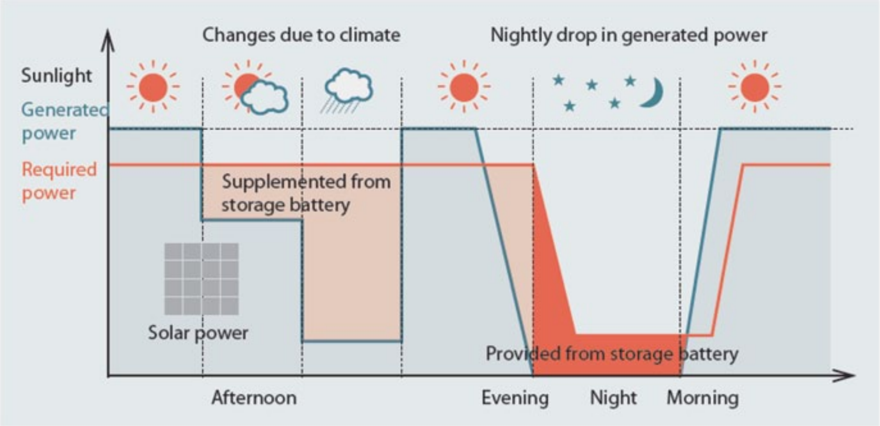


Fig. 7.2 Daily adjustments of flows to and from the batteries to stabilize power provision. (GSES 2012)

In the above configuration, we have applied current technology to connect small sources of renewable energy with a secondary battery system, as well as the effective fusion/collaboration between locally- produced household energy creation and the usage of public commercial sources of electricity. The system also needs to include balancing controls to reflect the fluctuations in power supply depending on the time of day, season and weather. When the weather is poor and not enough solar power is generated for consumption, the shortfall can be compensated for by electricity supplied from the storage battery to stabilize power provision. Power can also be provided from the lithium-ion storage batteries for a certain amount of time at night or during power failure. An illustration of the daily fluctuations and adjustment of the power flow to and from the batteries is in Fig. 7.2.

7.2.4 DC Circuitry and Lighting

When the usual household electrical system is considered, there are many cases where the AC of the supply has to be converted to DC in order to use the electricity—typical examples being mobile devices, computers, and some digital TVs. Thus if we are considering the original source starting as DC, the traditional system wastes energy on 2 conversions—first from the DC supply from the PV solar to the

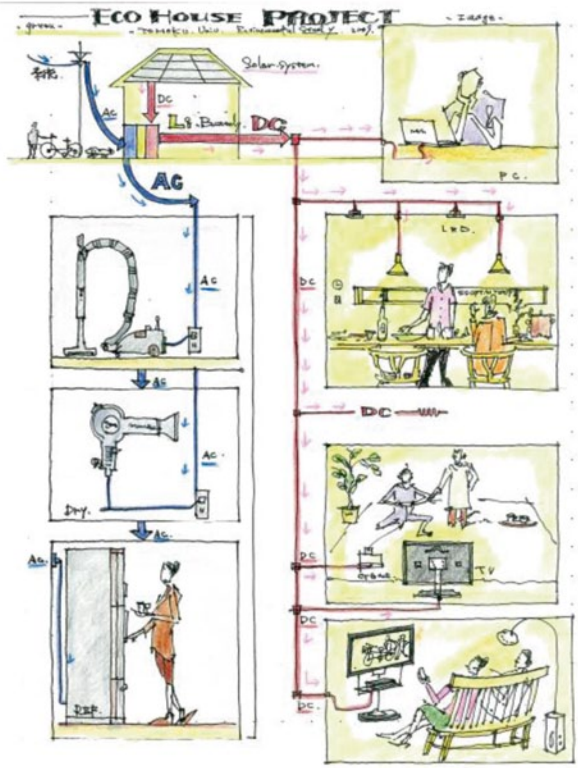


Fig. 7.3 Vision of dual (AC and DC) supply to household and uses. (GSES 2012)

AC grid, and then secondly from the AC grid through the transformer to the DC-using device. By maximising the usages of electricity in DC form, and providing that direct from the renewable energy DC supply, two conversion inefficiencies can be removed. To expand the usage of DC, an internal lighting system has been installed using a 300 V system connected with LED lights. Where lower DC voltage is required this can be converted from DC 300 V to the appropriate voltage (for example such as DC 24 V, DC 12 V, DC 5 V) by a DC/DC converter. By using high-voltage DC supply, which supplies power with minimal energy conversion, energy use is made highly efficient. For universities and office buildings, high voltage would be advantageous. However, the home allows selection of the appropriate voltage. Currently, solar panels are installed in houses; they can easily generate DC power at home using solar power (sunshine). In addition, the home has many electronics goods operating by DC. (Ex. Computer, Audio, TV, LED lighting, mobile electronics, wearable electronics, etc.) It is not necessary to use centralized power generation which burns fossil fuels or nuclear power that requires transmission lines. Power generation is possible in the home by small, distributed generators using natural energy. The current situation is no longer the same as in the late 1880s "War of Currents". Both DC (made in the home) or AC (purchased from the power company) can be used as illustrated in Fig. 7.3.

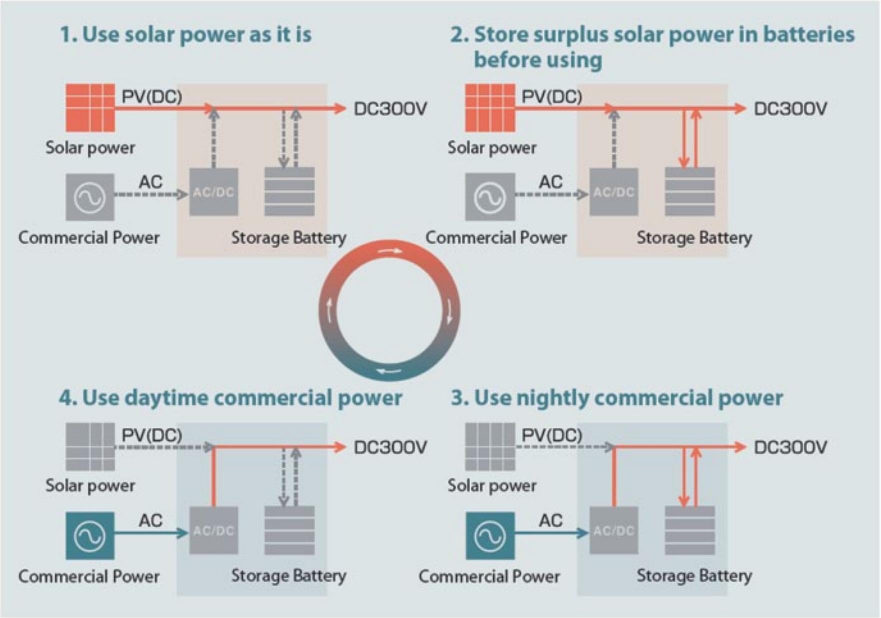


Fig. 7.4 Energy Options and control. (GSES 2012)

7.2.5 *Energy Management System (EMS) and Visualisation*

The basic principle of the energy management system is shown in Fig. 7.4, whereby the ideal balance is set between available renewable energy and back up commercial power.

The energy supply and consumption and other basic information on the system is collected and processed via the EMS. The basic data collected and analyses conducted are shown in Fig. 7.5 and a reproduction of the actual display examples in Fig. 7.6. By visualizing the flow of electricity in real-time and by using animations, it is possible to provide an intuitive understanding of the situation, and by providing energy-saving advice for the situation depicted on the same screen, it is possible to encourage appropriate energy saving action. Consumption and results of energy-saving activities, and energy saving ratios for each floor are calculated, compared and displayed, thus raising energy-saving awareness.

7.2.6 *Smart Building and Energy System Aspects*

The actual schematic of the main building and the associated additional services such as a charging point for an electric vehicle are shown in Fig. 7.7. The concept is to use both AC power supply from the public grid and local DC power supply of natural energy. Both the commercial electricity and renewable energy can be used independently; moreover energy can be saved by a combination of IT and the DC

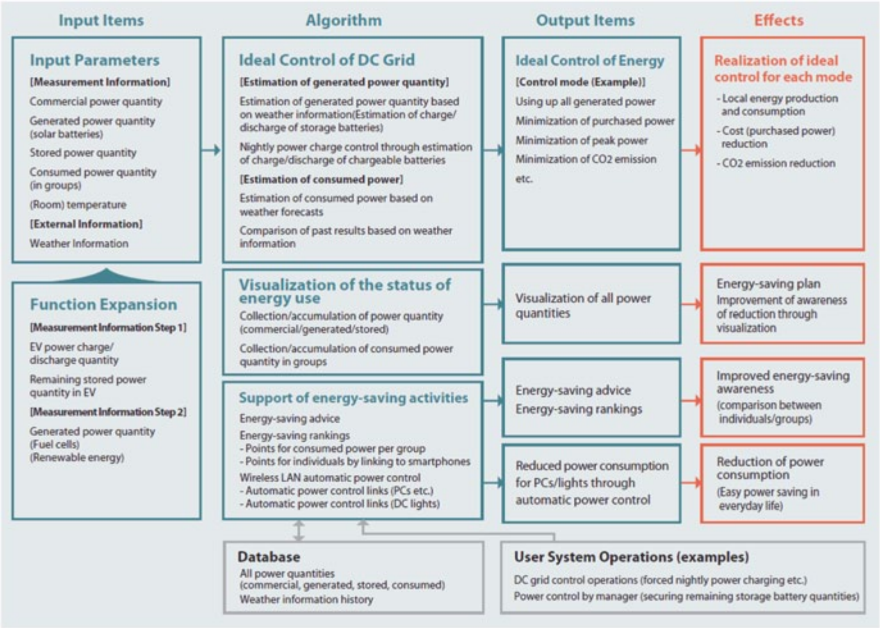


Fig. 7.5 Basic data collected and analyses. (GSES 2012)

Fig. 7.6 Examples of visualisations from the EMS. (GSES 2012)

power supply. The system can also support the IT function automatically to stabilise the AC load and DC load variations. In addition, in case of emergency or disaster, a minimum level of supply can be provided through a combination of renewable energy and power storage.

In addition, developing this system provides the following features;

- Enhancement of IT functions by various sensors and control software.
- Real-time control technology and load change prediction of electrical energy generation due to climate change.
- Device development and system development on the use of high-voltage direct current technology to take advantage of the large DC power source.

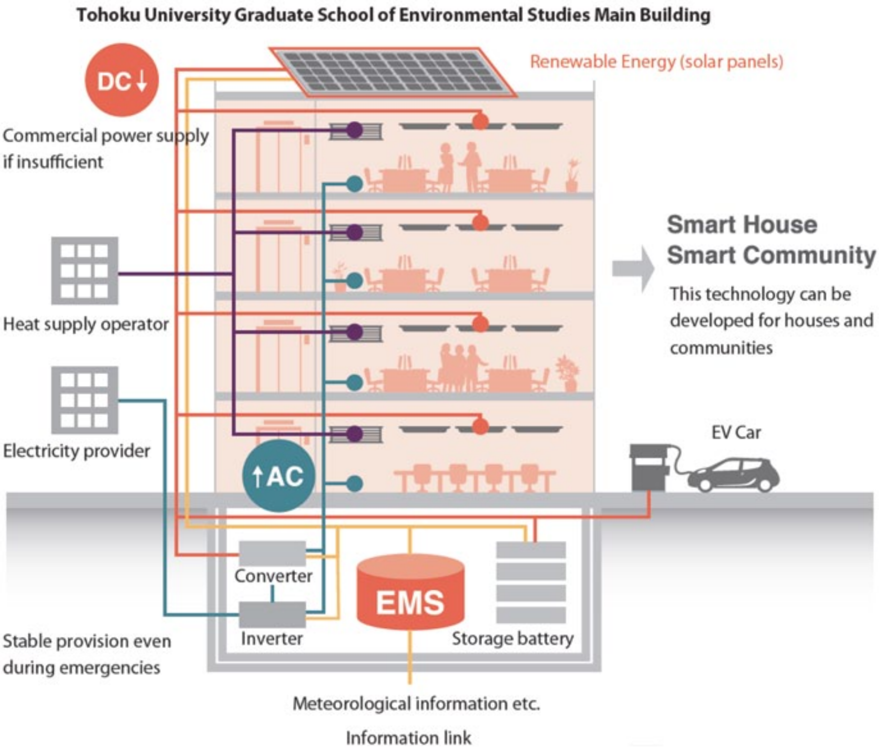


Fig. 7.7 Smart building configuration for the main building. (GSES 2012)

- Enhancement of IT functions by the various sensors and the control software.
- Combining the energy system of a stationary smart building/house with energy transfer applications such as electric vehicles (EV).

The experience of the Great East Japan Earthquake of March 11, 2011 and the subsequent accident at the Fukushima Daiichi nuclear power plant is at the root of these technological developments.

The adjoining 'Ecollab.' building was the forerunner of the main building configuration at a scale of about 1/10. It has a number of additional design features to minimize energy demand (Box 7.1) and also an experimental area for developing DC applications in kitchen and other household appliances- developing a DC lifestyle. (Fig. 7.3) 'Ecollab.' also deploys energy conservation methods in addition to the DC/AC hybrid control systems and provides a laboratory building with environmentally conscious, living quarters and lecture rooms for faculty and students.

Box 7.1 Special Energy-Saving Design Features of the 'Ecollab.' (GSES 2011)

The 'Ecollab.' was designed to use sustainable materials and also designed to minimise energy consumption by maximising naturally available ventilation through environmental design. The building was produced with local sustainable cedar timber from the university's own forests and farm. The open ceiling space in the design and skylights provide natural air ventilation while the walls were made using material that naturally controls humidity, thus reducing the need to use air-conditioning. High incidence of natural light reduces the need for artificial light during the daytime. The basic structure is shown in Fig. 7.8.

In addition to the use of natural light, solar heat collectors provide hot water. Such solar heat can be used as hot water or for floor heating during the winter but the question is how to use this effectively during the summer. In the 'Ecollab.', this extra solar heat is used for humidity control; water from the hot water tank is used to dry a desiccant which reduces the humidity of the air inside the building, in turn reducing demand for air-conditioning. It is estimated that this reduces the energy required for air-conditioning by over 20 % (Fig. 7.9).

7.2.7 Sources of Weak or Small Energy

Other sources of weak energy can also be exploited- either by capturing excess or waste from other uses, or by special micro-generation methods. Potential sources

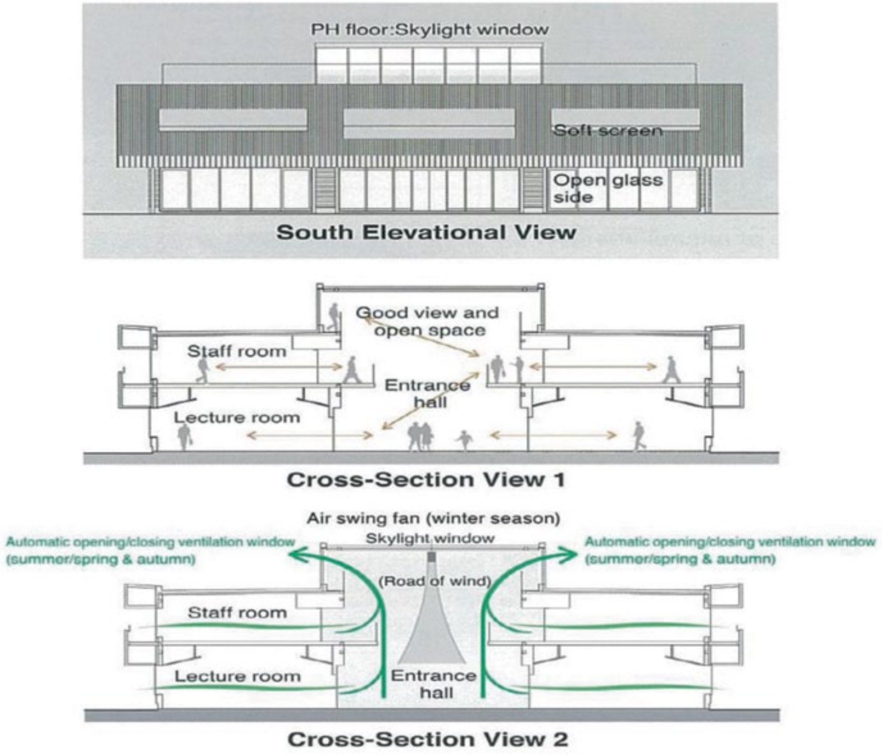


Fig. 7.8 Environmental design of the 'Ecollab'. (GSES 2011)

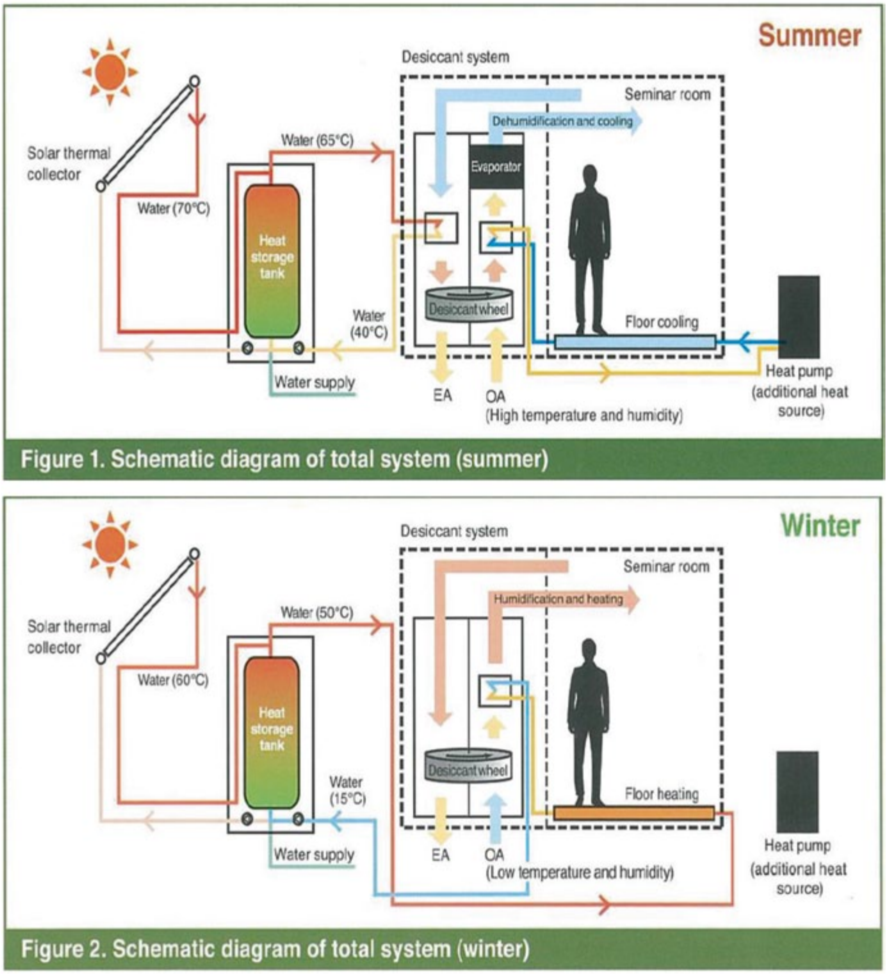


Fig. 7.9 Use of solar heat in reducing energy demand in winter and summer. (GSES 2011)

from micro-hydro exploiting the kinetic energy in rain water, shower, kitchen or even bath or toilet water as a micro-energy source. Local heat pumps, micro-wind energy as well as emergency generators using a dynamo-equipped bicycle can also be combined with rechargeable batteries to provide sources for small demands such as mobile phone chargers or LED lighting in emergencies. In the case of bicycle power generation (Fig. 7.10), cycling for 3–20 h is necessary to generate power of 1 kWh. Using Small energy is thus possible, but is still in the research stage, and the road to commercialization is not yet established.

Fig. 7.10 **a** Example of power generation by bicycle. **b** Having fun while producing electricity and teaching a 'green' lifestyle

Fig. 7.11 Photographs of the night on March 11, 2011 "Electricity in the earthquake area and the Sanriku coast completely stopped"

7.3 Next Generation Energy for Tohoku Recovery (NET) Project

Following the 2011 disasters, the resilience of local energy supplies became an important issue (Fig. 7.11), and Tohoku University worked with a number of local authorities to develop R&D projects aimed at a more sustainable and resilient energy system suited to local needs. Up to this point, renewable energy has customarily been used for businesses or connections to the grid. But the vulnerability of such large-scale energy delivery systems led to a desire to search for novel next-generation energy and control systems that could contribute to the Tohoku region's recovery.

As local authorities took their own recovery actions, Tohoku University, as the central academic institution of the region, set up its own recovery actions beginning immediately after the disaster. One of those actions is this Tohoku University Environmental Energy Project. Starting with an initial disaster forum on June 17, 2011, just after the earthquake, the core institution of Tohoku University has held 7 disaster fora to evaluate the conditions of stricken areas and consider recovery strategies. Furthermore, on November 17, together with Tohoku localities and universities nationwide, the Tohoku Recovery Clean Energy R&D Symposium was held addressing next-generation energy and its application (NET 2012).

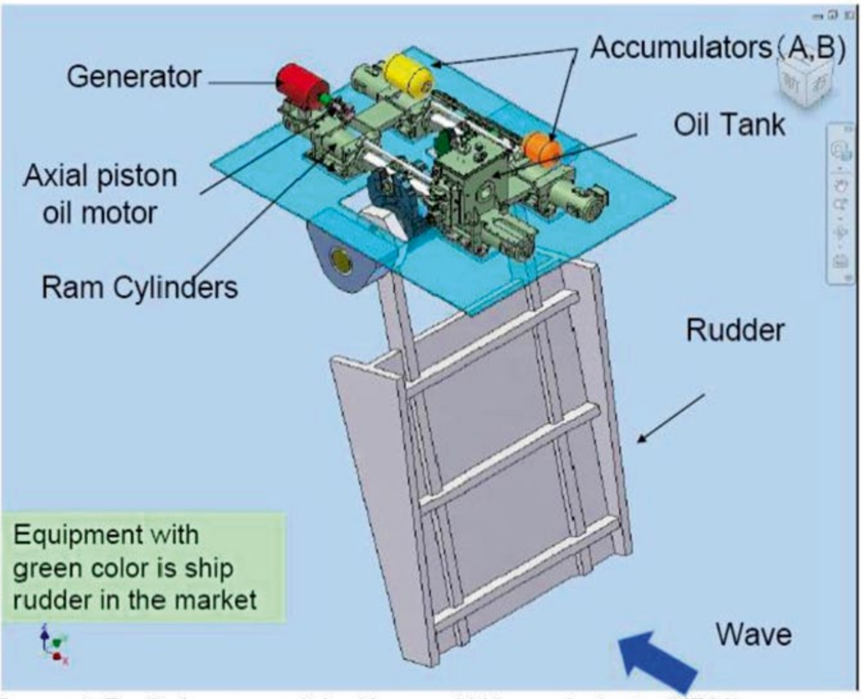
Emerging from these fora, Tokyo University suggested the use of wave and tidal energy in Kuji City, Iwate Prefecture and Shiogama City, Miyagi Prefecture; a Tsukuba and Tohoku University group put forth proposals for algae biofuels for Sendai; and furthermore a Tohoku and Tokyo University group created a Biomass Town concept for Ishinomaki City, Miyagi Prefecture and proposals for geothermal energy in Osaki City, Miyagi Prefecture. Architecture for an indispensable mobility-capable local energy control system was also laid out in a project that brought together plans for green energy. This was the start of the Next-generation Energies for Tohoku Recovery project. This NET project has three main elements.

The first anticipates obtaining renewable ocean energy from Tohoku's abundant waves and other ocean sources. With the cooperation of Kuji City, this research project is putting in place an open water trial of wave energy in Kuji Bay, Iwate Prefecture, using two 40 kW prototypes based on an original design developed with parts sourced from various makers and fabricated/installed by local enterprises which have suffered the damaging effects of the Great East Japan Earthquake and Tsunami. Furthermore, in Matsushima Bay near the Urato Archipelago in Miyagi Prefecture where the tide is amplified, through cooperation with Shiogama City, an open water trial of tidal energy is being installed using an original 5 kW prototype (again assembled from parts sourced from various makers and fabricated/installed by local enterprises). These are shown in Fig. 7.12.

It is hoped that the results of this research will be an important first step towards widespread adoption of renewable ocean power, data generated will facilitate the valuation of appropriate renewable feed-in tariffs, and with the support of authorities in many more of Tohoku's stricken localities, local generation capability can be installed, thus unlocking the possibility of energy self-sufficiency.

The second project sees wastewater treatment as a potential source of biomass energy other than the currently available generation of methane through anaerobic digestion. In many cases, residual sludge is incinerated as waste, consuming a great amount of energy in the process. The technology to exploit the oil-yielding heterotrophic algae Aurantiochytrium which is capable of using the organic matter in wastewater, together with the nitrogen/phosphorus nutrient-utilizing Botryococcus oil-yielding autotrophic algae will be installed at Sendai's Minamigamo wastewater treatment plant (which sustained massive damage in the tsunami) but has since been restored (Qi et al. 2014).

This will allow biofuel production from wastewater and its efficient use to be developed, with the aim of establishing a technology base which will enable designs for practical full-scale implementation. Thus, instead of consuming energy, a means of producing energy from wastewater treatment will be found; by utilizing heterotrophic algae to process organic matter and autotrophic algae to process inorganic matter together, energy efficiency will increase; and new technology may be



(Source): Preliminary result by Kawasaki Heavy Industry(KPM)

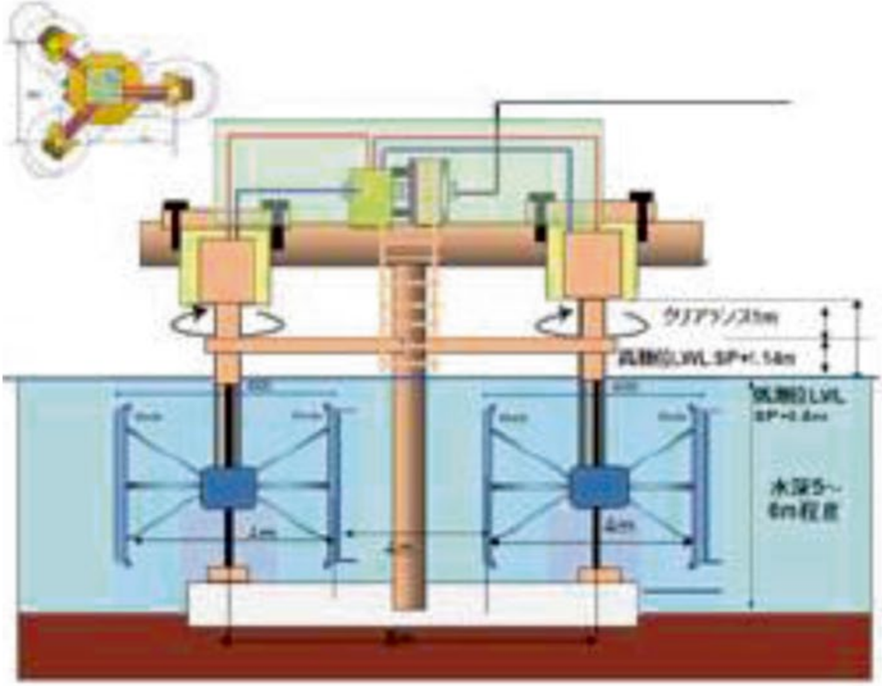


Fig. 7.12 Schematic of devices to harness wave and tidal energy. (NET 2012)

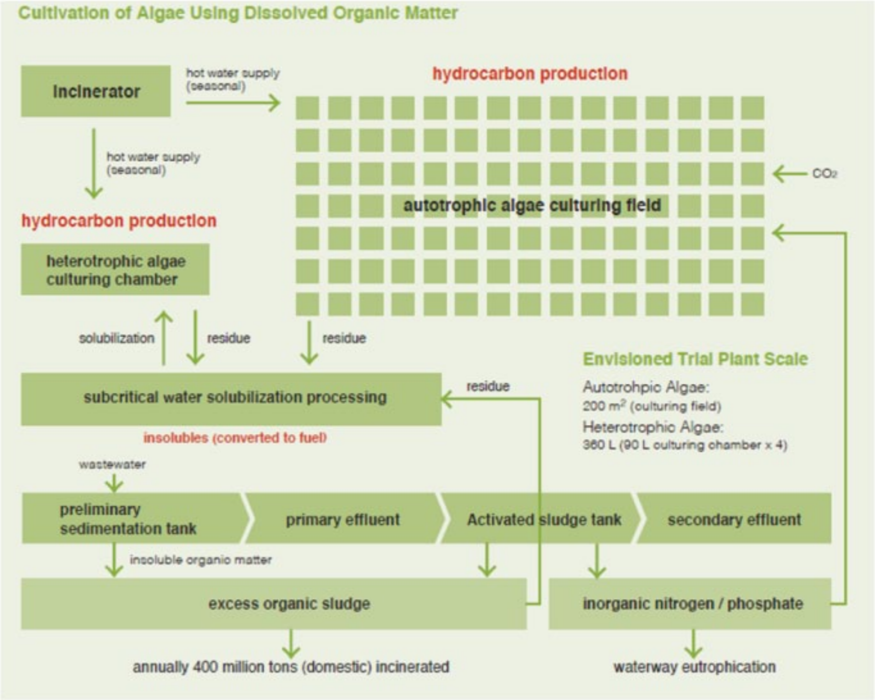


Fig. 7.13 Use of sewage treatment system to produce algae. (NET 2012)

developed applicable for future use in wastewater treatment everywhere. A conceptual diagram is shown in Fig. 7.13.

The third project involves R&D to develop a world-leading local renewable energy-compatible Energy-Mobility Integrated Management System (EMIMS) which is resilient to disasters. In the short term, research will focus on gathering information on mobility, database systems, information integration management, information provision and human behaviour modelling incorporating transportation mode choices, and energy/mobility relations studies. In addition, for the EMS-controlled DC current and capacitance system to maximize the efficiency of use of local renewable energy, a trial of an active signage system model to make EMS visible will be conducted at the Tohoku University Campuses.

Such systems can be useful not only during disasters but also offer efficiency and flexibility in day-to-day circumstances. For example, when using electric vehicles, the battery itself can be used to store energy (e.g. from solar panels) when the car is not in use for transport. Electricity from the EV to a home can then be supplied when required- bi-directional use.

The renewable-energy utilizing energy and mobility integrated energy management systems from this research can be expected to provide greater energy security and labour savings, and more favourable economics. In normal conditions, modelling of traffic and congestion as well as management of buses and other

Fig. 7.14 Research and development of EMS control hot spring thermal energy system. (NET 2013)

transport modes will provide recovering localities with next-generation mobility management. Finally, in emergency conditions, evacuation coordination showing open routes, emergency transportation management, and energy transfer management utilizing EVs will be possible, to improve mobility during disasters and to save lives in localities stricken by future earthquakes.

A trial of an EMS-controlled geothermal system will be conducted at Naruko Town (Osaki City) experimental installation. This is one of Japan's many hot springs where there is an abundance of low temperature heat, as well as residues from local rice production which provide a source of biomass. Research is underway (Fig. 7.14) in cooperation with local governments to develop a binary geothermal power generation system that operates efficiently at low temperatures, combined with energy recovery by methane fermentation of biomass residues. Currently energy conversion efficiency is as low as 7 % or less, but this is promising as a means of natural energy utilization equipment in local communities. The current method is to use hot spring water to heat the heat transfer medium (ammonia and water mixture) on the primary side of the evaporator. The inlet temperature of about 100 °C is reduced to about 70 °C which is still sufficient residual heat for greenhouse cultivation.

An additional potential use for residual heat is to support a hybrid methane fermentation system using cow rumen fluid and rumen microorganisms to digest herbaceous woody biomass which is unused by general biomass processes (Fig. 7.15). Combining electricity generation from low grade geothermal heat and methane from fermentation of food and other organic waste provides a valuable energy source for a hot spring inn and spa. This is also of interest to tourists who are able to participate in a community-based bio-energy utilization system.

Fig. 7.15 Research equipment for methane fermentation system. (NET 2013)

7.4 Conclusions

In conclusion, the energy shortage after the Great East Japan Earthquake of March 11, 2011 has underlined the importance of more resilient local sources of energy which can contribute to a more sustainable world. This has reinforced our research objectives towards a number of key targets for research at Tohoku University including:

- Fusion of natural energy and utility power.
- Fusion of mobility and stationary power.
- Systems which combine use of emergency and normal times.
- Management and technology development on community-based dispersed energy sources.
- Ocean energy, bio-energy, geothermal energy, solar energy, wind, hydro and these fusion utilizations.

Furthermore,

- Promotion of the further use of renewable energy/natural energy
- Making use of previously unused “small energy sources” around us;

These will open the door for us to a “future of happy sustainability.”

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Chapter 8
Biomass Energy Using Methane and Hydrogen from Waste Materials

Yu-You Li, Samir Gadow and Qigui Niu

Abstract Biomass is playing an increasing role in renewable energy but has disadvantages where the biomass source competes with food supply, biodiversity and other essential components of a sustainable society. At Tohoku University, we are researching sources of alternative fuels such as bio-hydrogen and bio-methane from secondary sources such as wastewater treatment and reuse. In this chapter we present an overview of key concepts related to biomass energy production through various bacterial processes using single and two-phase fermentation technologies. Additionally, we also describe potential sources of biogas technology in Japan including cattle manure, chicken manure, sewage sludge and co-digestion in methane fermentation.

Keywords Biomass energy · Bio-hydrogen · Bio-methane · Environmental sustainability

8.1 Introduction

The production and use of bioenergy is rising in many countries to diversify energy sources, promote environmental quality, energy security and economic growth. Modern biomass energy can provide several benefits, including development of rural economies, improving household income, mitigating climate change, and providing access to alternative energy sources. On the other hand, bioenergy can also be associated with biodiversity loss, deforestation, and additional pressure on global water resources. For this reason, it is desirable to avoid primary resources and seek waste materials or other secondary resources as a biomass feedstock. For instance, worldwide municipal solid waste (MSW) generation is about 2 billion t per year,

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Y.-Y. Li (✉) · S. Gadow · Q. Niu
Civil and Environmental Engineering Department, Tohoku University, Sendai, Japan
e-mail: yyli@epl1.civil.tohoku.ac.jp

Y.-Y. Li
Graduate School of Environmental Studies, Tohoku University, Sendai, Japan

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which is predicted to increase to 3 billion t by 2025 with increasing urbanization. The production of fruit and vegetable waste is also very high and is becoming a source of concern in municipal landfills because of its high biodegradability. The potential sources of material for biomass energy are thus significant.

Our research on the urban water environment and bioenergy focuses on clean and renewable energy, solid waste management, wastewater treatment and urbanization. In the area of wastewater treatment, we focus on the use of commercial and novel membrane processes and investigate the performance and enhancement of lab-scale wastewater treatment using novel membrane bioreactors and the Up-flow Anaerobic Sludge Blanket Reactor (UASB). This chapter provides an overview of the current state and future prospects for related biomass energy technologies based on wastes as feedstock.

8.2 Biomass Sources and Waste

The term ‘biomass’ refers to organic substances that have stored energy through the photosynthesis process, and is one of the most abundant and well-utilized sources of renewable energy in the world. Biomass can be classified as in Fig. 8.1 according to whether they are dry, moist or ‘other’ which includes a number of wastes. The processes used for its utilization in terms of power generation or transport fuels include direct combustion, biochemical conversion and thermo-chemical conversion.

In Japan, around 322 million t of biomass is produced annually. Although the biomass recycling rate is 76 %, the remainder is not recycled and can be regarded as waste of which the largest sources are sewage sludge, waste paper, food waste, non-edible agricultural products and forest residues. Material flows for 2006 are shown in Fig. 8.2 and include a number of major sources which can potentially be used to produce hydrogen or methane through biological processes.

8.3 Bio-hydrogen Fundamentals and Technology

8.3.1 Background

Hydrogen is used for chemicals and electronic devices production, hydrogenated fats and oils in the food industry, steel processing and desulfurization, and reformulation of gasoline in refineries. In addition, much research and development is underway on using hydrogen in transport with terms such as ‘the hydrogen economy’ widely used. However currently, over 95 % of the 50 million t of hydrogen produced annually worldwide is from fossil fuels, so that its use makes little contribution to reducing CO_2 emissions.

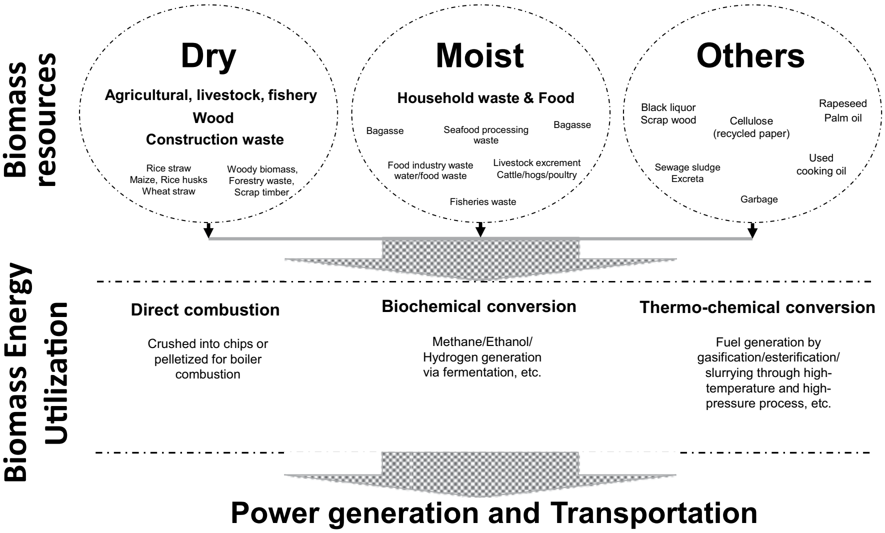

Fig. 8.1 Biomass resources and biomass energy utilization

Various methods available for producing hydrogen are shown in Fig. 8.3. Included in these are three ways to produce hydrogen biologically, with no external energy input required: bio-photolysis, photo-fermentation, and dark-fermentation. Among these technologies, dark fermentation is considered the most promising; at 3–4 mol H_2/mol glucose, the hydrogen yield is the highest and various types of organic wastes can be utilized. In recent years, a group of bacteria has been discovered that has the remarkable property of growing near and above 100 °C. Under such hyper-thermophilic anaerobic conditions, yields of hydrogen close to the theoretical stoichiometry have been obtained using glucose as the carbon source. These yields are superior to those found in other studies using fermentative microorganisms but many challenges remain before this could be used to produce hydrogen from the most abundant source of biomass—cellulose[1].

To date, many studies have been carried out on fermentative hydrogen production from pure sugars and from feedstocks, such as by-products from the agricultural and food industry, municipal waste, or wastewaters. However, few studies have been dedicated to continuous hydrogen production using cellulose because cellulose is particularly difficult to hydrolyze and break down to its component glucose monomers. Moreover, most studies on bio-H_2 production from cellulose have used batch reactors, and bio-hydrogen production from cellulose using continuous mode under hyper-thermophilic conditions has not yet been reported.

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[1] Leith and Whittaker (1975) estimated the global stock of cellulose as ~9.2×10^{11} tons, produced at an annual rate of 0.85×10^{11} tons.

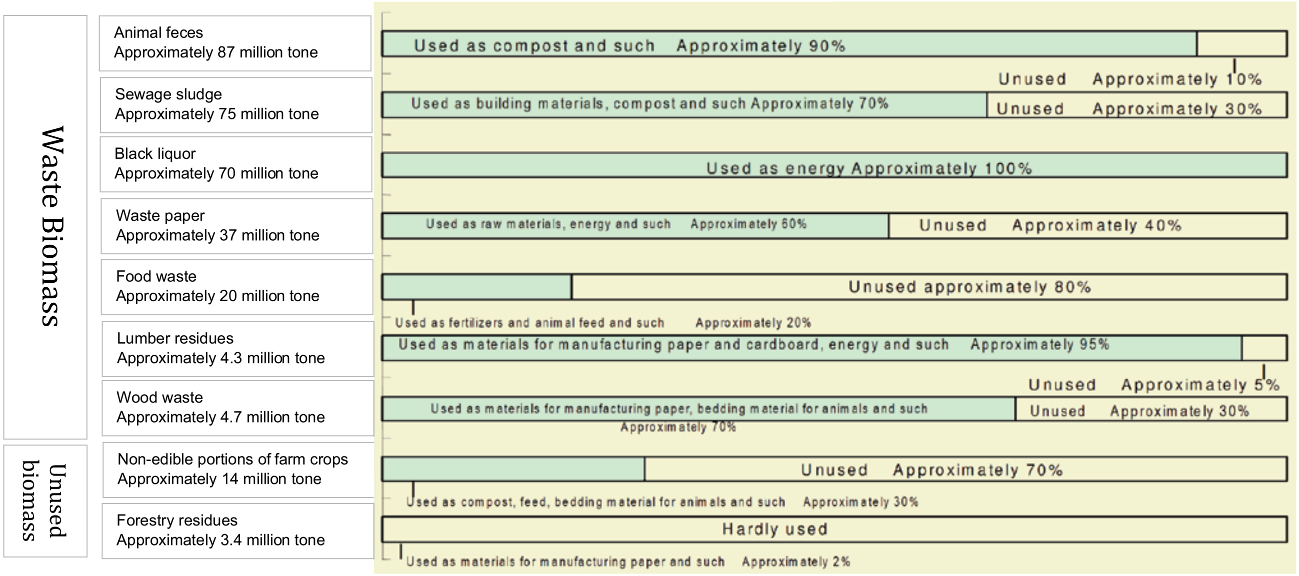


Fig. 8.2 Annual biomass production and recycling rate 2006

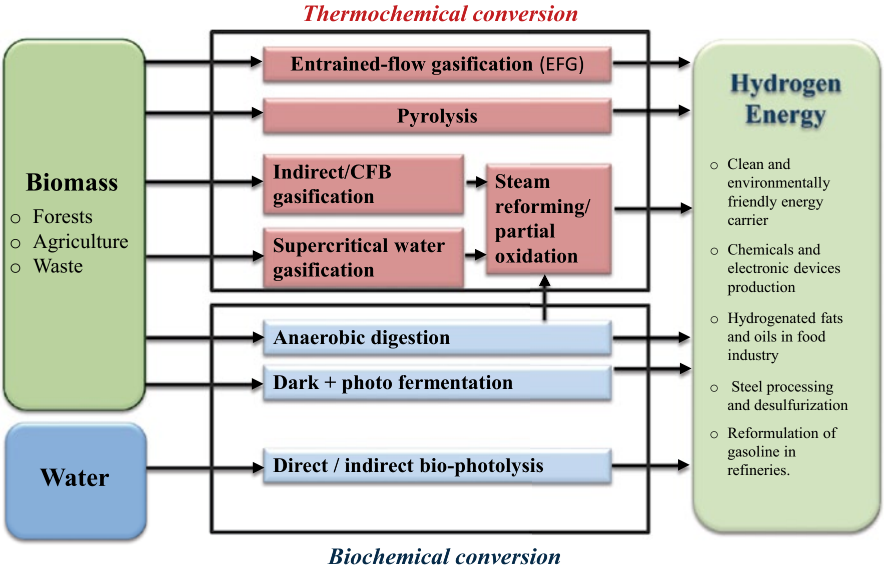


Fig. 8.3 Renewable Hydrogen energy system

8.3.2 Dark Fermentation to Produce Hydrogen

Dark hydrogen fermentation processes produce gases which mainly contain hydrogen and carbon dioxide but in addition may also contain methane, carbon monoxide and hydrogen sulfide, depending on the system and substrate. The basic building block of cellulose (glucose) could in theory produce up to 12 mol hydrogen per mole of glucose if completely oxidized to hydrogen and carbon dioxide (Eq. 8.1). However, there would be no metabolic energy in this case and this has not been reported.

$$C_6H_{12}O_6 + 6H_2O \rightarrow 12H_2 + 6CO_2 \quad \Delta G_0 = +3.2\ \text{kJ} \tag{8.1}$$

Hydrogen is mainly produced along with acetate and butyrate production pathways, as indicated by Eqs. 8.2 and 8.3, with a greater H_2 yield when coupled with acetate rather than butyrate.

$$C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CH_3COOH + 2CO_2 \quad \Delta G_0 = -206\text{kJ} \tag{8.2}$$

$$\begin{aligned} C_6H_{12}O_6 &\rightarrow 2H_2 + CH_3CH_2CH_2COOH \\ &+ 2CO_2 \quad \Delta G_0 = -254\text{kJ} \end{aligned} \tag{8.3}$$

Dark fermentation thus offers the potential to produce 3-4 mol H_2/mol glucose. The use of mixed cultures for dark fermentation offers more practical advantages

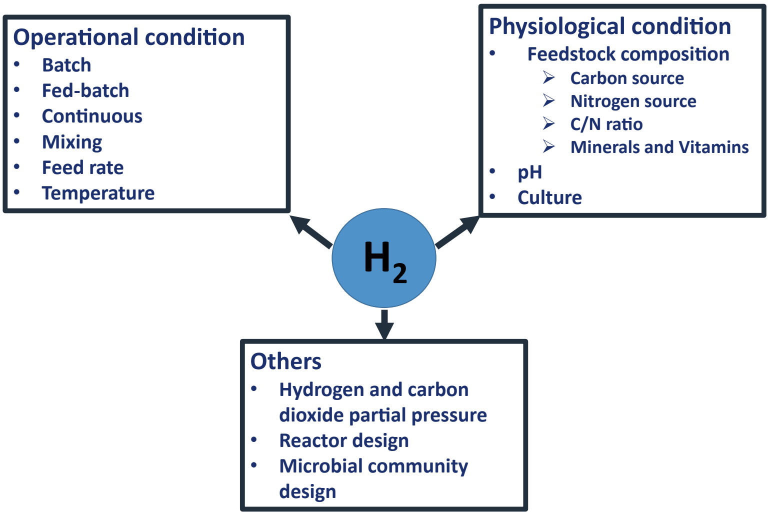


Fig. 8.4 Main parameters affecting the anaerobic (dark) hydrogen fermentation process

over axenic (mono) cultures since this mode can utilize a wider range of feedstocks without sterilization, and can be easier to operate and control. However several problems arise when using mixed cultures; one of these being the coexistence in nature of H_2-producing and H_2-consuming bacteria (e.g. methanogens) which oxidize H_2 and reduce CO_2.

8.3.3 Parameters Affecting Dark Hydrogen Fermentation

Dark hydrogen fermentation is affected by temperature, pH, inorganic content and inocula (Fig. 8.4). Temperature is the most important factor for bacterial growth. The relationship between temperature and chemical reaction rates can be adapted to microbiological processes within limited temperature ranges, and can be modeled using the Arrhenius equation (specific thermodynamic data for hydrogen fermentation using mixed microflora are rarely available). In general, dark hydrogen fermentation reactions can be operated at the following temperature ranges: mesophilic (25–40 °C), thermophilic (40–65 °C), hyper-thermophilic (>65 °C).

Most experiments on continuous dark hydrogen fermentation have been conducted at 35–55 °C and not under hyper-thermophilic conditions. However, hyper-thermophilic hydrogen fermentation has the advantages of:

1. *A high hydrogen production yield and rate is achieved.* It has been reported that extreme-thermophilic anaerobic hydrogen fermentation can result in the production of more hydrogen and higher hydrogen production rates than mesophilic hydrogen fermentation. It also has been reported that at 70 °C, the hydrogen

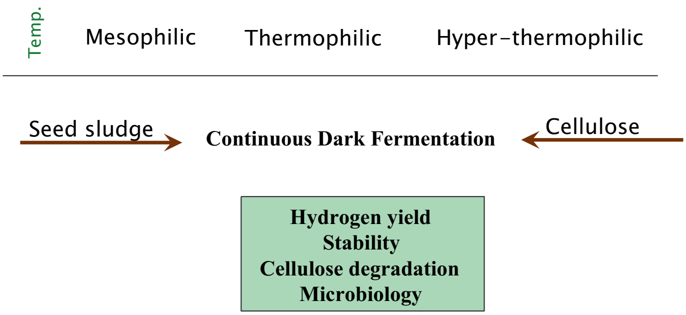


Fig. 8.5 Development of direct bioconversion of cellulose to hydrogen by continuous dark fermentation using anaerobic mixed microflora. (Gadow et al. 2012)

yield reaches the theoretical maximum of 4 mol H_2/mole glucose, whereas at mesophilic and thermophilic conditions, the hydrogen yield is typically less than 2 mol hydrogen per mole glucose.

2. *Pathogens are reduced*. High temperature minimizes contamination by hydrogen consumers such as methanogenic archaea, since the hydrogen-producing reaction is favoured at high temperatures, and hydrogen utilization processes are negatively affected with temperature increase.

Studies on the microbial hydrogen production structure of mixed cultures have been carried out in the mesophilic and thermophilic temperature ranges. While a few studies have been focused on hyper-thermophilic ranges using pure cultures, none have involved the use of mixed microflora according to the approach in Fig. 8.5, which we now describe in more detail.

8.3.4 Temperature and Stability of Bio-Hydrogen Production

In the research approach in Fig. 8.5, continuous H_2 fermentation was carried out using three different temperatures (37, 55 and 80 ºC) in order to identify the best conditions for H_2 production from cellulose, using the detailed configuration in Fig. 8.6. While a stable but low hydrogen production was obtained under mesophilic temperatures, hydrogen production was higher and more stable under thermophilic and hyper-thermophilic temperature conditions.

This experiment showed that the degradation efficiencies of cellulose and hydrogen yield were increased as the temperature increased from mesophilic through thermophilic to hyper-thermophilic temperatures. At 55 and 80 ºC, temperature enhanced the ability of mixed culture to degrade cellulose to hydrogen, consistent with other studies. At 37 ºC on the other hand, hydrogen and methane were produced. The different reaction pathways at the three temperature ranges are shown in Fig. 8.7.

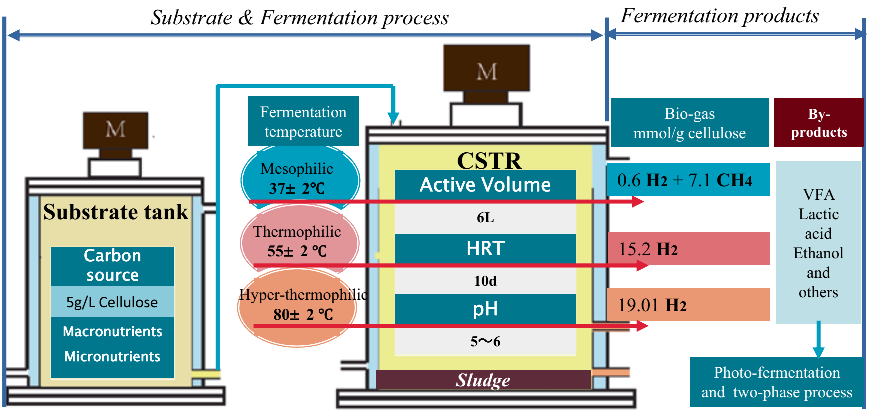
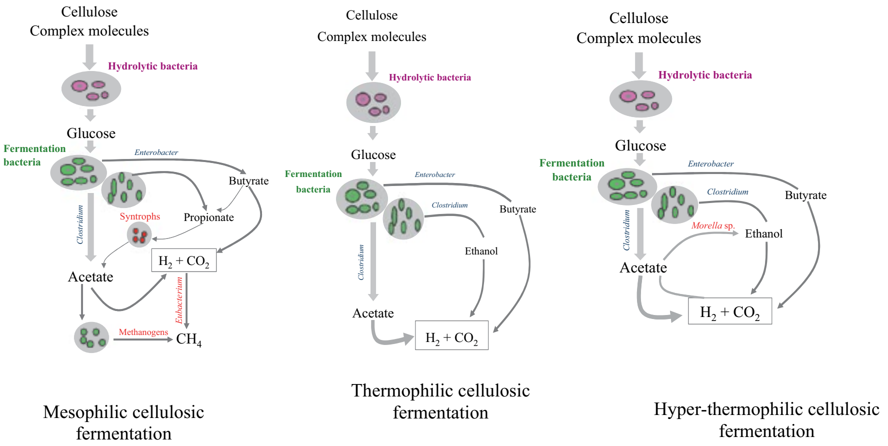


Fig. 8.6 Continuous cellulosic dark hydrogen production under different fermentation temperature. (Gadow et al. 2012)



Mesophilic cellulosic fermentation

Thermophilic cellulosic fermentation

Hyper-thermophilic cellulosic fermentation

Fig. 8.7 Effect of temperature on microbial community dynamics in cellulosic-hydrogen fermentation. (Gadow et al. 2013)

8.3.5 Stoichiometry of Hydrogen Production from Fermentation of Cellulose

The stoichiometry equations of hydrogen production from fermentation of cellulose in Fig. 8.7 are calculated as follows:

Mesophilic reactor

$$\begin{aligned}(C_6H_{10}O_5)_n \rightarrow\ & 1.28nCH_4 + 0.11nH_2 + 0.44nCH_3COOH \\ & + 0.35nC_3H_7COOH + 3.31nCO_2 + \text{others} \end{aligned} \tag{8.4}$$

Table 8.1 Comparison between actual hydrogen yield (Y_{exp}) and the estimated hydrogen yield (Y_{est})

Temperature (ºC)	Yield of acetate or butyrate (mol product/mol glucose)		Hydrogen yield (mol H_2/mol glucose)		Ratio of Y_{exp}/Y_{est}
	Y_{HAC}	Y_{HBU}	Y_{exp}	Y_{est}	
37±2	0.44	0.35	0.11	1.58	0.07
55±2	0.53	0.50	2.73	2.06	1.33
80±2	0.63	0.49	3.43	2.24	1.53

Estimated by (2x Y_{HAC}+2x Y_{HBU})
Y_{HAC} acetate yield, Y_{HBU} butyrate yield

Thermophilic reactor

$$\begin{aligned}(C_6H_{10}O_5)_n &\rightarrow 2.73nH_2 + 0.53nCH_3COOH\\ &+ 0.50nC_3H_7COOH + 2.6nCO_2 + \text{others}\end{aligned} \tag{8.5}$$

Hyper-thermophilic reactor

$$\begin{aligned}(C_6H_{10}O_5)_n &\rightarrow 3.43nH_2 + 0.63nCH_3COOH\\ &+ 0.49nC_3H_7COOH + 3.01nCO_2 + \text{others}\end{aligned} \tag{8.6}$$

From Eqs. 8.4, 8.5 and 8.6, it is clear that fermentative characteristics in each reactor (including yields of hydrogen and intermediate products) are different at different fermentation temperatures. Stoichiometrically, 2 mol of hydrogen is generated concomitant with 1 mol of acetate or butyrate (Eqs. 8.2 and 8.3).

Table 8.1 compares actual hydrogen yields (Y_{exp}) with the estimated hydrogen yield (Y_{est}). The results show that the ratio of experimentally obtained hydrogen to those estimated was 0.07, 1.33 and 1.35 under mesophilic, thermophilic and hyper-thermophilic temperatures respectively.

This indicates that most acetate and butyrate yields were produced during hydrogen production under thermophilic and hyper-thermophilic temperatures. On the other hand, most acetate and butyrate yields were produced during methane and low hydrogen production under mesophilic temperatures.

8.3.6 *Effect of Temperature on the Net Energy Gain*

The net energy gain is the total energy produced from hydrogen generation minus any energy required to raise the influent volume from ambient to fermentation temperature. Estimates of net energy gain under three different temperatures for different influent cellulose concentrations, calculated based on the H_2 yield obtained in this study, are presented in Fig. 8.8.

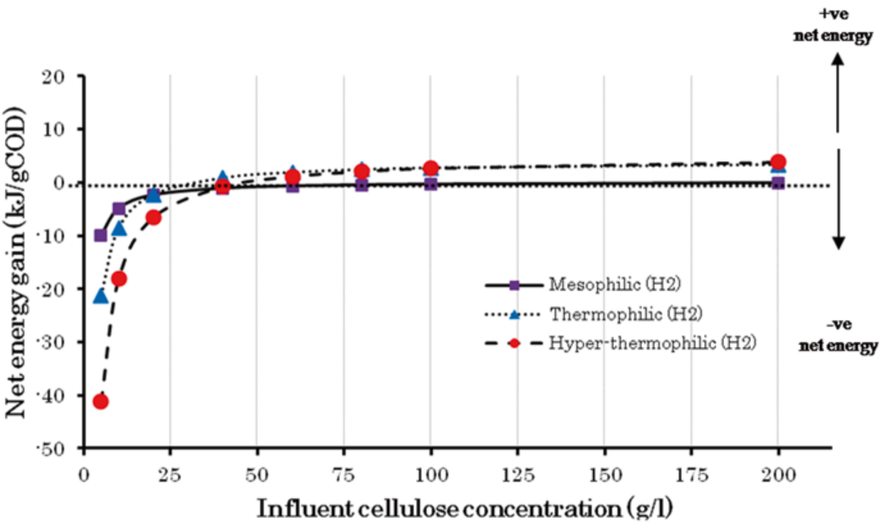


Fig. 8.8 Net energy gain at different fermentation temperatures for different influent cellulose concentrations

As can be seen from Fig. 8.8, even though the higher fermentation temperatures (thermophilic and hyper-thermophilic) are viewed as favorable for high yield and stability of hydrogen production, the net energy gain was significantly negative relative to mesophilic conditions at low concentrations of cellulose ≤20 g/l. These results are consistent with those reported for thermophilic temperatures (55 °C), where the same net energy gain was obtained (−20.7 kJ/g COD) using cellulose-containing wastewater and −22.6 kJ/g COD using starch wastewater (Karnayakage et al. 2012). If cellulose concentrations can be increased to ≥40 g/l however, the thermophilic fermentation is expected to have a better economic performance for bio-H_2 production. This is especially the case when using feedstocks which are pretreated to break down cellulosic biomass by chemical, mechanical or thermal disintegration which overcomes the rate limiting step of biological hydrolysis, improving the anaerobic fermentation process and biogas yield.

8.4 Methane Fermentation

8.4.1 Background

Methane fermentation is a well-established technology used for treating organic residues almost regardless of their composition. It is carried out by heterogeneous microbial populations involving multiple biological and substrate interactions with end production of methane (55–75 vol %), CO_2 (25–45 vol %) and fermentation

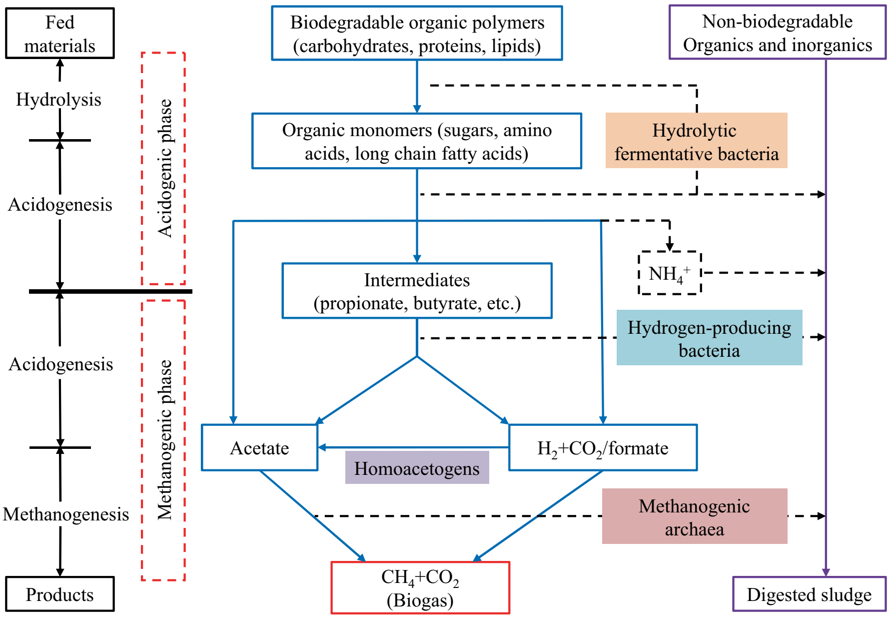


Fig. 8.9 Schematic representation of the methane fermentation with the microorganisms responsible for each step

metabolites. Furthermore, fermentation enables a controlled stabilization of the organic material, can reduce greenhouse gas emissions and contributes to the closing of nutrient cycles. Indeed, the methane fermentation process can be applied for treatment of various types of bio-waste in a more sustainable way than many alternative processes (Niu et al. 2013, 2014; Qiao et al. 2013). Bio-methane can also be used in a combined heat and power plant (CHP) to generate heat and electricity, increasing the efficiency of its use.

8.4.2 *Methane Fermentation Conditions and the Functional Microbial Communities*

Methane fermentation is effected by various specialized groups of bacteria in four successive steps, each step depending on the preceding one (Fig. 8.9):

1. Hydrolysis: where by complex molecules (carbohydrates, lipids and proteins) are depolymerized into soluble compounds by hydrolytic enzymes.
2. Acidogenesis: a biological reaction where simple monomers are converted into volatile fatty acids (VFA).
3. Acetogenesis: a biological reaction where volatile fatty acids are converted into acetic acid, carbon dioxide, and hydrogen. The first process is catalyzed

Table 8.2 Microorganisms involved in methanogenesis Taxon (order and type) with metabolic substrates and typical habitats

Taxon (Order)	Typical genus	Major metabolic substrate	Typical habitat
Methanobacteriales	*Methanobacterium, Methanobrevibacter, Methanosphaera, Methanothermobacter, Methanothermus*	H_2 and CO_2, formate, methanol	Anaerobic digesters, rumen, paddy soil, decaying woody tissues, anaerobic activated sludge etc.
Methanococcales	*Methanococcus, Methanothermococcus, Methanocaldococcus, Methanotorris*	H_2 and CO_2, formate	Marine sediments, hot springs etc.
Methanomicrobiales	*Methanomicrobium, Methanoculleus, Methanofollis, Methanogenium, Methanolacinia, Methanoplanus, Methanospirillum, Methanocorpusc ulum,Methanocalculus*	H_2 and CO_2, 2- propanol, 2-butanol, 2-butanone	Anaerobic digesters, soil, marine sediments, hot springs, decaying woody tissues, anaerobic activated sludge, etc.
Methanosarcinales	*Methanococcoides, Methanohalobium, Methanohalophilus, Methanolobus, Methanomethylovorans, Methanimicrococcus, Methanosalsum, Methanosaeta/ Methanosarcina,*	H_2 and CO_2, formate, $MeNH_2$, acetate	Hypersaline marine sediments, anaerobic digesters, animal gastrointestinal tracts, etc.
Methanopyrales	*Methanopyrus*	H_2 and CO_2	Marine sediments

by enzymes called carbon monoxide dehydrogenase. The second $CO_2+4H_2 \rightarrow CH_3COOH+2H_2O$ is called the Wood-Ljungdahl pathway (homoacetogenesis).

4. Methanogenesis: a biological reaction where acetates are converted into methane and carbon dioxide, while hydrogen is consumed.

To be useful for bioenergy production, a microbial community must have a stable metabolic function over time, despite the unavoidable perturbations and disturbances that occur in real world systems. The activity of microorganisms in anaerobic fermentation processes depends mainly on water content, temperature, pH, redox potential, and the presence of inhibitory factors. The microorganisms involved in methanogenesis Taxon (order and type) are shown in Table 8.2. Five orders of methanogens can be separated into two functional groups: aceticlastic methanogens and hydrogenotrophic methanogens. *Methanosarcina* and *Methanosaeta* can utilize the acetate to product methane.

The methane fermentation process can be affected by many factors such as the operational and physiological conditions shown in Fig. 8.10. Biogas production and water content of the initial material are interdependent. Below 20 % by weight, hardly any biogas is produced. With increasing water content biogas production is enhanced, reaching its optimum at 91–98 % water (by weight). The process of biomethane production is also very sensitive to changes in temperature, and the degree

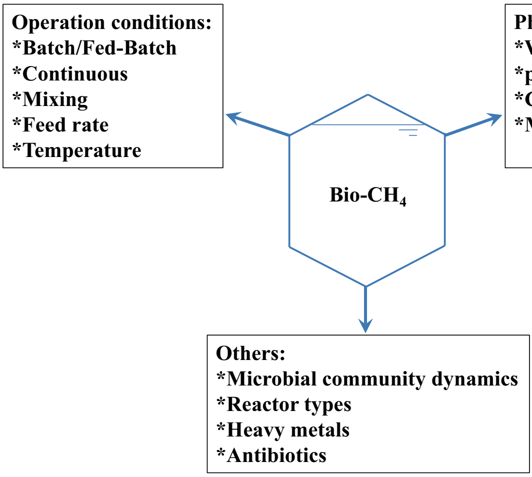


Fig. 8.10 Main parameters affecting methane fermentation

Table 8.3 Comparison of mesophilic and thermophilic processes

Process operation	Mesophilic (35 °C)	Thermophilic (55 °C)
Process stability	Higher	Lower
Temperature sensitivity	Low	High
Energy demand	Low	High
Degradation rate	Decreased	Increased
Retention time	Longer or the same	Shorter or the same
Sanitation	No	Possible

of sensitivity depends on the temperature range. The pH optimum for methane fermentation is between pH 6.7 and 7.4. If the process becomes acidified and the pH drops below 6, the balance in the biomass is upset and acid-producing bacteria will dominate the acid-consuming bacteria, so that the medium becomes inhibitory or toxic to the methanogenic bacteria. In addition, strong ammonia production during the degradation of proteins and urea may also inhibit methane formation with a pH higher than 8.

For engineering applications, mesophilic and thermophilic methane fermentation are the most commonly used methods. Mesophilic fermentation usually requires over a 20-day hydraulic retention time (HRT), but is not so efficient in the reduction of volatile solids and the deactivation of pathogenic organisms. To overcome these limitations, interest has grown in thermophilic digestion, using the higher metabolic rate of thermophilic microorganisms. Although better performance in the reduction of volatile solids (VS) and deactivation of pathogenic organisms can be obtained from thermophilic digestion, the effluent quality and ability to dewater the residual sludge are poor, and require additional energy to heat the digester (Table 8.3).

Table 8.4 Potential of biogas production in Japan. (Li and Nishimura 2007)

Feed stock	Amount (Mt/year)	Biogas yield (m^3/t)	Methane (%)	Methane production (Gm^3/year)	Crude oil equivalent (Ml/year)
Municipal solid wastes	22	130	60	1.72	1720
Livestock wastes	89	30	60	1.60	1600
Sewage sludge	75	14	60	0.63	630
Total	186	174	60	3.95	3950

Especially, thermophilic digestion is more sensitive to operational conditions such as temperature and the organic loading rate, as well as to the characteristics of the influent sludge.

8.4.3 Applications of Biogas Technology in Japan

Anaerobic treatment of organic solid wastes and industrial wastewater is becoming increasingly common in Japan. Over 300 industrial wastewater plants are currently using either UASB or Expanded Granular Sludge Bed (EGSB) treatment processes. However considerable potential remains as summarized in Table 8.4, where the potential volume of methane and its crude oil equivalent is shown for three major waste sources. Fermentative methane production from organic solid wastes is thus considered to be one of the dominant technologies for recovering biofuel from the biomass stock in Japan. It is noteworthy that the total amount of annual potential methane production corresponds to about 3950 Ml of crude oil, comparable to the 2010 national goal of overall biomass utilization of 4000 Ml/year.

The stoichiometry of energy production from different biomass sources based on work in our laboratory is shown in Table 8.5. We now consider some of the issues related to the three specific waste sources of cattle manure, chicken manure and sewage sludge.

8.4.3.1 Cattle Manure

The estimated potential of methane recovery from livestock waste (1.6 billion m^3/year) is the second largest following that from MSW (1.7 billion m^3/year) in Japan. A number of biogas plants treating livestock waste have been established since 2000, and Table 8.6 shows the operating data of biogas plants which treat livestock waste. Most of these plants employ mesophilic and continuous stirred tank reactor (CSTR) processes.

Table 8.7 shows the process mode of biogas plants treating livestock waste in Japan. Half of the 70-plants treat only livestock wastes, with cattle manure being the most utilized followed by swine manure. In these plants, the biogas recovered from digesters has been converted into heat or electric energy and successfully utilized.

Table 8.5 Calculation and stoichiometry of methane fermentation

Biomass	Organic	Gas production(Nm^3/kg-$VS_{degradation}$)	CH_4 (%)
Carbohydrate	$(C_6H_{10}O_5)_n+nH_2O \rightarrow 3nCH_4+3nCO_2$	0.83	50.0
Protein	$C_{16}H_{24}O_5N_4+14.5H_2O \rightarrow 8.25CH_4+3.75CO_2+4NH_4^++4HCO_3^-$	0.764	68.8
Lipid	$C_{50}H_{90}O_6+24.5H_2O \rightarrow 34.75CH_4+15.25CO_2$	1.425	69.5
Cooking scrap	$C_{17}H_{29}O_{10}N+6.5H_2O \rightarrow 9.25CH_4+6.75CO_2+NH_4^++HCO_3^-$	0.881	57.8
Cattle manure	$C_{22}H_{29}O_{10}N+6.5H_2O \rightarrow 9.25CH_4+6.75CO_2+NH_4^++HCO_3^-$	0.970	56.0
Kitchen garbage	$C_{46}H_{73}O_{31}N+14H_2O \rightarrow 24CH_4+21CO_2+NH_4^++HCO_3^-$	0.888	53.3
Sewage sludge	$C_{10}H_{19}O_3N+5.5H_2O \rightarrow 6.25CH_4+2.75CO_2+NH_4^++HCO_3^-$	1.003	69.4
Chicken manure	$C_{7.5}H_{12.4}O_{4.8}NS_{0.13}+4.15\ H_2O \rightarrow 3.7\ CH_4+2.8\ CO_2+NH_4^++HCO_3^-+0.13\ H_2S$	0.75	63.5

The characteristics of cattle manure are summarized in Table 8.8. In addition, the average performance of cattle manure fermentation is shown in Fig. 8.11, and the whole process including dewatering and waste water treatment is illustrated in Fig. 8.12. As shown in Fig. 8.11, the average biogas yield from cattle manure fermentation was 37.7 m^3/m^3_{inf} (60.1 % CH_4 content), with the extent of reduction in total solids (TS) reaching 32.3 % in the digested sludge. The bio-methane has been converted into heat or electric energy with benefits for the farmers (Table 8.7).

8.4.4 Chicken Manure

With the increase in intensive and mechanized poultry breeding industries, large amounts of waste are being produced. Annually, about 13 million t of chicken manure (CM) is generated in Japan, which corresponds to 65 % of total food processing waste. Based on the characteristic of CM (Table 8.9), methane fermentation of chicken manure allows for bioenergy recovery as well as minimizing the waste, and has distinct advantages over conventional treatments, as illustrated in Fig. 8.13.

A laboratory scale CSTR reactor (Fig. 8.14) has been developed with an average performance shown in Fig. 8.15 for both ammonia-stripped CM and raw CM. Below total ammonia nitrogen concentrations of 5000 mg/L, the process can deliver a steady performance. Methane fermentation of CM has a number of benefits as a manure treatment technology, including greenhouse gas emissions and odor reduction, increased nutrient availability, and reduced pathogen risk. However high organic nitrogen content leads to increases in volatile fatty acid production at the expense of methane. In one proposed design, CM 10 t/day feed with total solids of 10 % in

Table 8.6 Operating data of biogas plants treating livestock waste in Japan. (JARRRS 2014)

Process	Substrate	Capacity (t/d)	Temperature	Biogas production (Nm^3/t)	VS reduction (%)	Year
CSTR	Mixed manure + MSW	55.9	M	37.4	52(COD_{Cr})	1998
CSTR	Cattle manure	15	M	33.3		2000
CSTR	Cattle manure	18	M	21.1		2002
CSTR	Mixed manure	4.7	T	38.9		2002
CSTR	Cattle manure + MSW	13.3	M	13.2		2003
CSTR	Cattle manure	32.8	T	19.8		2004
CSTR (Multi stage)	Cattle manure +Agricultural waste	3.2	M	22.2		2004
CSTR (Fixed bed)	Cattle manure	5	M	37.8		2004
CSTR	Cattle manure	13.5	M	35.6	30	2005
CSTR	Cattle manure +Agricultural waste	5		20		2005
CSTR	Cattle manure+MSW	4.9	M	61.2		2005
BIMA[a]	Mixed manure + MSW + Sludge	67.8	M	17.4		2005
CSTR	Mixed manure + Agriculture waste	85.3	M	38.1		2006
CSTR	Swine manure + MSW + Sludge	58.6	M	53.9		2006
CSTR	Mixed manure	10	M	25.2		2006
CSTR (Multi stage)	Cattle manure	94.8	M	41.1	35–40	2007
CSTR	Mixed Cattle manure	5.5	M	20		2008

T Thermophilic digestion, *M* Mesophilic digestion

[a] Biogas Induced Mixing Arrangement

a full scale reactor could produce 6000 m^3CH_4/d, which would be able to generate 1800 kWh/d of electricity.

8.4.5 Sewage Sludge

During the 1960s and 1970s, the extension of mains sewage across Japan accelerated the pace of construction of anaerobic digesters in waste water treatment, with as many as 180 plants being equipped with anaerobic digesters. In more recent years,

Table 8.7 Processing mode of biogas plants in Japan

		Number of plants
Substrate	Cattle manure	28
	Swine manure	9
	Mixed manure	6
	Manure + MSW	4
	Manure + MSW + Sludge	9
	Unidentified	15
	Total	70
Capacity	< 10 t/d	27
	10–50 t/d	19
	> 50 t/d	12
	Unidentified	12
	Total	70
Biogas utilization	Electric	10
	Heat	28
	Electric + Heat	32
	Total	70
Effluent	Liquid fertilizer	35
	Wastewater treatment	5
	Unidentified	30
	Total	70

Table 8.8 Characteristic of cattle manure

Biomass		Total amount		TS (mg/L)	VS (mg/L)	T-N (mg/L)	T-P (mg/L)	T-K (mg/L)
		t/year	t/day					
Cattle manure	Farm 1	2920	8	125,000	87,500	4500	500	1200
	Farm 2	1825	5	90,000	63,000	4000	550	1000
	Farm 3	913	2.5	155,000	10,8500	4800	600	900
	Farm 4	730	2	120,000	84,000	3700	400	1100
	∑/ average	6388	17.5	122,500	85,750	4250	513	1050

the interest in biomass energy has led to a fresh look at the anaerobic digestion of sewage sludge by governments and researchers alike.

There are two typical flow paths in sludge treatment when using anaerobic digestion: both start with centrifuging and proceed to anaerobic digestion and dewatering, but one process finishes up with a composting step, and the other with sludge incineration. Figure 8.16 shows an example of the sludge treatment centers in Yokohama city. With a treating capacity of 40,000 m^3/d of wastewater, the Yokohama treatment center successfully treats sewage sludge using four mesophilic anaerobic digesters. The digesters produce 4082 m^3/d of biogas with 58 % methane content, and the digested sludge (TS 2.21 %) is dewatered and composted.

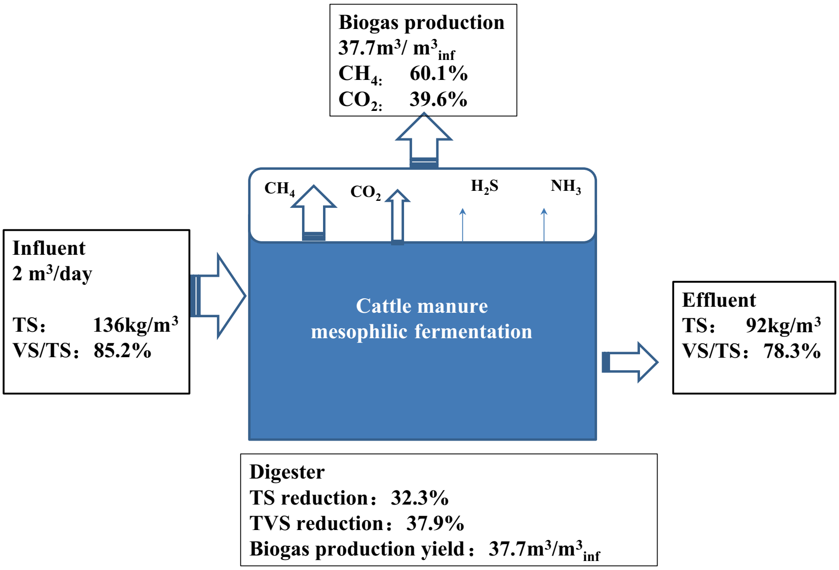


Fig. 8.11 Average performance of cattle manure fermentation

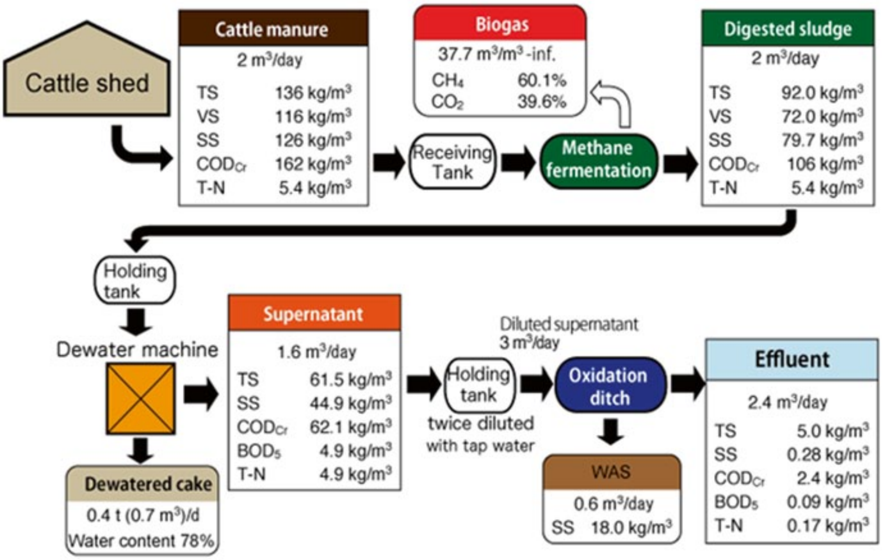


Fig. 8.12 Flow diagram for cattle manure fermentation

Table 8.9 Characteristic of chicken manure

Biomass	Kinds	Total amount		TS (mg/L)	VS (mg/L)	T-N (mg/L)
		t/year	t/day			
Chicken manure	Raw CM	13	0.035	112	82.7	6450
	Ammonia stripped CM	–	–	89.3	61.3	3590
	∑/average	13	0.035	–	–	–

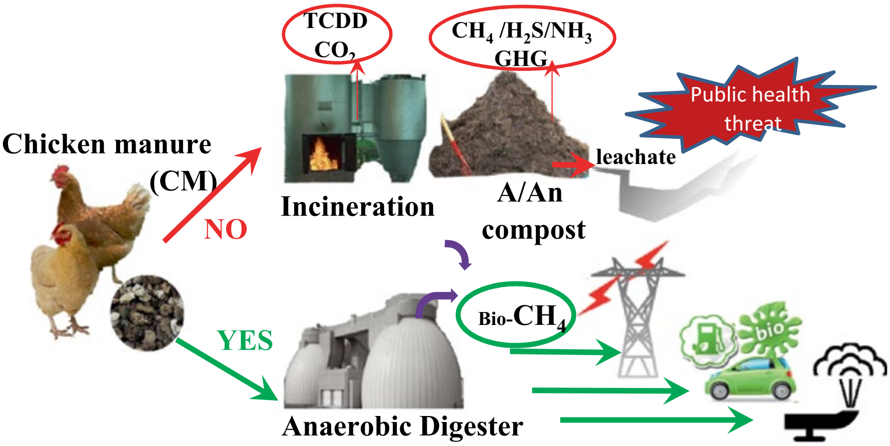


Fig. 8.13 Comparisons of chicken manure treatment

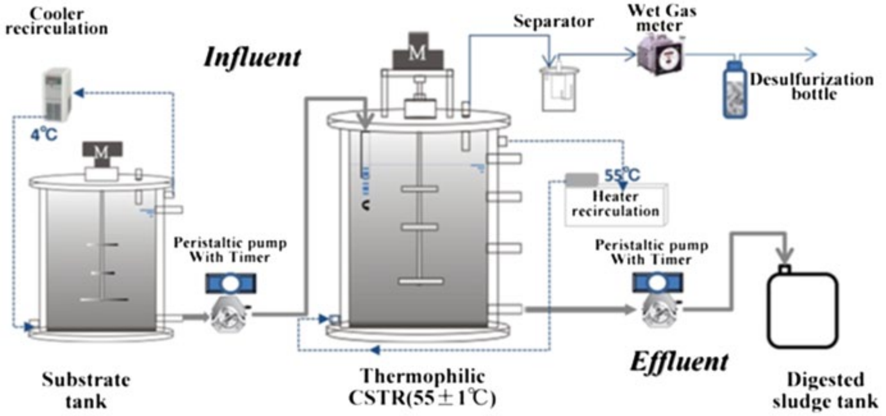


Fig. 8.14 Schematic diagram of continuous experiment

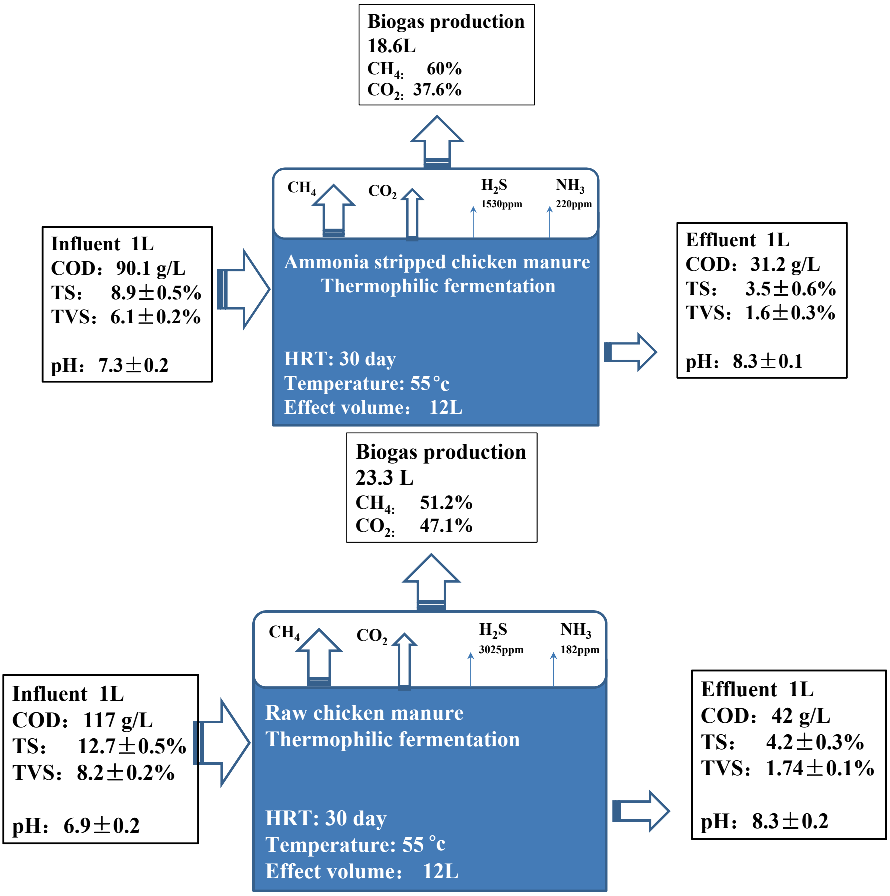


Fig. 8.15 Average performance of the thermophilic methane fermentation on ammonia-stripped CM and raw CM

The mean conditions for all 305 methanogenic plants operated in Japan are as shown in Fig. 8.17. The average gas composition was 60 % methane (36 % of CO_2 and 1164 ppm of H_2S) and the average biogas yield was 11m^3 of gas per m^3 of sludge processed. Average TS and VS reductions were 51 % and 57 % respectively. The average pH in the digesters remained stable throughout the year at ~7.25. TS, VS and COD reductions were 44.2, 54.2 and 60 % respectively. Biogas production magnification ranged from 20 to 30, which was twice the average values of other waste water treatment plants (WWTP) in Japan.

8.4.6 Co-Digestion

Anaerobic digestion can also be applied to wastes from different sources in a co-digestion process. One example of biomass utilization based on both animal waste

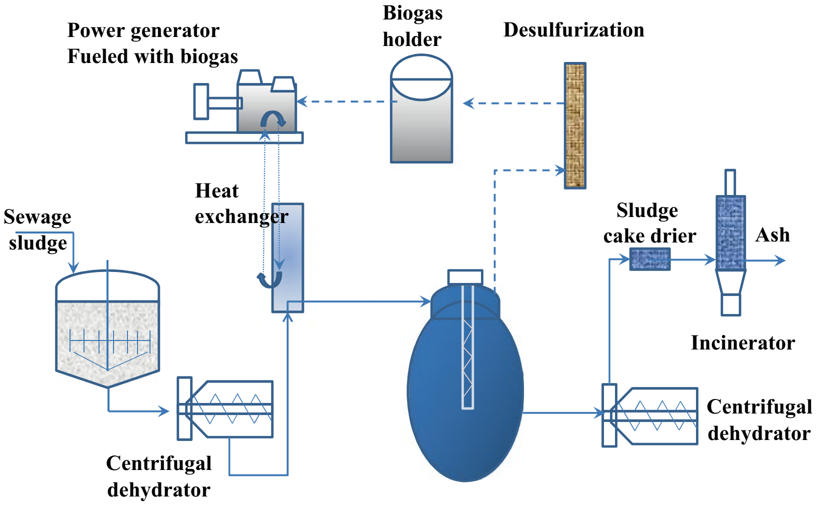


Fig. 8.16 Flow chart of the Hokubu sludge treatment center in Yokohama

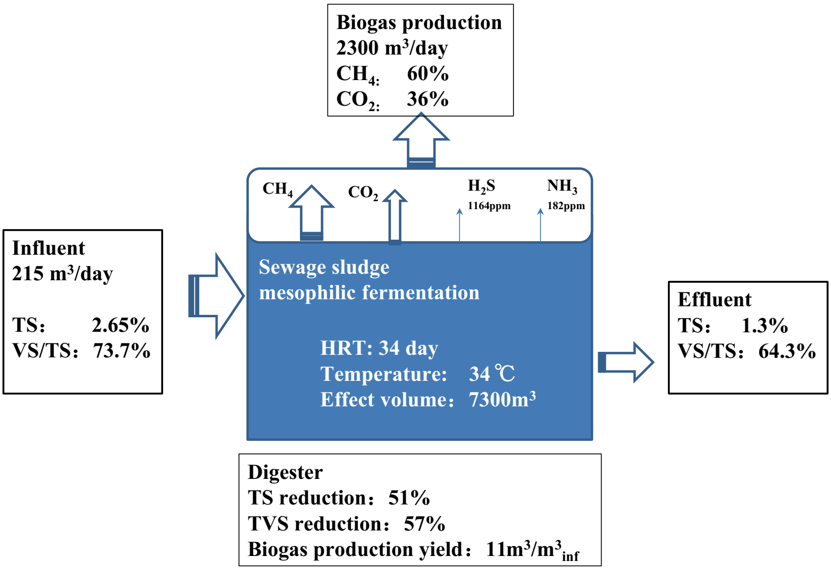


Fig. 8.17 Average performance of the 305-methanogenic plants in Japan 2001

and food wastes collected from farms and food factories exists in Yagi, Kyoto Prefecture. This integrated system (Yagi Bio-ecology center (YBEC)) is shown in Fig. 8.18 (Ogawa 2005).

The YBEC is a typical example of a biogas plant in successfully operation. The animal and food wastes are collected from farms and food factories in Yagi (a small town with a population of 9000) and this provides 42,000 t of biomass

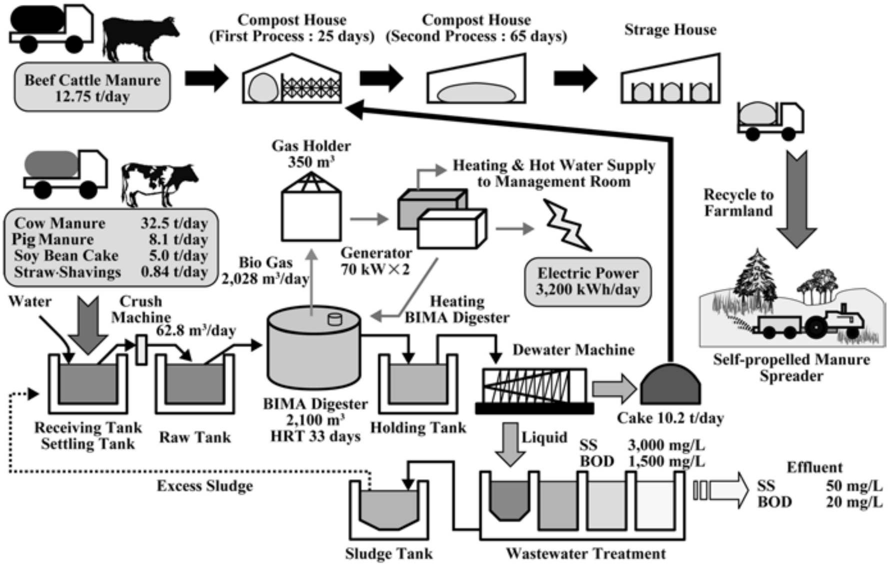


Fig. 8.18 Flow diagram of Yagi bio-ecology centre

Table 8.10 Characteristics of the biomass resource at YBEC

Item		Manure from 650 dairy cattle		Manure from 1500 pigs	Tofu reuse
		Raw manure	Dewatered liquid		
Total Solids	mg/L	136,700	47,500	65,700	233,000
VTS	mg/L	115,000	37,500	55,000	220,600
Suspended Solids	mg/L	89,000	34,500	44,500	24,850
BOD	mg/L	24,000	6500	25,500	840,000
COD_{Cr}	mg/L	130,000	64,000	82,000	7
pH		7	7	6	7290
Total N	mg/L	5530	1950	4370	2400
NH_4+N	mg/L	2500	1200	4900	1698
Total P	mg/L	1290	395	1470	–

every year (comprised of 25,171 t of livestock waste and 4827 t of food waste in 2004). 65 % of the biomass is treated by anaerobic digesters; as shown in Fig. 8.18, the animal and food wastes are mixed in the storage tank, and then fed either to a mesophilic digester (volume of 2100 m^3 at 37 °C) or a pilot thermophilic digester (volume of 600 m^3 at 55 °C). The hydraulic retention time and treatment capacity are 33 days and 62.8 t/day for the mesophilic digester, and 26 days and 23.2 t/day for the thermophilic digester.

Biomass characteristics are summarized in Table 8.10. The average biogas production rate for the thermophilic digester is 1.00 $Nm^3/d/m^3$-digester, approximately

Table 8.11 Average characteristics of influent and effluent and performance of digesters

Characteristics		Influent	Effluent from mesophilic digester	Effluent from thermophilic digester
pH		6.5	7.9	8.1
TS	mg/L	66,250	44,250	46,880
VTS	mg/L	54,880	32,880	34,250
COD_{Cr}	mg/L	72,500	34,250	35,250
VFA	mg/L	8520	50	353
T-N	mg/L	3050	3040	3160
NH_4^+-N	mg/L	1330	1840	2090
Alkalinity	mg/L	6280	12,120	12,630
T-P	mg/L	515	490	510
Coliform bacteria	CFU/ml	722,500	5300	248
Fecal coliform	CFU/ml	439,200	1332	28
Performance			Mesophilic digester	Thermophilic digester
COD_{Cr} reduction	%		52.8	51.4
Biogas production	$Nm^3/d/m^3$-digester		0.9	1.0
Methane content	%		Average 55.4	

1.1 times that of the mesophilic digester. The average methane concentration in the biogas from both digesters is 55.4 %. Average characteristics of influent and effluent and the performance of the digesters are shown in Table 8.11. Higher *E. coli* and *F. coli* reduction through digestion was observed in the thermophilic digester than in the mesophilic digester. In YBEC, a balance is basically maintained between the electric power produced from the biogas and that consumed in the plant. If any excess electricity is produced, it is sold off to the WWTP. After the digested sludge is dewatered, the liquid is treated by a wastewater process and the solid is composted.

8.4.7 Two-Stage Process with Combined Hydrogen and Methane Production

A two-stage anaerobic digestion system can be envisaged to produce both hydrogen and methane. As shown in Fig. 8.19, compared with the single phase, a two-phase configuration not only degrades more waste, but also gains more net energy from the system. In a single stage anaerobic digestion, a variety of higher organic acids, such as propionic, butyric, and lactic, as well as alcohols and ketones, are also formed during the breakdown of the organic substrates by acidogens. However,

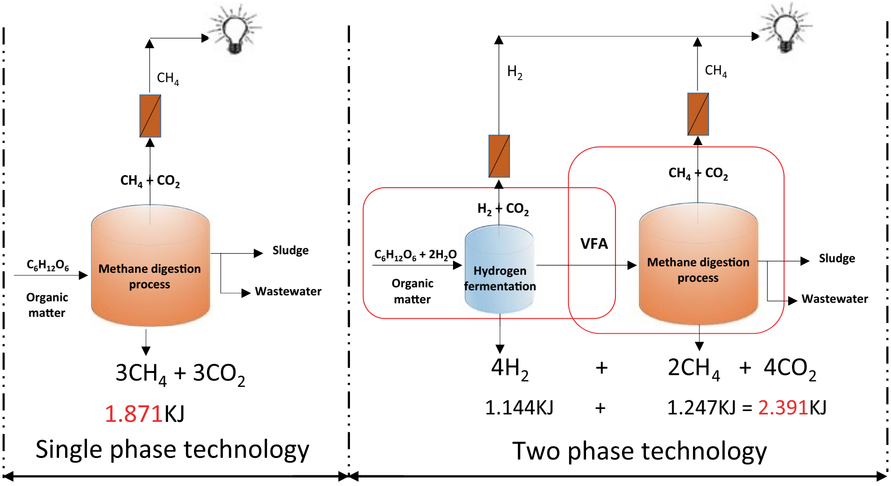


Fig. 8.19 Total energy gained from single phase and two phase processes

in a well operated process, these products are mostly converted to acetic acid and hydrogen (see Eqs. 8.2, 8.3), which, in turn, are converted to methane gas in a two-phase anaerobic process (see Eqs. 8.8, 8.9).

Methane fermentation

$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2\left(2673 kJ/mol\right) \tag{8.7}$$

$H_2 + CH_4$ fermentation

$$C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CO_2 + 2CH_3COOH$$

$$2CH_3COOH \rightarrow 2CH_4 + 2CO_2 \tag{8.8}$$

$$C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CH_4 + 4CO_2\left(2926 kJ/mol\right) \tag{8.9}$$

Separating the acidogenic and methanogenic steps in the anaerobic digestion process, provides enhanced stability to the different groups of microorganisms and better process control. However, despite their higher loading rates, improved process stability and flexibility, there are few commercial two-stage anaerobic digestion units. The added complexity and expense of building and operating commercial two-stage systems have so far counteracted the yield and rate enhancements. The theoretically higher biogas yields have also been questioned since the acidogenic phase separation prevents the hydrogen to methane pathway (Reith et al. 2003).

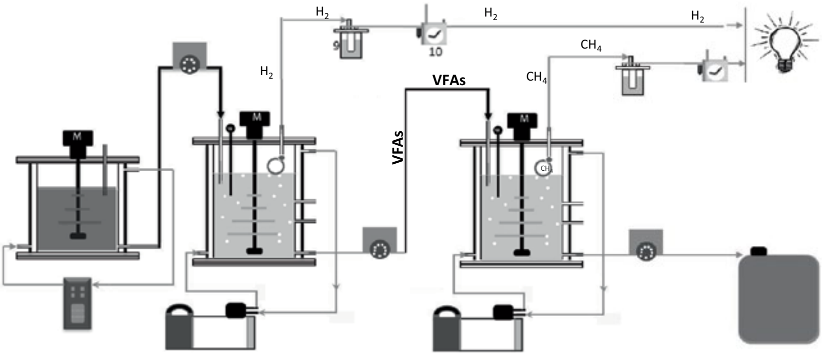


Fig. 8.20 Schematic diagram of experimental apparatus in the two phase process. *1* Feedstock tank, *2* Feed inlet, *3* Mixer, *4* Recirculation cooler, *5* Sampling pump, *6* fermentation reactor, *7* Hot water recirculation, *8* Thermometer, *9* Gas-water separation chamber, *10* Wet gas metter, *11* Sample port, *12* Effluent pump, *13* Digestion sludge tank

8.4.8 A Case Study at Tohoku University of Bioenergy Production from Food Waste by a Two Stage Process

As we have seen above, although methane and hydrogen fermentation are well-developed technologies, co-production of hydrogen and methane in the course of anaerobic digestion of organic wastes is at only the early stages of development. We have thus evaluated production of bio-hydrogen and bio-methane and their relation to the nature of organic waste materials, using a continuous two-stage thermophilic fermentation process shown in Fig. 8.20. Three kinds of actual food wastes were used, specifically, potato, kitchen garbage and okara (Kobayashi et al. 2012).

The results show that bio-hydrogen potential not only depends on the carbohydrate content but also on the hydrolysis pH of the waste, which is affected by the nature of the waste materials. Production rates for H_2 and CH_4 were 2.1 and 1.2 l/l/d for potato; 1.7 and 1.5 l/l/d for kitchen garbage; and 0.4 and 1.4 l/l/d for okara in the continuous processes. The biogas yields were 20–85 ml H_2/g VS added and 329–364 ml CH_4/g VS added, respectively. The H_2 yield increased and the CH_4 yield decreased in the order of potato, kitchen garbage and okara.

Potato and kitchen garbage food waste appear to be more promising for sequential H_2 and CH_4 production in a two stage fermentation process. On the other hand, okara food waste might be suitable for a cost-effective CH_4 production process, owing to there being no need for any pre-treatment. These results can thus inform selection of the most appropriate anaerobic process, and have shown that a two-phase process can effectively separate H_2-producing bacteria from methanogenic archaea in an economically and technically feasible process, to produce hydrogen and methane simultaneously from waste.

Further research (Chu et al. 2010) on the two stage system shows that the activity of the H_2-producing bacteria can be effectively separated from that of methanogenic archaea, which makes a process for producing hydrogen and methane

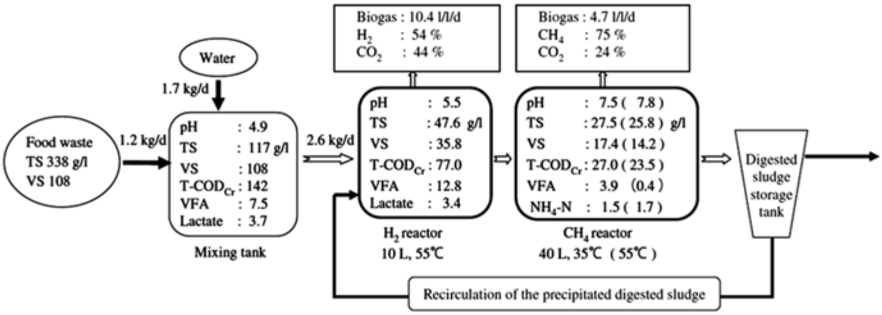


Fig. 8.21 Operation performance of hydrogen and methane production from food waste in a two-stage process. (Chu et al. 2010)

simultaneously from waste potentially feasible on both economic and technical grounds. Figure 8.21 shows the operation performance for hydrogen and methane production from food waste from an average of two runs (Run1: 55 ºC H_2 reactor 35 ºC CH_4 reactor; Run2: 55.8 ºC H_2 reactor 55 ºC CH_4 reactor). In the hydrogen production stage, biogas production rate was stable at 10.4 l/l/d and composed of H_2 (52–56 %) and CO_2 (41–47 %) with no CH_4 detected. In the mesophilic or thermophilic methanogenic phases, biogas production rate was stable at 4.7 l/l/d and composed of CH_4 (70–80 %) and CO_2 (20–29 %). H_2 and CH_4 production appeared to be more dependent on the composition of waste than fermentative temperature; moreover the methanogenic reactor was more effective in hydrolysis and removal of food waste at thermophilic temperatures.

Three important advantages of this process can also be emphasized. First, enriching H_2-producing bacteria can be achieved by optimizing design parameters such as pH, HRT and temperature, and using mixed-seed organisms without any inoculum pre-treatment. Second, hydrogenesis in thermophilic condition can replace the pre-treatment of feedstock to kill pathogens in waste materials and suppress the indigenous microorganisms; moreover diversity of H_2 producing microflora can be achieved. Third, this study represents the first finding of the *Clostridium* sp. strain Z6, which was found to be the predominant H_2-producing bacteria, in this thermophilic H_2 fermentative system.

8.5 Conclusions

Experience of applying dark fermentation to the treatment of various types of organic wastes is long-established and has already made a significant contribution to improving the recovery of resources and providing local sources of renewable energy in the form of bio-methane in a single-phase process. However, recent research suggests that the potential for bio-hydrogen production is also significant and further research and development may lead to economically viable two-stage processes where both hydrogen and methane can be produced from a range of different feedstocks. Therefore, two-stage anaerobic fermentation may potentially lead to higher energy recoveries and further research efforts should be directed to ensure process efficiency and stability.

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Chapter 9
Resource Logistics Analysis on Phosphorus and its Applications for Science, Technology and Innovation (STI) Policy

Kazuyo Matsubae and Tetsuya Nagasaka

Abstract Phosphorus is an important strategic resource for agricultural food production and the chemical industry. Natural phosphate ore is traded worldwide as a raw material for fertilizers; however, owing to the growing demand for fertilizers worldwide, its deposits could deplete within the next century. The average price of the ore in 2008 was approximately twice that in 2007. Considering the limited supplies of phosphorus, it is important to evaluate the quantity and availability of currently untapped phosphorus resources. Thus, we developed the Integrated Phosphorus Cycle Input Output (IPCIO) model to estimate the phosphorus requirements for economic activities and to evaluate the recycling effects of reutilizing currently untapped phosphorus resources. The model's accounting framework includes four natural resources, 25 phosphorus-related commodities in physical terms, and 389 intermediate sectors of the Japanese economy for 2005.

Keywords Resource logistics · Sustainable resource management · MFA · Stakeholders · Supply chain · STI policy

9.1 Introduction

Scientific technologies are researched, developed, and then disseminated to wider society under resource and environmental constraints. Resource limitations lead to the creation of new green innovative technologies, which in turn generate additional resource demands. In fact, innovations in science and technology (S&T) are important drivers of economic performance, although we still have inadequate knowledge to develop scientific and technological innovations to solve all problems in society. In order to facilitate innovation, it is necessary to understand the flow of resources in the supply chain. However, such a 'bottom-up' approach does not allow a comprehensive understanding of the changes in the resource demand structure of supply

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K. Matsubae (✉) · T. Nagasaka
Department of Metallurgy, Graduate School of Engineering, Tohoku University, Sendai, Japan
matsubae@m.tohoku.ac.jp

K. Matsubae
Graduate School of Environmental Studies, Tohoku University, Sendai, Japan

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chains caused by the application of innovation and the loss of resources through waste and exhaust emissions. Further, the current scenario of resource utilization creates a compilicated network among stakeholdes and is not conducive to the development of innovative technologies.

Considering the above points, we propose a method for visualizing resource logistics such as where, how, and how much resources are utilized in each field; what kind of changes are expected in the utilization of resources with the introduction of new technology; and what are the ripple effects of technological innovation in the supply of resources, which could face physical and economic barriers when used. The study also aims to extract the number of stakeholders involved in logistics and demonstrate the extent of their involvement.

Stakeholder dialogue is important for the introduction and implementation of new technology and insufficient knowledge sharing among them can lead to miscommunication. The visualization of resource logistics enables stakeholders to share information and be aware of the knowledge gaps among themselves. By clarifying resource logistics, it becomes possible to understand the flow of resources such as metals and materials, and the products processed within the supply chain. This also makes it possible to understand the efficiency of the system and to identify ways of avoiding resource risk. This study attempts to identify the critical nodes in the supply chain network, which will help in determining the areas that need further research and should be the focus of development in relation to new innovative technology, from the viewpoint of avoiding resource risk in the supply chain.

9.2 Resource Logistics Analysis

9.2.1 Method

The main framework for resource logistics is based on the input-output (IO) model, which follows the framework of the WIO-MFA model (Nakamura et al. 2007). In this framework, the amount of input i necessary to produce a unit of output j (i, $j=1,\ldots,n$) is assumed to be a_{ij}. A is assumed to be a matrix of size $n\times n$ (input coefficient matrix), which treats the input as element i, j. The action of two matrices on A yields $\tilde{A}$, which describes the actual output composition. The first matrix is a material flow filter Φ, eliminating a substance flow that cannot be expressed in terms of mass. This $n\times n$ matrix gives $\phi_{ij}=1$, when the input makes up the output mass, and $\phi_{ij}=0$ in other cases. For instance, when the input does not have a mass, as in the case of service businesses, or when the input has a mass but the output is limited to supplemental purposes, the matrix gives $\phi_{ij}=0$. The action of Φ on A enables a description of the substance flow necessary for the materials flow analysis (MFA). The second matrix is the yield coefficient matrix Γ. All raw materials used as input do not always form products in actual processes. Some of the materials are excluded as process losses. Therefore, Γ consists of a proportion γ_{ij}, defined as the ratio of the output to the input. The action of this matrix on A can eliminate input flow that will not be directed to the output. In other words, $\tilde{A}$ is calculated by Eq. (9.1), in which $\otimes$ is the Hadamard product and element i, j of $\tilde{A}$ is $\gamma_{ij}\phi_{ij}a_{ij}$.

$$\tilde{A} = \Gamma \otimes (\Phi \otimes A) \tag{9.1}$$

Let us now consider the phosphorus contained in residues such as wastewater, livestock manure, and slag. The input table describes the phosphorus that is input into each industrial sector. However, the phosphorus contained in fertilizers does not entirely transfer to agricultural products but accumulates in the soil, water, and other residues as well. For example, phosphorus is used in the production of pig iron, which uses 131×10^3 kilotons (kt) of iron ore, 20×10^3 kt of limestone, and 36×10^3 of coke, accompanied by 78.6 kt-P, 2.5 kt-P, and 9.4 kt-P amounts of phosphorus, respectively. However, the phosphorus used for steel products is one of the most important aversive substances, thus almost all the phosphorus ends up being removed as steelmaking slag. In this case, the yield ratio of phosphorus in steel materials is almost zero.

The next stage of the process is to divide n into three types of exclusive and nonempty groups—Product (P), Resource (R), and Material (M)—and divide $\tilde{A}$ into nine sub-matrices, as shown in Eq. (9.2), where $\tilde{A}_{PM}$ is $n_P \times n_M$, $\tilde{A}_{PR}$ is $n_P \times n_R$, and $n_P + n_M + n_R = n$:

$$\tilde{A} = \begin{pmatrix} \tilde{A}_{PP} & \tilde{A}_{PM} & \tilde{A}_{PR} \\ \tilde{A}_{MP} & \tilde{A}_{MM} & \tilde{A}_{MR} \\ \tilde{A}_{RP} & \tilde{A}_{RM} & \tilde{A}_{RR} \end{pmatrix} \tag{9.2}$$

P, R, and *M* meet the following conditions according to their processing levels:

a. Resources are collected from the global environment, not produced. $\tilde{A}_{iR} = 0$, $i = P, M, R$
b. Materials are produced from resources. $\tilde{A}_{iM} = 0$, $i = P, M$
c. Products are produced from materials and products. $\tilde{A}_{RP} = 0$

Under condition (a), resources are not produced within this system. In other words, this condition represents the lowest level of material processing. Under condition (b), materials are produced only from resources with a low level of processing, and not from the materials themselves. Owing to the equality of all levels of processing, these materials are not introduced into other materials. This requirement is necessary to avoid double counting. Under condition (c), a product is made from materials with a low level of processing, but a product with a low level of processing is introduced into a product with a high level of processing. Resources are not input directly into a product.

The application of this condition to $\tilde{A}$ gives the submatrix in Eq. (9.3):

$$\tilde{A} = \begin{pmatrix} \tilde{A}_{PP} & 0 & 0 \\ \tilde{A}_{MP} & 0 & 0 \\ 0 & \tilde{A}_{RM} & 0 \end{pmatrix} \tag{9.3}$$

When $\tilde{A}_{PP} = 0$, the material composition of a product is simply given by $\tilde{A}_{MP}$. The composition, however, generally forms $\tilde{A}_{PP} \neq 0$ because of the input of intermediate products such as parts. A matrix of the material composition C_{MP} is commonly given by Eq. (9.4):

$$C_{MP} = \tilde{A}_{MP}(I - \tilde{A}_{PP})^{-1} \tag{9.4}$$

Here, the element i, j represents the volume of materials that make up the unit product j. Thus, the column sum gives the weight of the unit output j. When a unit of a product is expressed in physical terms, for instance, as 1 t, the column sum of the applicable composition matrix also becomes 1 t. When the product is expressed on a monetary basis, for instance, as 1 million yen, the column sum of the applicable composition matrix represents the weight per 1 million yen.

9.3 Case Study: Resource Logistics on the Supply of Phosphorus in Economic Activities

9.3.1 Why Phosphorus?

Phosphorus is present only as a trace element on the Earth, but it is one of the important strategic resources for agricultural food production and the chemical industry. In 2005, approximately 147×10^3 kt of phosphate ore was mined worldwide. Of this, 24.7 % (36.3×10^3 kt) was produced in the USA, 20.7 % (30.4×10^3 kt) in China, and 17.1 % (25.2×10^3 kt) in Morocco, while essentially no deposits of phosphate ore exist in Japan or the EU. An increasing cause of concern is the growing demand for fertilizers worldwide, which could cause the deposits of the high-grade phosphate ore to deplete within the next century (Vaccari 2009). Moreover, the average price of the ore in 2008 was approximately twice that in 2007. Considering the limited supplies of phosphorus, it is important to evaluate the quantity and availability of currently untapped phosphorus resources.

It is evident that an increase in the global population will increase the demand for food; hence, the demand for larger quantities of phosphorus is expected to grow in the future. The global production of agricultural products is dependent on a small number of ore-producing countries. Phosphorus, like guano, is produced in part from the accumulation of bird manure, and although it mainly exists as an underground resource, its depletion rate has raised concerns. The demand for biofuels has also increased because of the diversification of energy resources and the need to reduce greenhouse gas emissions; hence, there is a major demand for crops such as sugarcane and corn as biofuel materials. The use of bioethanol is now increasing rapidly around the world, a trend that is also affecting crop production patterns. Bioethanol has the potential to become 'carbon-neutral' on a life cycle basis. However, growing such crops requires water and nutrients supplied by fertilizers, in addition to the need for fossil fuels in machinery used for harvesting. In this context, the securing of supplies of phosphorus has considerable implications that extend beyond food and agricultural policy.

Various authors have analyzed the flow of phosphorus from both economical use and recycling perspectives (Li et al. 2007; Neset et al. 2008; Matsubae-Yokoyama et al. 2010). From these analyses, we might better be able to go beyond the 'once-through mode of societal phosphorus metabolism' described by Liu et al. (2008). However, it is difficult to trace the supply chain of phosphorus used in products, because phosphorus and other plant nutrients are one of the most widely used elements in society. This point calls for taking a bird's-eye view for a better understanding of the flow of phosphorus including agricultural products and meat products (Goodlass et al. 2003).

9.3.2 Data

It was necessary to classify the flow of phosphorus by demand for this analysis. Thus, we first evaluated the flow of phosphorus within the Japanese economy. Second, we focused on the agricultural demand for phosphorus. The phosphorus requirement for one unit of agricultural production was estimated on the basis of fertilizer statistics and the lifecycle inventory data of livestock feed. Matsubae-Yokoyama et al. (2009) had evaluated the phosphorus flow of Japan in 2002. We evaluated the domestic phosphorus flow partly with reference to data from previous studies and analyzed the agricultural and related sectors in more detail with use of the Japanese input-output table for 2005, the food balance sheet, and other agricultural statistics.

Figure 9.1 shows the substance flow for phosphorus in Japan. The flow was estimated from the statistical data based on the above-mentioned 2005 data. To simplify the analysis, the total phosphorus flow was evaluated by considering each of the sectors shown in the flow and the total mass balance. Although there are other much smaller input and output flows, we omitted those with values smaller than 10 kt from the figure.

The Material Flow Analysis (MFA) reveals estimates of the domestic stock and flow of phosphorus in Japan. The total input of phosphorus into Japan is estimated to be 616 kt. Of this input, 40 % (251.1 kt) is used in fertilizers and 26 % (163.1 kt) is consumed by humans and livestock; the phosphorus through both routes finally ends up in either soil or water. In addition, 16 % (100.5 kt) phosphorus is utilized in

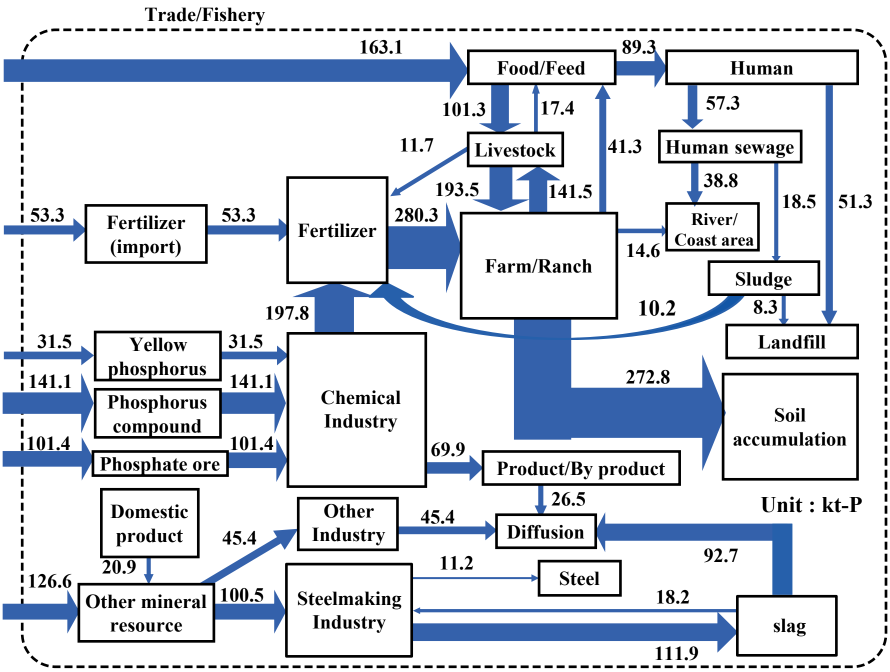

Fig. 9.1 Phosphorus flow within Japan. (Matsubae, 2011)

Table 9.1 Estimated Phosphorus flow relating chemical products in 2005 (ver.20130330)

	Injection (t-P)	Amount by use (t-P)								
		Food additive	Plasticizer	dye	Medicine	Surface acting agent	Cosmetics	Pesticide	Metal-surface treatment	Other Product
Phosphoric acid	35683.2	1591.5		71.4	1613.1	6088.0			16477.6	9841.6
Sodium phosphate	6832.2	2933.4		16.2	743.8				2011.5	1127.3
Anhydrous phosphoric acid	2269.7				290.9	216.6		1475.0		287.3
Phosphorus chloride	9753.5		1999.7		131.9	2337.8		1504.8		3779.2
Ammonium phosphate	968.4	140.6		54.5						773.3
Potassium phosphate	1241.9	917.8								324.1
Calcium phosphate	12036.2	9781.8			566.9		566.9			1120.6
Red phosphorus	261.4								25.8	235.7
Other	865.7							60.4		805.3
Total	69912.3	15365.2	1999.7	142.1	3346.6	8642.4	566.9	3040.2	18514.8	18294.3
Proportion by use(%)	100.0	22.0	2.9	0.2	4.8	12.4	0.8	4.3	26.5	26.2

the steel industry as a mineral resource, most of which is condensed in steelmaking slag. The remaining phosphorus (approximately 45.4 kt) is used in industrial chemical products (excluding fertilizers), accounting for 7.4 % of the total phosphorus input. The use and amount of phosphorus in chemical industrial products varies. There exist no clear data on how much phosphorus is present in various products of the chemical industry.

Further, it is important to clarify the flow of recycled phosphorus compounds; thus, we estimated the use of phosphorus in chemical products, as shown in Table 9.1, based on a market survey and interview data.

9.3.3 Tool: Integrated Phosphorus Cycle Input Output Table

9.3.3.1 Construction of the IPCIO

Based on the phosphorus flow data estimated so far, we established an Integrated Phosphorus Cycle Input Output (IPCIO) database and its analytical model with the following setups:

- IPCIO database with phosphorus contained goods flow.
- Phosphorus yield loss coefficient considering the difference between phosphorus input as intermediate goods and output as produced commodities.
- Phosphorus recovery technology matrix as scenario parameters.

We defined phosphate ore, coal, iron ore, and limestone as R and yellow phosphorus, dry phosphoric acid, and wet phosphoric acid as M. However, since many phosphorus-related commodities, such as phosphorus ore and phosphoric acid, do not exist as independent sectors in the conventional input-output table, it is not possible to examine the recycling of phosphorus through analyses employing the conventional input-output table. For example, phosphorus ore is aggregated in the sector called "other nonmetallic minerals," which excludes items such as limestone and ceramic mineral raw materials, and phosphorus compounds such as phosphoric acid and calcium phosphate are aggregated in the sector called "other inorganic industrial products." Therefore, while constructing the IPCIO model, the sector classification of the conventional input-output table was revised to include items such as phosphorus ore and phosphoric acid, which had been aggregated under the conventional sector, as independent sectors. Furthermore, for waste material such as iron and steel slag and sewage sludge, which are considered secondary resources of phosphorus, new sectors were created, since they are not present in the sector classification of the conventional input-output table.

While disaggregating and creating sectors, the method of classification differed depending on whether the row or the column of the input-output table was considered. For example, since phosphorus ore can only be 'raw material' for phosphorus products, it is not necessary to add 'phosphorus ore' as a sector in the column that represents supply destinations. On the other hand, since phosphoric acid is the supply destination for phosphorus ore (wet and dry phosphoric acid are produced from phosphorus ore) and raw material for various phosphorus products, it functions as both a supply source and a destination, and a disaggregation of sectors in both the row and column are required. By considering the above points, we extended the conventional input-output table as in Table 9.2 and created an accounting matrix that explicitly accounts for the flow of phosphorus-related commodities.

The allocation of the quantity of phosphorus required for each phosphorus-related commodity to each of the supply destinations can be done in the following ways:

1. The value of the quantity of phosphorus supplied to each sector is determined on the basis of the material flow estimated from industry statistics and data through interview.

Table 9.2 Sector disaggregation in the IPCIO database

Raw section (before)	**Raw section (after)**	
Other nonmetal mineral	Phosphate ore	Other nonmetal minerals
Egg	Poultry manure	Other egg products
Broiler	Poultry manure	Other broiler products
Pig	Pig manure	Other pig products
Beef cattle	Beef cattle manure	Other beef cattle products
Other dairy products	Dairy manure	Other dairy products
Organic manure	Organic manure (animal)	Organic manure (plant)
	Non-phosphorus organic manure	
Chemical fertilizer	Phosphate fertilizer	Complex fertilizer
	Non-phosphoruschemical fertilizer	
–	Waste manure	
–	Steel making slag	
–	Sewage, sludge	
–	Food residual	
Other inorganic chemistry industrial products	Wet phosphoric acid	Phosphorus chloride
	Thermal phosphoric acid	Ammonium phosphate
	Yellow phosphorus	Potassium phosphate
	Phosphoric acid	Calcium phosphate
	Sodium phosphate	Red phosphorus
	Anhydrous phosphoric acid	Other phosphorus compound
	Other inorganic chemistry industrial products	
Other chemistry end products	Metal-surface treatment	Other chemistry end products

Column section (before)	**Column section (after)**
Organic manure	Organic manure (animal)
	Organic manure (plant)
	Non-phosphorus organic manure
Chemical fertilizer	Phosphate fertilizer
	Complex fertilizer
	Non-phosphorus chemical fertilizer
–	Waste manure
Other inorganic chemistry industrial products	Wet phosphoric acid
	Thermal phosphoric acid
	Yellow phosphorus
	Phosphoric acid
	Sodium phosphate
	Anhydrous phosphoric acid
	Phosphorus chloride
	Ammonium phosphate
	Potassium phosphate
	Calcium phosphate
	Red phosphorus
	Other phosphorus compound
	Other inorganic chemistry industrial products
Soap, Detergent, Surface acting agent	Soap, Detergent
	Surface acting agent
Other chemistry end products	Metal-surface treatment
	Other chemistry end products

2. In cases wherein the supply/demand relationship with the supply destinations of the phosphorus-related commodity can be ascertained quantitatively from the production value tables by sector and commodity (which are appended to the input-output table), allocations of the domestic quantity of supply of a phosphorus-related commodity are made according to the monetary values of the intermediate demand. For example, by using this method, estimations were made for natural resources and secondary products of phosphorus, such as coal and surfactants. In the case of coal, all industrial sectors use coal with the same concentration of phosphorus. However, in the case of surfactants, although the use

Table 9.3 Inventory of phosphorus recovery technologies

			Recovery Technology							
			Decreased fertilizer	Carbonization of manure	Magnetic separation	HAP method	MAP method	Alkaline elution og ash	Heatphos method	Reduction and melting of ash
Resources required to recover 1t-P	Secondary resources for recovery of 1t-P (t-P)	Fertilizer	1							
		Poultry manure		1.43						
		Slag			1.61					
		Sewage				1.25	1.1			
		Sludge						2.22	2.86	1.47
	Recovery rate		1	0.70	0.62	0.80	0.91	0.45	0.35	0.68
	Injection for recovery of 1t-P (million yen)	Electricity		0.250	0.040	0.058	0.058	0.117	0.259	0.270
		Chemical drug		0.022		0.219	0.244	0.283	0.546	
		Fuel		0.165						0.035
		Others		0.011	0.003					
		Total	0.000	0.448	0.043	0.277	0.302	0.400	0.806	0.305

of phosphate surfactants and other surfactants varies significantly by industry, all industries use all types of surfactants in the same proportions.

3. In addition to the method in 2 above, the use or non-use of a given phosphorus-related commodity in an intermediate demand sector is classified in the form of binary data of 1, 0 from technical information, and this is used to complement the information on the proportions of the allocations of the monetary value.

9.3.3.2 Phosphorus Recovery and Recycling

There exist various methods for the recovery of phosphorus, such as the MAP (Monoammonium Phosphate) method, the HAP (Hydroxyapatite) method, and magnetic separation. Different methods require different technologies, which employ different materials and energy sources. Recovered phosphorus also takes on different forms depending on the technology used for its recovery. For example, the MAP method requires ammonia and magnesium oxide, and recovered phosphorus from sewage sludge forms $MgNH_4PO_4$, which can be substituted as fertilizer material. Other wastewater treatments require an adsorbent material and calcium hydroxide, and the recovered phosphorus forms hydroxyapatite, which can be substituted for fertilizer materials or phosphorus ore. Table 9.3 shows an inventory of such technologies.

Let us denote the following:

$X^P = \left\{X_{ij}^P\right\}$, $X^w = \left\{X_{ij}^w\right\}$, and $X^{NP} = \left\{X_{ij}^{NP}\right\}$ are phosphorus-related goods i, which are used in sector j; phosphorus contained waste generation; and input of non-phosphorus goods, respectively.

$$\hat{X}_{ij}^P = R_i X_{ij}^w \tag{9.5}$$

$$\hat{X}_{ij}^{NP} = g_{lm} X_{ij}^P \tag{9.6}$$

$R = \{R_i\}$ and $G = \{g_{lm}\}$ represent the recovery rate of phosphorus related goods i, and the recovery technology coefficient denotes that additional input of goods and services, *m*, to recover one unit of phosphorus-related goods, *I*, as shown in Table 9.3.

The Leontief inverse matrix sets an import and inflow endogenous type multiplier:

$$\tilde{B} = [I - (I - m)\tilde{A}]^{-1} \tag{9.7}$$

where $\tilde{A}$ is the input coefficient matrix as defined in Eq. (9.3) and m is the diagonal matrix of the import ratio (the ratio of imports to total domestic demand). Note that the m of yellow phosphorus is set to zero, as 100% of yellow phosphorus is imported because Japan does not have a domestic facility to produce it. Thus, in this analysis, the demand of yellow phosphorus implies the demand of imported yellow phosphorus.

In following scenario analyses, $\tilde{A}'$ is calculated by additional inputs (both positive and negative value) plus the default value of the intermediate input. The innovative effects of new phosphorus recovery technology in each scenario are derived by:

$$X' = [I - (I - m)\tilde{A}']^{-1} Y \tag{9.8}$$

where Y is the final demand vector.

9.3.4 Results

9.3.4.1 Phosphorus Requirement for Economic Activity

Figure 9.2 shows the amounts of phosphorus, estimated using C_{MP}, contained in products corresponding to production amounts of 1 million yen as well as the demand for phosphorus as a material ('material' refers to wet phosphoric acid, dry phosphoric acid, and yellow phosphorus). The results show that 1 million yen of rice and beef contain 1.71 and 0.02 kg of phosphorus respectively, and that a domestic demand for 10.08 and 2.10 kg of phosphorus arises in order to produce the fertilizer, feed, and agricultural chemicals required for their production. Food services corresponding to 1 million yen contain 0.05 kg of phosphorus, and a demand for 0.41 kg of phosphorus arises in order to supply it. In the demand for phosphorus in food services, in addition to the demand of food origin, there is also an influx in the form of detergents and food additives. The demand in these three sectors is mainly for wet phosphorus acid (required for fertilizer production), but it is expected that the proportion of phosphorus derived from dry phosphoric acid will be greater in the industrial sectors.

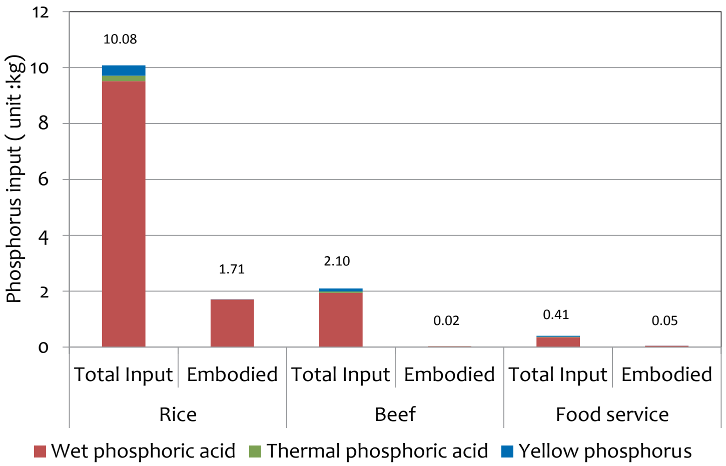

Fig. 9.2 The amount of input and embodied phosphorus demand associated with food demand (Unit: kg-P)

9.3.4.2 Selecting Stakeholders Based on the IPCIO Model

Japan has no phosphate ore deposits and therefore relies on imports for nearly all phosphorus resources. Of the phosphorus resources imported into Japan, 77 % (251.1 kt-P) is used for the manufacture of fertilizers, while the rest is used for the manufacture of industrial chemical products such as phosphorus compounds. The most significant stakeholder in relation to the consumption of phosphorus resources is therefore the agriculture sector, and the production process of rice plays a major part in this consumption. The agricultural sector is not only the largest consumer, but it also holds a prominent position in the accumulation and dispersion of phosphorus on agricultural land (Fig. 9.3). Phosphorus compounds manufactured by the chemical industry sector predominantly comprise dry phosphoric acid and yellow phosphorus derivatives, of which almost 20 % is used in applications for metal surface treatment. In spite of the fact that much of the phosphorus used is transferred into sewage sludge, currently the majority of phosphorus is not being recycled. Agriculture and metal surface treatment industries are therefore considered significant stakeholders from the perspective of both use and dispersion. Phosphorus that flows into the iron and steel industry to accompany iron ore, coke and others, is only present in minute quantities, but is almost entirely transferred to steelmaking slag. It is not recycled as a phosphorus resource, and thus, the iron and steel industry is also a significant stakeholder from the perspective of dispersion.

Furthermore, when the demand for yellow phosphorus in the supply chain was estimated, it was revealed that soap and synthetic detergent manufacturing as well as dyeing were processes with a high ‘per economic activity unit’ demand for yellow phosphorus (Fig. 9.4). Focusing on final products, the copying machine and automotive industries were identified as industries with the largest per unit demand,

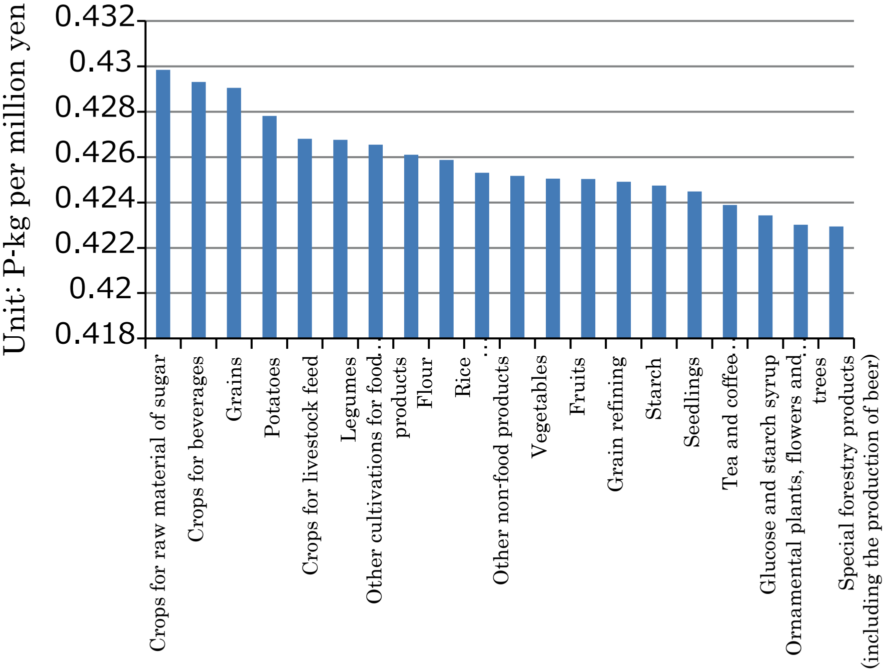

Fig. 9.3 Demand per 1 million yen for economic activities using phosphorus by weight

and although the phosphorus demands of these industries are small, they were revealed to be important stakeholders in terms of yellow phosphorus consumption. There is no production base for yellow phosphorus in Japan, and the country relies on imports from China for over 90 % of the supply. It was revealed that the supply of yellow phosphorus required for metal surface treatment, which is an intermediary process, could present risks to the supply chain of the automotive industry, which is an important industry for Japan.

9.3.4.3 Evaluation of the Effect of Innovative Technology to Recover Phosphorus from Waste Streams

Here, the prepared IPCIO model is used to estimate the demand for phosphorus-related commodities when there is a change in the final demand and to analyze the ripple effects accompanying the introduction of recycling technologies. We created the following four scenarios shown in Table 9.4, which are considered technically feasible, for the presumed recycling uses of phosphorus, based on the amounts of each of the potential secondary resources obtained from the results of the Material Flow Analysis and the recovery technologies that have been devised at present.

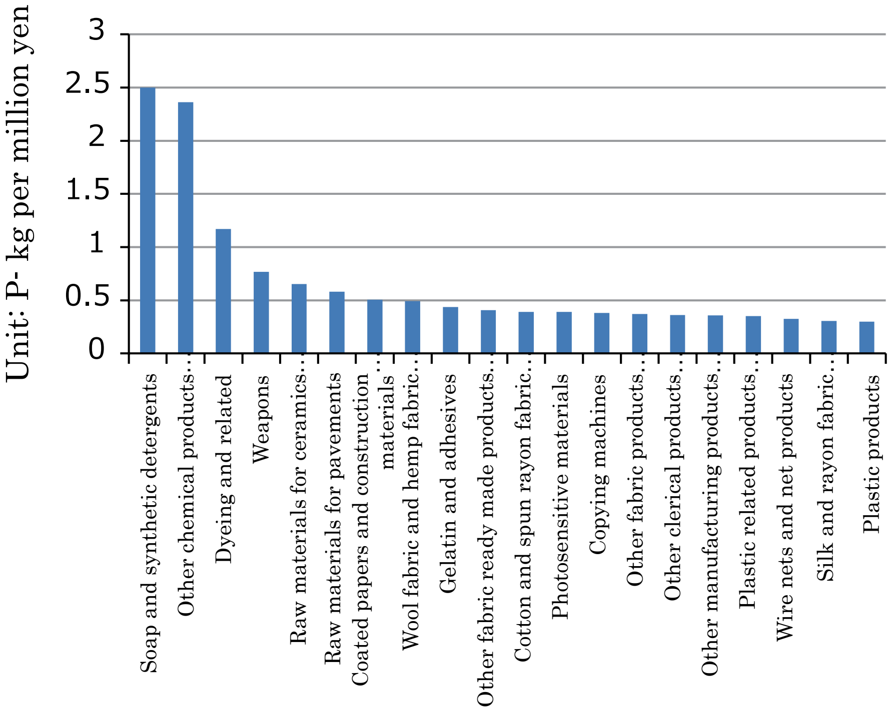

Fig. 9.4 Demand per 1 million yen for economic activities using yellow phosphorus by weight

Table 9.4 Scenarios for recycling uses of phosphorus

Scenario		Recovery source	Substitute
1	Carbonization of poultry manure	Poultry manure	Fertilizer
2	Phosphorus recovery from wastewater by HAP method	Wastewater	Fertilizer
3	Phosphorus recovery from sewage sludge by Heatphos method	Sewage sludge	Fertilizer
4	Yellow phosphorus recovery from incineration ash of sewage sludge	Incineration ash of sewage sludge	Yellow phosphorus

Examining the scenarios in Table 9.4 in more detail in Table 9.5 shows the following;

1. Carbonization of poultry manure
   Fertilizer created by reusing phosphorus through the carbonization of poultry manure is produced commercially. Thus, in this scenario, of the 222.8 kt of phosphorus in livestock excreta, 21.2 kt (which is half of the 42.3 kt of the poultry manure of broilers) was presumed to be subject to carbonization treatment for reuse as fertilizer.

Table 9.5 Summary of the results of scenario analysis

	Unit : t-P, million yen	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		Carbonization of manure	HAP method	Heatphos method	Reduction and melting of ash
Phosphate rock	t-P	-6420.8	-4349.5	-6468.4	0.1
Phospatic fertilizer	t-P	-3.6	2.3	8.7	0.1
Compound fertilizer	t-P	-4.9	3.2	12.0	0.2
Wet phosphoric acid	t-P	-6240.3	-4227.2	8.6	0.1
Yellow phosphorus	t-P	0.0	0.0	0.1	-12584.5
Ammonium phosphate	t-P	-71.9	-48.7	0.1	0.0
Sewage/Sludge	t-P	0.0	10000.0	-3728.7	2378.4
Other inorganic chemistry product	t-P	153.8	1644.4	2766.9	0.9
Petroleum products	t-P	2238.8	55.1	185.4	524.5
Utility electricity	million yen	3835.6	625.1	1825.8	3555.6
Water supply	million yen	186.4	2.4	8.4	5.1
Industrial water	million yen	-1.9	2.0	7.3	0.4
Sewer	million yen	-0.7	1.8	6.7	1.4

According to the model estimates, the amount of phosphorus recovered from 21.2 kt of phosphorus in poultry manure was 14.7 kt; the cost of electric power required for the recovery was 3688 million yen; the cost of chemicals was 323 million yen; the cost of fuel was 2436 million yen; and the cost of other raw materials was 158 million yen. Further, by reusing 14.7 kt of phosphorus from poultry manure as fertilizer, the phosphorus in poultry manure, which accumulates in the soil, such as in ranches, and is used for growing feed, such as pasturage, decreased by 14.7 kt, and the phosphorus originating from imported ammonium phosphate and wet phosphoric acid, which is used in fertilizer production, decreased by 14.7 kt.

2. Phosphorus recovery from wastewater using the HAP method

   The amount of phosphorus contained in wastewater discharged from human activity is 57.4 kt. Of this amount, 38.8 kt of phosphorus is dispersed into the water after treatment and 18.5 kt is concentrated in sewage sludge. In this scenario, 10 kt of phosphorus is recovered by the HAP method from the wastewater that was previously discharged into watercourses.

   In order to recover 10 kt of phosphorus from wastewater, it is necessary to treat 12.5 kt of wastewater containing phosphorus using the HAP method, and 580 million yen of electric power and 2190 million yen of chemicals are required for the recovery. However, by reusing 10 kt of phosphorus recovered from wastewater as sewage sludge fertilizer, the demand for phosphorus in compound fertilizers, which had been produced in the industrial sector, decreases by 10 kt.

3. In recent years, technologies have been developed for the recovery of high concentrations of phosphorus as bio-phosphorus ore and yellow phosphorus from sewage sludge, and their reuse in industrial fields as phosphorus products with high added value is expected. As a result of analysis of the scenario, it was found that by recovering bio-phosphorus from sewage sludge using the Heatphos

method, although the amount of import of phosphorus ore is reduced by 6.4% (6.5 kt-P), the amount of money used in the production by the entire domestic industry with the introduction of the scenario increases by 7575 million yen, compared to a saving of 972 million yen from a reduction in the import of phosphorus ore.

4. Yellow phosphorus recovery from the incineration ash of sewage sludge
   A scenario is presumed in which phosphorus is recovered in the form of high purity yellow phosphorus for utilization in the chemical industry sector, by subjecting the entire 18.5 kt of phosphorus in sewage sludge to the technique of incineration ash melting. In reality, all phosphorus contained in sewage sludge is not transferred to incineration ash, but here it is assumed that the entire 18.5 kt of phosphorus contained is transferred into the incineration ash melting process. In this case, it is possible to recover 12.6 kt of yellow phosphorus from incineration ash of sewage sludge containing 18.5 kg of phosphorus, and 3400 million yen of electric power and 435 million yen of fuel are required for the recovery. However, by inputting the recovered 12.6 kt of yellow phosphorus into the chemical industry sector, the amount of input of other yellow phosphorus that is imported, decreases by an amount corresponding to 12.6 kt of phosphorus.

In summary, by introducing scenarios of carbonization of poultry manure and of treatment of wastewater by the HAP method, the amount of import of phosphorus ore could be reduced by 6.3% (6.4 t-P) and 4.3% (4.3 t-P), respectively, when phosphorus is recovered and reused as raw material for fertilizer. Under the scenario of recovering yellow phosphorus by melting and reduction of incineration ash from sewage sludge, the amount of import of yellow phosphorus could be reduced by 40% (12.6 kt-P), the direct and indirect cost of utilities such as electric power, which accompany the recovery of yellow phosphorus is 3836 million yen, and the amount used in production by the entire domestic industry is 5991 million yen. It can thus be said that these could be very useful recovery technology and recycling scenarios in view of the possibility of improvements in the recovery technology and the rise in prices of phosphorus resources.

9.4 Discussion

9.4.1 Implication for Stakeholder Dialogue

The results of the analysis on the material flow of phosphorus reveal that about 14% of available phosphorus is being injected to support the production of rice, a principal agricultural product in Japan. It is clear that in order to support a rice production of 1 million yen, there are direct and indirect demands for a quantity of 10 kg of phosphorus, which is approximately six times the amount contained in the rice itself. The amount of phosphorus yield loss for producing 1 million yen of rice is 8.2 kg and much of this accumulates in the soil. The excessive fertilization of soil has been a subject of concern in Japan in recent years, which makes agriculture an important stakeholder for taking part in the reduction of phosphorus accumulated in the soil, or for the development of innovative technologies to use phosphorus more effectively.

In consideration of resource management with a focus on yellow phosphorus however, the stakeholders would be practically all users of chemical industrial products. Phosphoric acid is used in the refining of cooking oil and for pre-paint surface treatment, and industries that use products which go through such processes in the supply chain, could potentially become stakeholders. From the perspective of resource dissipation, it is also evident that wastewater treatment, as well as iron and steel industries, play equally important roles.

9.4.1.1 Implication for Economic Structure

Economic structure is discussed from the perspective of resource logistics. Japan, which has no domestic phosphate ore deposits, relies on imports for all required phosphorus resources. The only method available for reducing the resource dependency on other countries is to recover and recycle unused phosphorus resources in Japan. In order to improve the efficiency of recoveries and recycling, geographical integration and physical concentration of resources are required. The paths in which these can be implemented are from sewage sludge and incineration ash, which are residues that remain after urban waste materials have been processed. Steel making slag with concentrated phosphorus, a steel production resource, could also be used. Since the waste material processing infrastructure is relatively well organized in the economic structure of Japan, waste materials with a high potential for recovering phosphorus have already been made available, and phosphorus recovered from such products are used as sludge fertilizer raw materials. However, the amount recovered has been limited to 10.2 kt-P, which is not even 10 % of the phosphorus contained in the waste materials discharged from households. There is, therefore, a need to nurture an industry that applies recovery technologies, and an industry that can effectively utilize recovered phosphorus, for successful phosphorus resource recycling.

There is no doubt that the automotive industry is a key industry of Japan. There is, however, no manufacturing base for yellow phosphorus, which comprises about half of all required phosphorus in the supply chain. The production bases of yellow phosphorus in Asia are located only in China and Vietnam, with practically the whole supply dependent on these two countries. The production of yellow phosphorus has been completely scrapped by all domestic industries, due to the fact that it is an industry with an intensive demand for electric power. In China, however, a provision involving an imposition of 100 % export tariff on yellow phosphorus was implemented in 2008 for the purpose of resource protection, environmental conservation and energy conservation in their pursuit for a domestic infrastructure that provides a stable supply. It was suggested that since delays in the supply of yellow phosphorus present significant effects throughout the supply chain, that industries that are impacted by such effects can become stakeholders in the creation of innovative power saving technologies for phosphorus refining of high purity.

9.4.1.2 Implication for Energy and Resource Conservation

A comparative examination of innovative technologies through scenario analyses indicates a significant increase in the demand of electric power for phosphorus recovery technology. In situations where there are strict restrictions on electric power production therefore, it will be difficult to replace imports. It is thus considered that technology is needed that produces high purity phosphorus using a supply of heat other from electric power, such as residual heat or geothermal heat.

9.4.1.3 Contribution of Resource Logistics to Science, Technology and Innovation Policy

The identification of the stakeholders who consume the specific resources and materials based on resource logistics is expected to contribute an important perspective to resource strategy and policies and to promote related research and development. By presenting clear evidence, it is possible to integrate knowledge gained from research and stakeholders. In order to implement new technologies that are important to the resource strategy required by society, it is important to clarify what kind of support, research evaluation, and intervention by the government is required. The provision of evidence for formulating policy proposals to support the promotion of innovation through the collaboration of multiple stakeholders is therefore now required. It is expected that by using the Material Flow Analysis method as a rational method to extract stakeholders, we can quantify resource demand in the supply chain, and can promote efficient discussion regarding waste and resource issues.

Furthermore, the dialogue between stakeholders is important in the introduction and effective implementation of new technologies. However, when insufficient knowledge is shared amongst such stakeholders, the risk of miscommunication exists. In order to improve knowledge to be shared for dialogue, the visualization of resource logistics enables stakeholders to share information and identify gaps in knowledge among themselves. Clarifying such resource logistics requires an understanding of the flow of metal resources, materials, and processed and applied products in a supply chain, which helps in identifying efficiency and ways of avoiding resource risks. In doing so, critical links in the supply chains are identified. It is considered that the research and development agenda needs to be emphasized from the viewpoint of avoiding resource risks in the supply chain when new innovative technologies are identified.

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Chapter 10
Waste Materials in Construction: Sludge and Recycling

Hiroshi Takahashi

Abstract Various sludges and muds from construction or waste water treatment have high water contents and are very difficult to treat or use. This chapter describes research and development on how to transform such sludges into usable materials—both as a general fill material and as a soil which can be used in replanting projects such as for covering slopes alongside roads. The method developed uses paper residues as a source of fiber to aggregate soil particles and produce a fiber-stabilized soil which has suitable characteristics for reuse. This chapter also describes a number of case studies where the treated sludges and muds have been successfully applied in a range of projects.

Keywords Construction sludge · Fiber-solidification · Planting soils · Recycling muds

10.1 Introduction

Construction sludge, dredging muds, water purification and sewage sludge and similar wastes all contain a high water content, which makes direct use extremely difficult. As a result, the recycling rate is very low and, with the exception of very few cases of re-use, most are treated in industrial waste sludge treatment facilities, or given intermediate dehydration treatment followed by direct landfill. However, a lack of waste disposal facilities, and their remoteness with the associated high transportation costs is posing serious problems, so that the burden of illegal dumping of construction sludge seems never to end. The effects of this pollutant load on the Earth's environment is thus becoming a major problem, so that an effective means of using muds with high moisture content is required. The standard methods

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H. Takahashi (✉)
Earth Exploitation Environmental Studies, Graduate School of Environmental Studies, Tohoku University, Sendai, Japan
e-mail: htaka@mail.kankyo.tohoku.ac.jp

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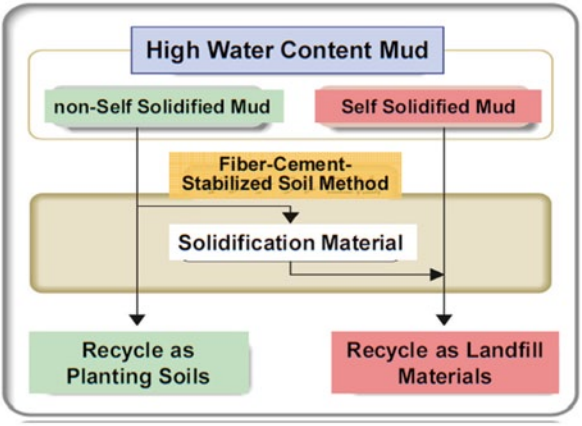

Fig. 10.1 Outline of fiber-cement stabilized soil method

for treating high moisture content muds include sun drying, dewatering, cement-based solidification but none of these can be seen as satisfactory (Takahashi 2006).

This chapter describes research to develop methods to deal effectively with high moisture content muds and sludges in order to create a re-usable resource. By adding textile materials, paper shredder residue and polymer additives, the quality of the sludges can be improved through a fibrous soil solidification method, leading to a high quality ground material which can be recycled (Mori et al. 2003).

The fibrous soil solidification method shown in Fig. 10.1 is a unique process with two options for the purpose of its application. In the case that the muds to be treated are from dredging, this process, not only treats the dredging mud (sludge), but can also solidify it using cement solidification materials so that the treated mud can be used as back filling material or in land reclamation. In the case of water purification (sewage) sludges, the soil can be used as a foundation soil for planting without solidification. With construction sludges, and with self-hardening cement sludges, their use is limited to backfill and land reclamation materials but in the case of non-hardening cement-containing sludges, the choice of treatment process can be adjusted to provide either fill materials or soils for planting vegetation in re-greening projects.

The most important feature of this method is to use textile materials or waste paper as local sources of fibers which impart various excellent characteristics to the sludge. This paper describes this ‘fiber-solidified soil treatment method in order to produce landfilling and reclamation materials’ and the ‘fiber-based treatment to produce soils suitable for reclamation planting (greening)’ in addition to providing typical examples of their use in construction projects.

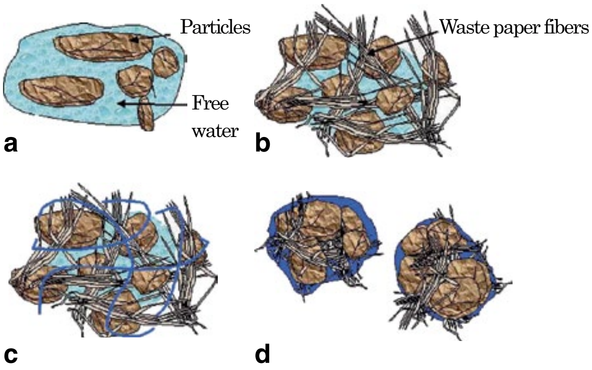

Fig. 10.2 Principle of the fiber-cement stabilized soil method

10.2 Fibrous Soil Solidification Process to Produce Backfill or Reclamation Materials

10.2.1 Principles of the Fibrous Soil Solidification Process

The principle of the fibrous soil solidification method is simply expressed as the following:

1. Regarding muds and sludges with high water content, as shown in Fig. 10.2, the soil particles are free to move in the water because it is in a state of low yield stress, and thus moves as a fluid. Due to this high moisture content, such muds are transported by pipeline or vacuum truck etc.
2. If materials such as waste paper[1] or textiles with high water absorption are added, as shown in Fig. 10.2, the free water around the soil particles is absorbed by the fibrous materials and a reduction in the moisture content is observed.
3. Moreover, if high molecular weight polymer additives are used to improve the agitation, as shown in Fig. 10.2, the water-soluble polymer is dissolved and adsorbed to the surface of the soil particles. This absorption forms cross-links between particles forming aggregate structures, trapping the water inside these aggregates, so that the liquid state is lost.
4. Finally, additives are mixed in and agitated, causing the mud to shear, so that a soil with high water retention is generated Fig. 10.2.
5. If the mud is not self-setting, to produce soils for use as fill and back filling materials, cement can be added to deliver the desired strength and solidification in the materials.

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[1] In our research the paper is sourced from recycled newspapers and similar materials shredded to a size of 15 mm; this paper debris is then used in the mixing process.

Table 10.1 Relationship between soil moisture content and paper, high molecular weight polymer and supplementary chemicals

Soil/water ratio (%)	Water content (%)	Amount of paper debris added (kg/m^3)	High molecular weight polymer added (Bon Terrain P) (kg/m^3)	Supplementary chemicals (Bon Terrain L) added (kg/m^3)
100	50.0	50	1.0	7.2
200	66.7	70		
300	75.0	80		
400	80.0	85		
500	83.3	90		

10.2.2 Amount of Paper Shredder Residue

In developing this process, the first matter which has to be established is to decide the optimum amount of shredded paper and polymer additive. In particular, since it is assumed that the effect of the shredded paper on the water content of the sludge will be critical, various levels of water content in the sludge, amounts of shredded paper and polymer additives, have been investigated to establish their effects on the process, and on the handling and observed characteristics of the soil, its quality and aggregate structure. The results of the changes in water content, paper shredder residue, and quantity of additives and polymers are shown in Table 10.1.

10.2.3 Fiber Strength Characteristics in the Soil Solidification Process

In order to use treated soil as back fill and reclamation material, an understanding of soil strength characteristics is essential. Therefore, we prepared a treated sample of 50 mm diameter and 100 mm height, and carried out compression tests (Mori et al. 2003). The results are shown in Fig. 10.3. In the case of solidification, increasing the load also increases the compression strain, but the solid only shrinks by 1–2 %, so the compressive stress increases to a maximum value up to the point of breakage. In contrast, if the soil is solidified using fibers, the destructive distortion is 7–8 % and, even after breakage the compressive stress is not reduced rapidly, and residual strength also grows. In other words, the fibrous solidified waste soil, compared with traditional cement solidification materials, provides a greater distortion before breakage and higher residual strength, which is an important special feature.

Figure 10.4 shows the state of breakage in the samples after testing. A clear fracture surface is seen in the solidified soil, which resembles the fracture shapes which occur in rocks and concrete. In contrast, the fiber-solidified soil does not produce a clear surface, and the sample as a whole grew in a so-called barrel-shaped deformation. This is because the inside includes fibrous substances so that soil particles and fibers are intertwined in a complex manner, making destruction difficult because at the same time the stress is distributed through the fibers.

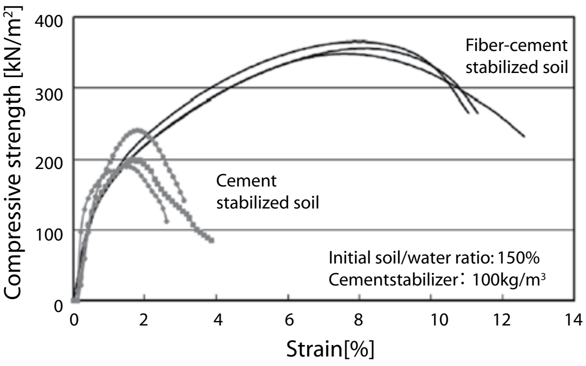
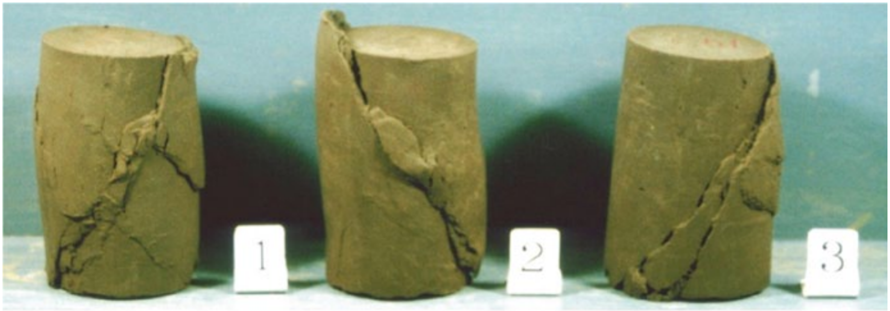
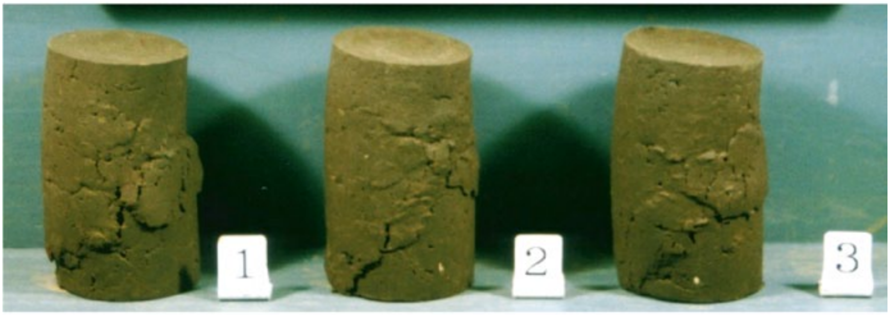


Fig. 10.3 Result of experiment on strength of fiber-cement stabilized soil



Cement stabilized soil failure conditions



Fiber-cement stabilized soil failure conditions

Fig. 10.4 Results of stabilized soil compressive tests

10.2.4 Wet and Dry Cycling Durability Test

With traditional cement solidified materials subjected to drying and wetting cyclic tests, there are reports of weakening in strength. As a result, in the event that soil solidification is used, in order not to suffer such adverse effects, it is considered that in areas of heavy freezing such as mountain areas, such materials must be protected

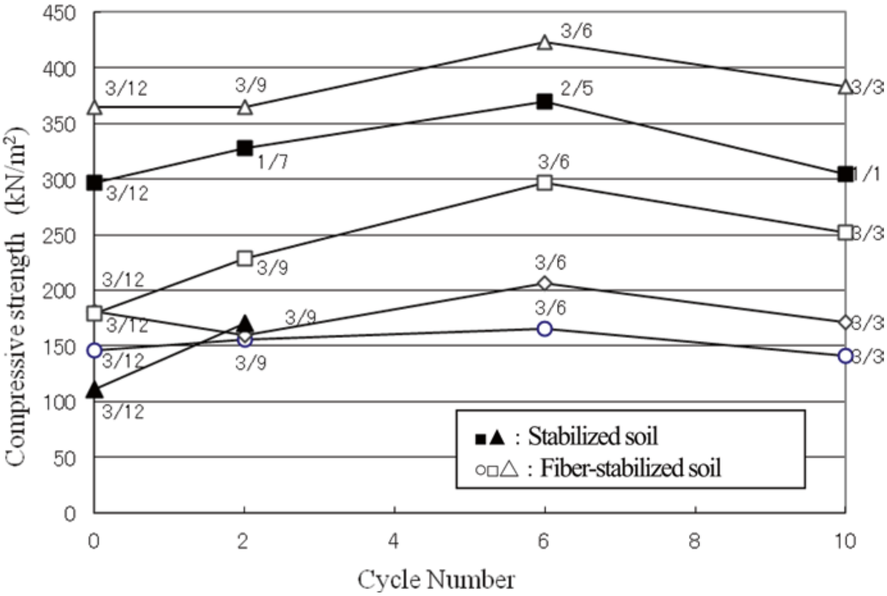


Fig. 10.5 Results of drying and wetting cyclic tests

from the elements by covering (Matsubara et al. 2000; Ogawa et al. 1996). We thus subjected fiber-solidified soils to drying and wetting cyclic tests in order to evaluate their durability (Mori et al. 2005).

Figure 10.5 shows the relation between the number of cycles and the compressive strength. ▲ marked solidified soils were subjected to a 2-cycle test, and the compressive strength values plotted; however the specimen was heavily worn, and after 3 or more cycles, it completely collapsed so it was not possible to continue. In contrast, the fiber-solidified soil showed no cracking or weakening even after the end of the 10th cycle. This shows that the fiber-solidified soil resistance to wet and dry cycling tests is very high and it is not necessary to restrict areas in which this soil can be used. Figure 10.6 shows the sample after the completion of the drying and wetting cyclic tests.

10.2.5 The Dynamic Strength of Fiber-Solidified Soil

In September 2003, the Tokachi-oki earthquake caused sewer inspection hatches and manhole covers to float up, and subsidence damage to sewerage facilities was also reported in on-site investigations. Many areas required soil as back-filling material to be used in repairs and an effective infill material was needed (Fujiu et al.

Fig. 10.6 Condition after completion of drying and wetting cyclic tests (initial water content 105 %, cement stabilizer supplement 100 kg/m^3)

Cement-stabilized soil after 2nd cycle

Fiber-cement stabilized soil after 10th cycle

2003). The fiber-solidified soil contains the fiber inside the soil so is considered to have good dynamic strength. Thus if such strong reinforced materials are used, it can provide an earthquake-resistant base material to repair suitable areas. So, using cyclic triaxial compression tests, we considered the dynamic strength of the fiber-solidified soils.

In Fig. 10.7 are the results of cyclic triaxial compression test on fiber-solidified mountain sandy soils (Takahashi et al. 2008). The horizontal axis is the elapsed time from the start of the test, and the vertical axis indicates excess pore water pressure. Where excess pore water pressure increases this makes liquefaction easy and dynamic strength is low. Compared with the mountain soil, the solidified soil had large dynamic strength, but the solidified soil containing fibers showed little increase in excess pore water pressure, and exhibited greater dynamic strength when the fibers were included. In other words, the fiber-solidified soils showed both good static and dynamic strength and also superior stress- deformation characteristics, showing that it is suitable for use as a seismic-resistant ground material. In the March 11, 2011 Great East Japan Earthquake, many areas suffered damage from ground liquefaction. I would like to recommend that fiber-solidified soil be used in the earthquake resistance and disaster recovery construction.

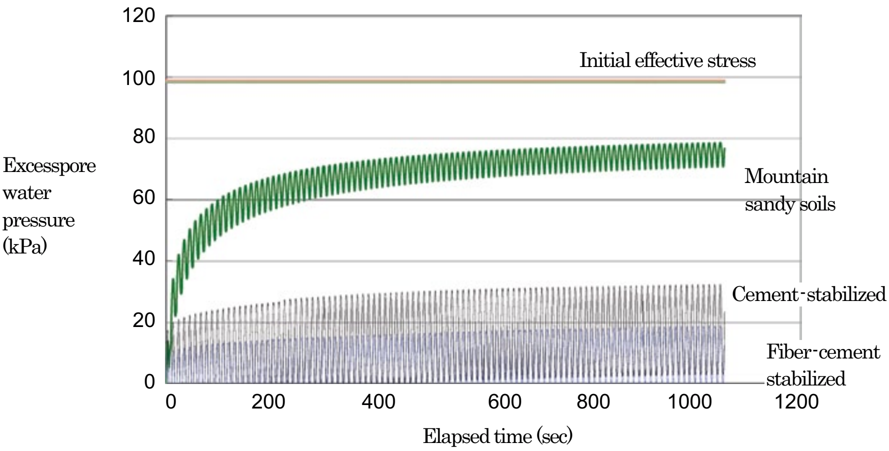


Fig. 10.7 Cyclic tri-axial compression test results

10.2.6 Construction Case Studies

10.2.6.1 Technology for Using High Moisture Content Soil in Embankment Construction for the Hamao Basin Embankment Work (Tohoku Regional Bureau of the Ministry of Land Infrastructure and Transport (MLIT), Fukushima River National Highway Office)

The Tohoku Regional Bureau of MLIT proposed to use private company technologies and patents in construction projects to achieve cost-reductions and increase the rate of recycling and in fiscal year 2002, selected four technologies towards this objective. One of these technologies was the fiber-solidification method for using high moisture content soils in embankment construction, and this was employed at Sukagawa town, Fukushima Prefecture, in the Hamao river basin construction project. This construction in the Hamao area of the Abukuma river catchment is to protect downstream areas from flood damage. In addition to factors of duration, cost and feasibility when excavating the retarding basin, the soil excavated would also be used in the construction of the levee around the basin, requiring an effective technology to make economic use of high water content muds. In the Fiscal 2002 year construction, 3000 m^3 were processed by the fiber-solidified soil method and used on the embankment building work. Subsequently, the embankment suffered no erosion from rain, nor have any cracks appeared in the bank, showing again that the fiber-solidified soils have high-durability, and that this was highly suitable for this type of project (Fig. 10.8).

Fig. 10.8 Construction of river bank in Hamao area, Fukushima Prefecture. The backhoe on the *right* side of the photo is putting in high moisture content mud into the pits; the *left* backhoe with mixing attachment is mixing with paper and materials and providing agitation

10.2.6.2 East Sendai Channel Construction (Tohoku Regional Development Bureau of MLIT, Sendai River National Highway Office)

This construction project is from Odawara, district to Honmachi in Aoba district of Sendai City, to protect Highway 45 with an underground drainage channel of 1.37 km length. The construction started with a basin shaft and facility under the road at Odawara and progressed through jacking and tunneling with construction of continuous underground walls formed by self-hardening liquid cement. Moreover, the construction site had adopted a policy of zero emissions, so the fiber-solidification method was used to treat waste sludges. At the site, the spoil from the excavation carried out at night in the jacking shaft construction was stored in a pit, and during the daytime, the soil was solidified using the fiber-solidification method. Because this was close to the centre of Sendai City, there was little spare room at the site for the generated sediment, so the solidified sludges were removed as soon as they were processed by dump truck, and could be used in the nearby Sendai Route 4 No. 1 bypass widening construction site; as a result, achieving complete zero emission levels. The site's limited space also required high efficiency heavy equipment; also vibration and noise levels were measured to ensure low vibration and low noise construction with respect to the local environment. This makes it an excellent example of avoiding generation of waste and achieving zero emissions- an eco-friendly construction site (Fig. 10.9).

Fig. 10.9 Construction of public utility conduit in Sendai (Miyagi Prefecture). Unlike Fig. 10.8, the construction site is located close to the center of town, so there is only limited work area requiring heavy equipment to be efficiently located and uncluttered. Upper right half of the photograph shows the 'Bon terrain' method location with loading and mixing underway

It should be noted that in 2007, the contract to extend the channel included a special specification that the fiber-solidification method should be used for the treatment of muds. This demonstrates that the benefits of the special characteristics of this method are fully appreciated.

10.2.6.3 Imokawa River Landslide Dam Construction Emergency Measures (Hokuriku Regional Development Bureau of MLIT, Yuzawa Erosion Control)

In October 23, 2002 at 17.56, an earthquake of magnitude 6 on the Japanese scale struck the Chuetsu region of Niigata Prefecture. Ojiya city (formerly the municipalities of Yamakoshi Nagaoka, Horinouchi and Kawaguchi) was affected by a big landslide of rocks and soil, causing extensive damage and blockage of housing, roads, railways, rivers, etc. This included large amounts of very soft soils. In order to effect a speedy recovery, the access roads to the affected areas needed to be restored as soon as possible, so the fiber-solidification method was used in the former Yamakoshi Village area disaster recovery construction works. This improved the

Fig. 10.10 Urgent countermeasures construction to respond to sediment-related disasters. Paper shredder residue mixed with soft soil; the rapid stabilization helps speed up the restoration work

local soft sediment so it could be used to make a temporary works area, and then in building a detour route while the reconstruction of highway 291 took place (Takahashi et al. 2006). This demonstrated that this approach can also be used at disaster recovery sites (Fig. 10.10).

10.2.6.4 Sunaoshi River Channel Excavation Works (Sendai Miyagi Prefecture Civil Engineering Office River Erosion Control Third Section)

In the March 11, 2011 Great East Japan earthquake, depending on location the tsunami height exceeded 10 m. Sediment carried by this huge tsunami deposited in the Sunaoshi river channel in Tagajo city blocking the channel. These tsunami deposits carried sediments from the bottom of the sea, and using these in the construction of the new river embankment was difficult. However, after using the fiber-solidification technique, the sediment could be improved to the level required for use in the river levee embankments. The soil liquefaction resistance rate (FL) of the improved sediment was 1.5–13 times that of general fill material (sandy soil) of FL 0.12, so is much more resistant to liquefaction. In addition, an increased shear resistance increases the stability of the soil, river levees and road embankment, and

Fig. 10.11 Condition improvement using fiber-cement stabilized soil-based construction at Suna-oshi river, Tamajo, Miyagi Prefecture

can also be used in a new land readjustment project for relocated victims to provide earthquake resistant ground. In Fig. 10.11, the improvement through using the fiber-solidification method on the sediments is shown.

10.3 Fiber Treatment of Soils to Produce a Base for Planting (Greening)

10.3.1 Deciding the Quantity of Paper Debris and Performance Evaluation of Planting Base Materials

The fibrous soil solidification method involves adding to the mud/sludge shredded paper debris and polymer additives which, after around 30 min of agitation, converts a difficult to dewater sludge into a soil with good strength and deformation properties; in the case of non-self-setting water treatment sludges, the pH can be improved giving a soil which can be used for planting vegetation. The author has compared the effectiveness in greening using foundation planting material produced by the fiber solidification process on construction sludges with the normal compost

Table 10.2 Target values for properties suitable for planting

	Basis of decision	Unit	Target value	Remark
Water holding ability	Effective water retention capacity	(l/m$^{3)}$	Above 100	pF1.5–3.8 range
Permeability	Coefficient of permeability	(cm/s)	More than 10^{-3}	
	3-phase distribution (solid, air, water)	(%)	Less than 30 solid	pF measurement of 1.5
			Above 25 air	
Lightweight	Specific gravity under wet conditions	(–)	Below 1.0	pF measurement of 1.5
Fertilizer holding ability	CEC(Cation Exchange Capacity)	(cmol/kg)	Above 6	

pF value indicates the strength in which the water in the soil is adsorbed by capillary force

used for planting derived from bark. In these results, the vegetation growing on a base of fiber-solidified sludge is better than that growing on bark-derived compost (Yamazaki et al. 2004). In addition, if you consider the soil's physical characteristics, the fiber-solidified soil, in comparison with normal commercial artificial lightweight soils, has good water retention capacity, light weight and also holds nutrients well, and is thus confirmed as a very promising greening base material.

Incidentally, the purpose of adding paper debris which is the special feature of this method, is to aggregate the high water content muds such as construction sludge without dewatering, and in doing so modify it into a transportable state. When the modified soils are utilized as landfill material, the amount of paper debris added is determined based on the water content ratio. However, in the case of producing planting soils, if the amount of paper debris added is determined solely based on the water content, the quality of the planting soil produced is not constant, because the ratio of the amount of soil to the amount of paper debris in the planting soils is not constant. Therefore, in order to produce planting soils of fixed quality regardless of the water content of the original sludge, the appropriate ratio for the amount of soils to the amount of paper debris was investigated (Yamazaki et al. 2008).

The necessary performance criteria for planting soils are 'water holding ability', 'lightweight', 'permeability' and 'fertilizer holding ability'. Accordingly, target values which the planting soils should satisfy were set as shown in Table 10.2.

Incidentally, when planting soils are produced in a factory, it is possible to reduce the water content of the modified soils fully by solar drying or other methods. However, when construction sludge is recycled into planting soils at the construction site, and subsequently used on site as the base for planting on slopes, it is difficult to reduce the water content fully. Therefore, in this study, the planting soils were made by two methods- a WET method and a DRY method. In the WET method, the water content of the planting soils produced was adjusted to be 40 ± 5 %, and in the DRY method, the water content of planting soils produced was adjusted to be 10 ± 5 %. These planting soils were made by changing the additive amount of paper debris, which is shown below, and the associated ‘water holding ability’, ‘lightweight’, ‘permeability’ and ‘fertilizer holding ability’ were evaluated quantitatively.

WET method

No.1-1 amount of soil particles: paper debris = 0:10 (paper only).
No.1-2 amount of soil particles: paper debris = 4:6
No.1-3 amount of soil particles: paper debris = 6:4
No.1-4 amount of soil particles: paper debris = 7.5: 2.5
No.1-5 amount of soil particles: paper debris = 9: 1
No.1-6 amount of soil particles: paper debris = 9.5:0.5
No.1-7 soil grain Quantity: paper debris = 0:10 (soil particles only).

DRY method

No.2-2 amount of soil particles: paper debris = 4:6
No.2-3 amount of soil particles: paper debris = 6:4
No.2-4 amount of soil particles: paper debris = 7.5: 2.5
No.2-5 amount of soil particles: paper debris = 9:1
No.2-6 amount of soil particles: paper debris = 9.5:0.5

Figure 10.12 shows the test results. The larger the ratio of the amount of soil to the amount of paper debris means less paper debris is required and a more economic composition, because the cost of the paper is expensive. Consequently, the minimum additive amount of paper debris which satisfies all target values is the most suitable amount of paper debris to be added. It is confirmed from Fig. 10.12 that the most suitable ratio of the amount of soils to the amount of paper debris, and which satisfies the target values of ‘effective water holding ability’, ‘coefficient of permeability’, ‘proportion of solid and air phase’ and ‘cation exchange capacity’ is 5.0 in the DRY soils. On the other hand, in the WET soils, the most suitable ratio between the soil amount and the amount of paper debris is 6.0, although the target values for ‘specific gravity in the wet condition’ and ‘proportion of air phase rate’ were not satisfied. In other words, if the proportion of soil in the sludge can be calculated and the amount of paper debris to be added is determined to achieve a ratio of soil to paper debris of 5.0–6.0, planting soils of fixed quality can be produced from muds of different water contents.

The test results showed that it was hard for WET soils to satisfy all the performance criteria. However, it can be considered that if the proportion of the soil phase in the planting soils and permeability are increased by allowing some of the gravitational water[2] to drain, all performance criteria will be satisfied. In order to realize the above conditions, the addition of framework structure materials such as wood chips in the produced planting soils may be effective.

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[2] Gravitational water is water which is not attached by absorption to soil particles or in capillaries and is thus more mobile.

Fig. 10.12 Effect of paper debris on physical characteristics of planting soil

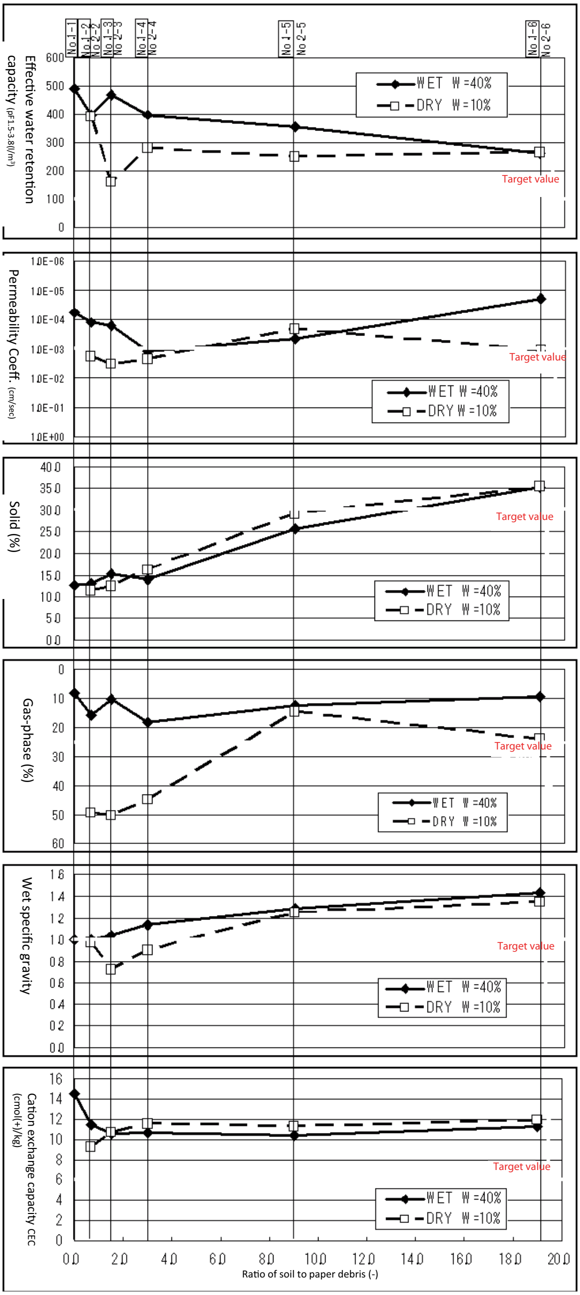

Fig. 10.13 Spray construction (*left*) and greening of the face after growth of vegetation (*right*): National Highway 13

10.3.2 Construction Case Studies

10.3.2.1 Rokuro Sayama Road Improvement Project (Tohoku Regional Development Bureau of MLIT Yamagata River National Highway Office)

The construction was the planting (greening) of the slopes resulting from the construction of a cutting to remove a bottleneck in Highway 13 between northern Yamagata Prefecture and southern Akita prefecture. The project had a total area of 9.9 km of earthworks between Kanayamacho/Tobinomori and Mamurogawa. The cutting produced much soil mixed with roots, branches and leaves, making recycling on site difficult. The tree residues were thus chipped to provide an alternative to the usual shredded paper in the fiber-solidification process. The resulting material was sprayed onto the slope as a base for replanting and provided significant cost savings relative to the standard slope spray methods, as well as making effective use of the waste materials (Fig. 10.13).

10.3.2.2 Fiscal Year 2004–2007 Akasa 8th Dam Embankment Construction (Tohoku Regional Bureau of MLIT Shinjo River Office)

Road construction and construction of an erosion-control dam in Ookura-village Mogami-county Yamagata Prefecture produced large quantities of soil with residues of trees (roots, small-diameter trees and branches). To make effective use of this material, the wooden material was chipped and mixed in the fiber-solidification method and applied to the slopes as a base material. The area included cracks in the rock and springs and a steep slope of 1:0.3, so there was concern whether the coating might erode and slip. However even after the winter snows had melted, there was no slippage and the new vegetation was growing steadily. Three months after the coating

Fig. 10.14 Spray construction (*left*) and greening of the face after growth of vegetation (*right*): Okura, Mogami, Yamagata Prefecture

was completed, 100 % of the vegetation was established, showing that the fiber treatment mixed with chippings had produced a resistant soil foundation (Fig. 10.14).

10.3.2.3 Oita City Hall Green Roof Construction

This example is of using water purification sludge as a base for vegetation in a rooftop greening project. Figure 10.15 shows the Oita City Hall building; in the image, the area enclosed by the dashed line is where the vegetation's base material was produced from the water purification sludge. The whole image shows the grassy area adjacent to a sandy beach, and birds perching on adjacent trees may spread seeds from adjacent areas, thus continuing to bring new life to the roof, while also finding a useful application for waste materials and communicating a positive message of effective recycling of resources.

Fig. 10.15 Oita city hall rooftop greening

10.4 Conclusion

The fiber-solidification method has the major characteristic of treating high water content waste soils, muds and sludges by adding paper shredder residues. The fibers which are generated internally to the soil quality produce a ground material with a variety of excellent characteristics. This method has been evaluated highly both for its academic and social contribution and by end of March 2014 had been applied in 360 cases with a total of 530,000 m^3. In addition, the technique has received the MLIT National Technology Development Award and commendations for collaboration between government, industry and academia, thus showing the extent to which it is externally recognized. It is our wish from this chapter that the fiber- solidification method will find increasing use across Japan.

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Chapter 11
Recycling of Waste Plastics

Toshiaki Yoshioka and Guido Grause

Abstract Society produces more plastics than steel every year, and these pose major challenges in resource recycling. The principles of 3R are introduced and their application to plastics. Obtaining high-value products from recycling of the many different varieties of plastics in the waste stream is a major challenge for collection, separation and chemical processing. The main processes used for the major plastics (including PET, PVC composites etc.) are introduced and the legal and administrative framework for plastics recycling in Japan described. For instance, PET can be recycled as raw material for reprocessing PET, but other types of plastics pose major challenges and are often recycled for only low value uses such as a source of heat. This chapter looks at current approaches to recycling plastics and how it may be possible to convert them into higher-value raw materials.

Keywords PET recycling · PVC · Plastic recycling · 3Rs · Energy recovery

11.1 Introduction

In the modern world, life without plastics is unthinkable since it is used in every part of our daily life—for bringing groceries home, for clothing, transportation, entertainment, in medical equipment, and many other applications. Most plastic goods are used only for a very limited time and thrown away after use, so that society must manage large amounts of waste in order to protect the environment, human health, and reduce the use of resources and land.

Only about 100 years have passed since the first commercial use of the synthetic macromolecular materials we call plastics. Celluloid made from cellulose as a bio-derived resource, nitric acid, and camphor was already purchased from the 1880s as a predecessor to modern plastics. The high availability of crude oil exploited from the 1860s however, caused the development of bio-based materials to end. With the development of chemicals by new petrochemical routes, the first fully synthetic

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T. Yoshioka (✉) · G. Grause
Graduate School of Environmental Studies, Tohoku University, Sendai, Japan
e-mail: yoshioka@env.che.tohoku.ac.jp

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plastic material was commercialized as Bakelite in 1908 (made from phenol and formaldehyde), and as phenol resin still used in electronic devices or impregnated wood.

Most of today's most important plastic materials: polyvinyl chloride (PVC), polystyrene (PS), polyethylene (PE)) were developed in the 1920s and 1930s. However, it was after the end of World War 2 that the real breakthrough of plastics occurred. World-wide consumption of various plastics was just 7000 t in 1960 and is expected to top 300 million t in 2015 with an annual average growth rate of 9 %. The volume of plastic production today is higher than that of steel and this is the reason why we can call our era the plastic age!

11.1.1 From Resource to Waste

To produce most plastics, energy and chemicals are used which are both derived from fossil fuels. About 5 % of crude oil production is converted into chemicals; the remaining 95 % is used as an energy source in cars, homes, and power plants. Since crude oil is not directly usable, the oil has to be processed before it can be used. Crude oil consists of thousands of compounds, mostly hydrocarbons, which are as a first step separated by their boiling points- a process called rectification carried out in refineries with typical annual capacities between 500,000 and 1,000,000 t. The products still contain hundreds of compounds and are classified by their boiling points: gases below room temperature; gasoline, naphtha, kerosene as liquid products; paraffin wax and asphalt are solid products at room temperature.

Crude oil contains a high content of high boiling point compounds with a low market value, so these are upgraded by chemical reformation: their long molecule chains are reduced by heat and catalytic cracking. High boiling fractions are also burnt to provide the energy necessary for processing crude oil in refineries and cracking facilities.

Valuable compounds can be separated for use in the chemical industry. Gases such as ethene, propene, and butadiene are directly used for the production of polymers such as PE, polypropylene (PP), butadiene rubber (BR), and also in the production of other chemicals important for plastic production: i.e. vinyl chloride, ethylene oxide, acryl nitrile. Important liquid compounds from crude oil are benzene, toluene, and xylene. These compounds are not directly used for plastic production, but represent important raw chemicals for the production of styrene, phenol, toluene diisocyanate or terephthalic acid, which are used for PS, phenol resin, polyurethane (PU), and polyethylene terephthalate (PET), respectively.

Most plastics are disposed of soon after production and use; sometimes by conventional incineration; sometimes by landfill. The establishment of a resource-oriented recycling society which includes plastic recycling poses challenges because of the many different plastic materials which have to be treated separately in order to gain valuable products. This means that rather similar to the specific production methods of plastics, so too a specific treatment method for each plastic has to be found.

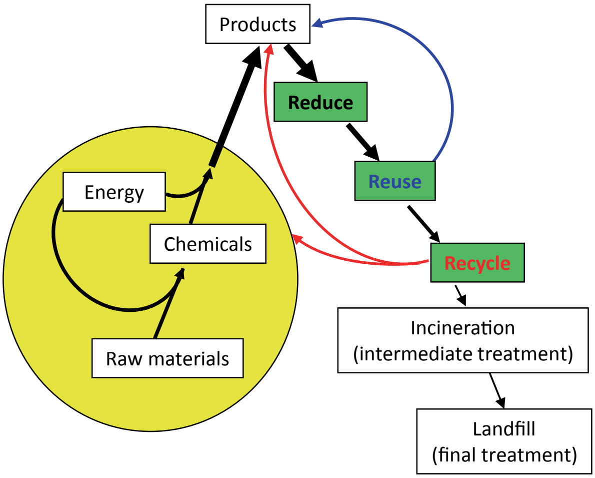


Fig. 11.1 Material cycles according to the principles of 3R

11.2 The Principles of 3R

The increasing volume of waste and the depletion of resources call for a more sophisticated waste management approach. All goods ending up as waste consumed resources and energy in their production and much of that is still present in the waste in the form of chemical and structural information. Production increased the order or organization in these materials, which in physical chemistry is called a decrease in entropy of the system. This order is permanently lost after disposal (increasing entropy), when materials are incinerated without energy recovery or landfilled. Modern waste management aims at preventing such losses in resources and order. For this purpose, the 3R (reduce, reuse, recycle) waste management rules were developed in which the order reflects the priority (Fig. 11.1). Definitions and borders of the concept vary and the concept may also be expanded to 4R or 5R by adding redesign or recover energy, etc. We will give a short explanation of the different ideas behind these waste management rules in this section.

Reduce The reduction of waste is achieved in different ways. 'Down-gauging' aims at the reduction of material that is necessary to fulfil a certain purpose. It can be achieved by reducing the layers of packaging of a product or by changing the design of a device without affecting its functionality. Redesign is sometimes listed as an additional 'R' and not limited to the visual appearance. The more efficient arrangement of modules in a TV set or forms for cutting paper or plastic foil are other examples. Some regulatory measures may also help in the reduction of plastic waste; for instance, the free distribution of plastic bags is replaced in many countries by a compulsory charge or even prohibition. It has to be mentioned that reducing resources is often accompanied by savings in money.

Reuse Reuse is the idea that goods can be used several times for one purpose or still fulfil a task after their initial life has ended. As an example, empty PET or glass bottles are returned to the shop by costumers. This requires the establishment of a collection system often connected with a refund system and transport back to the bottling plant. This is most worthwhile environmentally when the distance between refilling and sales is short, since long distances might require higher energy consumption in transport than saved by reusing. Another example is the reuse of modules from broken down electronic devices, which can be used as spare parts for identical machines. Since whole pieces with their complex structures are reused, the loss of order (entropy) is reduced to a minimum.

Recycle Recycling comprises many very different measures for the reduction of waste. Mechanical recycling is described as primary recycling if the mechanical properties of the recyclate (the recycled material) resemble those of the original material. This can only be achieved for a few plastic materials, since even materials with the same molecular structure differ in their molecular weight and frequency of branches, resulting in differences in their properties. Moreover, impurities and additives have a negative impact on the recyclate. One material that satisfies the requirements for primary recycling is PET. About 40% of PET consumption is related to the production of PET bottles. After separated collection from other plastics, PET is cleaned, ground, and treated to repair damage caused by the first use. Since PET fractions of different origin still have comparable properties, no deterioration of properties is observed. Today's PET recyclate can be re-used in contact with food (food grade).

In case the recyclate cannot meet the original specifications, the process is described as secondary recycling. Especially if plastics from different origins are mixed, consistent properties cannot be maintained; 'down-cycling' is observed. As an example, polyolefins such as low density PE (LDPE), high density PE (HDPE), linear low density PE (LLDPE), and PP have very similar densities, which make separation difficult. As a consequence, pure fractions of one material are not obtained and material properties do not match requirements. These materials are often used for lower quality applications. The structural organization of the material is lost during grinding when primary and secondary recycling is employed, while the molecular structure remains unchanged.

The purpose of tertiary recycling is the recovery of chemicals, which can be reused in the chemical industry and especially in plastics production. For this purpose, the chains of the macromolecules are split thermally or chemically and monomers recovered. For instance, polymethyl methacrylate (PMMA) decomposes thermally at 450 °C forming methyl methacrylate (MMA), which can be reused to polymerize to PMMA. The recovery of monomers from PET is more complicated, requiring additional chemicals. In the presence of water, terephthalic acid and ethylene glycol are obtained; in the presence of ethylene glycol bis2-hydroxyethyl terephthalate (BHET) is formed and these compounds can be used for the production of new PET. The demands on the material are still high. Clean, correctly sorted materials are preferred. Therefore, chemical information remains intact with the formation of low molecular weight compounds, even if the macromolecular chain is destroyed.

A second form of tertiary recycling is the conversion of plastic waste into fuels. This comprises mainly liquefaction and gasification. Both methods can be used for mixed waste fractions containing plastics, biomass, and other materials. In liquefaction, mainly heat is used in the absence of oxygen to break down the molecular structure of polymers. The aim is to obtain a synthetic crude oil (syncrude) with a high content of hydrocarbons that could be processed in petrochemical facilities. Gasification aims for the conversion of waste plastics and biomass into carbon monoxide and hydrogen. Steam, oxygen, or carbon dioxide are used as reactants. Both carbon monoxide and hydrogen can then be used for the synthesis of hydrocarbons (Fisher-Tropsch process), ammonia (Haber-Bosch process) and other important substances. The chemical information is mainly destroyed during these processes.

The term quaternary recycling is used in an ambiguous way. Often it is used for the recovery of energy as we describe below. Sometimes composting of biodegradable polymers is implied, referring to the conversion of polymeric materials into new biomass.

Recovering energy: energy recovery is the last step in the utilization of waste materials. Incineration of waste in power plants results in electricity and usable heat. Waste plastics can also be converted in coke ovens into coke, which is used in blast furnaces. Moreover, waste plastics are also directly introduced into blast furnaces for the reduction of iron ore. In cement kilns, waste plastics are also used for the decarbonation of limestone. In the latter cases, the production of steel and cement are the new materials obtained. Materials used for these purposes have the lowest requirements since any material with sufficient carbon content can be utilized. Often materials are used that were not found suitable for recycling and separated as refuse derived fuel (RDF). Both structural and molecular order are destroyed. Remaining inorganic ashes are commonly landfilled.

With a few exceptions, the reduction or handling of waste streams incurs financial costs, which means that waste management is expensive. As a consequence, the motivation in economy and society to put efforts into waste processing is quite limited. For this reason, many countries have put regulations in place to control the waste flow. Such regulations comprise rules for materials that have to be collected, sorted, and processed, may ban certain materials and substances, and apply other requirements. Regulatory structures might be very different from country to country. In the USA, the responsibility is divided between states and local authorities, leading to a patchwork of competences. In Europe, the European Commission took over many competences from the member states and released directives, which have to be put into national law by member states. In Japan, regulations were centralized by the Japanese government and most date from the beginning of this century. The Basic Law for Establishing the Recycling-Based Society acts as the framework for measures that should lead to a sustainable handling of resources. Under this basic law, are laws for the Promotion of Effective Utilization of Resources, for Waste Management Regulation and Recycling, and waste management supported by various subsidiary recycle laws for individual waste groups such as automotive waste and electric and electronic waste (see Chap. 2).

11.3 Groups and Composition of Plastics

In contrast to pure substances, plastics are in general compositions of different compounds. They are prepared by the reaction of monomers to form long polymer chains. In a single plastic material, polymer chains with various chain lengths are present, and strictly speaking each chain length represents one pure substance with its own physical and chemical properties. Therefore, the properties of the bulk material are derived from the combination of all the chains present. If a polymer made from the same monomer differs in the composition of the chains, it may also differ in its properties. In general, the molecular weight of a polymer chain is a multiple of the monomer molecular weight. The number of monomers connected in one chain is called the degree of polymerization. Since various chain length are present, the polymer is commonly characterized by its molar mass distribution. Several definitions are used, but most important are the number average M_n and the weight average M_w of the molar weight. The number average tells us at what molar mass the highest number of chains can be found. The weight average tells at what molar mass the chain length fraction with the highest mass can be found. Since longer chains contribute more to M_w than to M_n due to their higher molar mass, M_w is always higher or equal to M_n. The quotient of M_w and M_n is called the polydispersity index PDI:

$$PDI = \frac{M_w}{M_n}$$

For a pure substance PDI is 1. For most polymer formulations, the PDI is much higher. Some PE or PS polymer might reach PDIs of 6 and higher.

11.3.1 Polymer Groups

Polymers are also defined by their method of synthesis. Most common are polymers obtained by a polymer chain reaction. Monomers with double bonds are linked together forming long chains. The chain reaction is started either by an initiator or a catalyst. The initiator is only able to start a limited number of chain reactions and is consumed during the process. A catalyst is able to start chain reactions several times so that only a small amount of catalyst is required. The reaction proceeds until the chain reaction is terminated. Once terminated, a second activation of the chain is in general not possible. Typical examples are PE, PP, PS, and PVC (Fig. 11.2). The polymerization of more than one monomer at the time is also commonly conducted, resulting in copolymers. Examples for copolymers are acrylnitrile-butadiene-styrene copolymer (ABS) and ethylene-propylene-diene monomer rubber (EPDM). Another possibility is the combination of two different polymer chains in a graft polymer. One example is high-impact PS (HIPS) in which at first styrene is polymerized and after styrene is consumed, small amounts of butadiene are added forming polybutadiene at the end of the PS chains.

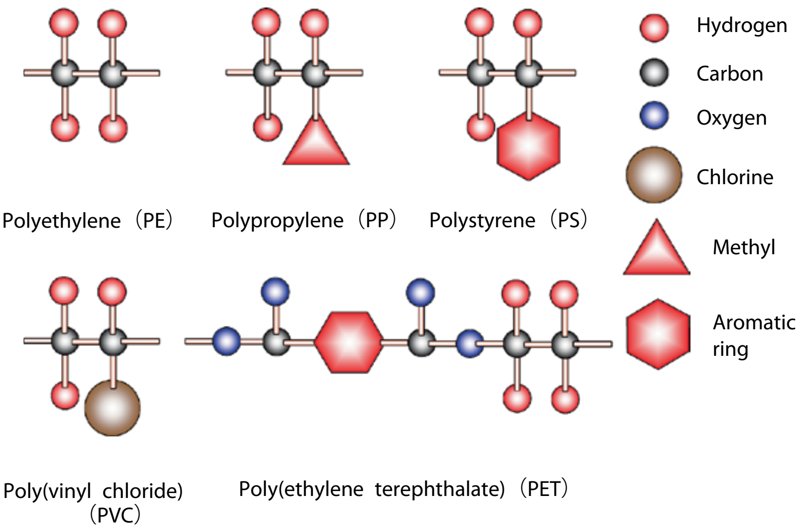


Fig. 11.2 Structures of polymers (*PE, PP, PS, PVC*) and PET as an example for a polycondensate

Polycondensation and polyaddition are performed by different principles. In both cases two different reactive groups are combined to form a connection between monomers. With every reaction step a stable molecule is obtained. At first, two monomers form a dimer; dimers might then form trimers and tetramers containing three and four monomers respectively. After that, short chains of oligomers and finally, long polymer chains are obtained. All these dimers, trimers, oligomers, and polymers are stable chemical compounds. The reaction can be interrupted, for instance by cooling, and later continued by heating. Small molecules such as H_2O or HCl are removed during polycondensation, while polyadducts are formed by the rearrangement of atoms. A typical polycondensate is PET (Fig. 11.3a). It is formed by the esterification reaction of terephthalic acid with ethylene glycol and water is released as a by-product. After each reaction step, a molecule is formed with alcohol and acid groups at the chain ends which then react with each other forming cycles. The reaction can be reversed by adding water. PU is an example for a polyadduct between diisocyanates and alcohols (Fig. 11.3b). The reaction proceeds comparable to that of PET; however, no by-product is obtained.

The large variety of different plastic materials makes it necessary to ensure sufficient separation when sorting materials for recycling. For this reason, a labeling system was developed comprising the most important polymers (Fig. 11.4). This system allows the consumer to identify different plastic materials and separate them if required.

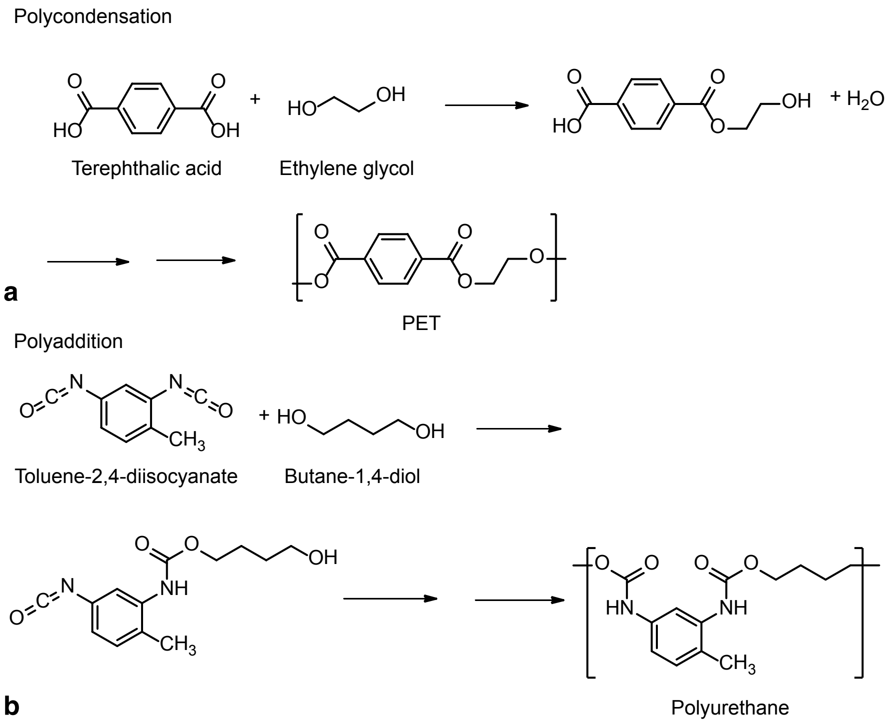
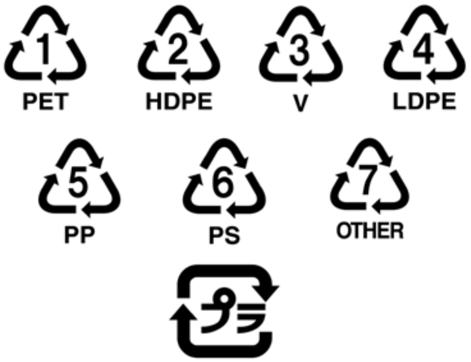


Fig. 11.3 Polycondensation of PET and polyaddition of PU. **a** Polycondensation. **b** Polyaddition

Fig. 11.4 Labels for plastic types



11.3.2 Additives

A plain polymer may often not meet the required properties for use. Flame resistance, flexibility, and stability against environmental conditions have to be adjusted with additives before a product reaches the consumer. Additives have a strong

Table 11.1 Examples for the composition of rigid and flexible PVC

Rigid PVC		
Additive	*% wt.*	*Function*
PVC	82.4	Polymer
MBS[a]	13.2	Impact modifier
Sn stabilizer	2.47	Stabilizer
Monoglyceride	0.99	Emulsifier
Processing aid	0.82	Processing aid
LDPE	0.082	–
Pigment	0.012	Pigment
Flexible PVC		
PVC	36.8	Polymer
$CaCO_3$	28.3	Filler
DINP[b]	23.9	Plasticizer
Chlorinated paraffin	6.99	Flame retardant
Alkylbenzene	1.84	–
Pb stabilizer	1.10	Stabilizer
Calcium stearate	0.74	Stabilizer
Wax	0.37	Lubricant

[a] Methyl methacrylate/butadiene/styrene: 15:70:15

[b] Diisononylphthalate

impact on the material properties. As an example, rigid and flexible PVC are made from the same polymer but their properties are clearly different. Rigid PVC is hard, easy to break, while flexible PVC can bend in any form. Table 11.1 shows typical compositions of flexible and rigid PVC. It can be seen that that in flexible PVC the amount of additives exceeds that of the PVC itself. Because of that flame retardant has also to be added, while in rigid PVC the amount of chlorine in the PVC is sufficient to ensure flame resistance. We will now consider classes of additives and the effects and obstacles they may cause during recycling.

Flame Retardants Most plastics are hydrocarbons and thus resemble other crude oil products in structure and combustion behavior. To prevent unintended fires therefore, compounds are added which interfere with the combustion process in various ways. Halogenated flame retardants form radicals which interrupt the radical propagation of combustion. Phosphor-based flame retardants cover the surface of burning plastic with polyphosphates, preventing the evolution of burnable gases and increase the amount of char formed. Metal hydroxides release water, which has a cooling effect on the plastic and a diluting effect on the burnable gas. Halogenated flame retardants make recycling processes more complicated. They are not completely removed during material recycling and remain present in products made from recycled material, even if they are not intended to be there. During chemical recycling, they interfere with depolymerization processes and contaminate the product fractions.

Plasticizers Plasticizers make rigid materials flexible. They tend to migrate from plastic materials into the environment; phthalic acid esters (phthalates) plasticizers are suspected to have a hormone-like behavior.

Fillers Fillers are very often inexpensive materials added to substitute for the polymer without changing the properties significantly. Most fillers are inert inorganic substances such as $CaCO_3$, sand, or soot. They only slightly interfere with recycling processes and removal is often easily achieved.

Stabilizers Especially for PVC, stabilizers are essential because of its low thermal stability. Stabilizers in PVC add to double bonds left by HCl and prevent therefore a faster dehydrochlorination. PVC stabilizers are often based on heavy metals. These can easily contaminate recyclates and products obtained from chemical recycling.

11.4 Overall Plastic Treatment in Japan

Plastic production and demand increased strongly in the 11980–2000 period and has since remained at a constant level. The amount of plastic waste has followed this trend. Today about 10 million t of plastic waste are generated each year, of which about 77 % was treated in 2010. Most of the plastic waste was used for energy recovery (32 % for the generation of electricity, another 11 % for heat, and 6 % were used as RDF). Only 27 % of the plastic waste was actually used in different recycling techniques: 23 % for material and 4 % for chemical recycling. 10 % of the plastic waste was incinerated without energy recovery and another 13 % landfilled.

11.5 PET Recycling

About 40 % of PET is used for plastic bottles, another 40 % for fibers, and the rest for other applications, mainly PET film. Transparent amorphous PET is mainly used for the fabrication of bottles, because of the very good barrier properties against gases such as oxygen and carbon dioxide. The barrier is improved further by attaching a layer of silicon dioxide or aluminum oxide to the inner side of the bottle, making it suitable for carbon dioxide containing soft-drinks. Crystalline PET is very resistant against both heat and cold. Therefore, it is used for trays that are suitable for freezing and microwaving. In Japan, PET is collected separately from other plastics and made available for recycling.

The possibilities for PET recycling are many (Fig. 11.5). Mechanical recycling is used for obtaining fiber and sheet grade PET. Advanced methods can even deliver bottle grade PET. Chemical recycling is conducted by solvolytic processes which can be seen as a reversed production process (the process is called glycolysis when ethylene glycol is used). Mainly oligomers of PET are obtained, which can be

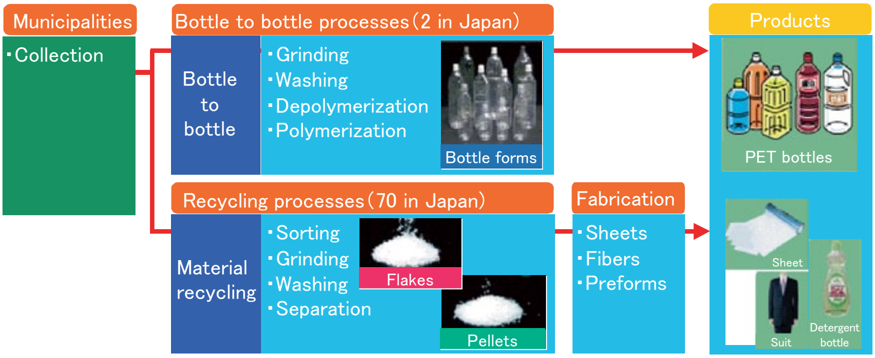


Fig. 11.5 Recycling material flow sheet of bottle PET

polymerized to new bottle PET. Hydrolysis is conducted in the presence of water to produce terephthalic acid and ethylene glycol, both of which can be used for the production of new bottle PET. Differences in the PET grade (fiber, sheet, bottle) are mainly related to hygienic concerns. Today's newly produced PET is in general of bottle grade, which allows usage in contact with food. However, PET collected for recycling is an unknown substance. No one knows what the consumer did to the bottle between opening and collection- it might have been used as a container for chemicals or other hazardous substances. Furthermore, the original content might have deteriorated or developed strong odor or taste, which cannot be eliminated by a simple washing process. Therefore, special efforts have to be made in order to obtain bottle grade PET recyclate.

11.5.1 Material Recycling

The first step in material recycling of PET is the separation of metal cans and glass bottles, which might be incorporated in the PET bottle collection (Fig. 11.6). Then the bottles are baled- that is compressed in order to reduce volume for transport. At the recycling facility, the bales are opened and foreign objects are removed. Then the bottles are cut into small pieces and washed. After that caps and labels are removed. The most common separation techniques are density separation and infrared separation. Caps and labels are commonly made from PP which has a density of about 0.9 g/cm^3 and is much lower than that of PET (1.38 g/cm^3). In a simple water bath, PP swims at the surface and PET sinks where it can be collected for further processing. During infrared separation, the ground flakes pass an infrared sensor on a belt. The position of non-PET particles is processed by a computer. Then these particles are removed by shots of aimed pressured air. In the end, sole PET flakes are left for further processing. These flakes are not suitable for applications in contact with food but they can be used for fibers, sheets, or other useful products. Other materials are collected and thermally processed as RDF.

Fig. 11.6 PET material recycling

The mechanical recycling process discussed above is not able to provide bottle grade PET. For this purpose additional steps have to be taken. First of all, only material with a sufficient purity can be used and contaminated material should be avoided. After material has been selected, the next steps are the same as for fiber grade PET: sorting, grinding, washing, separation from other plastics. Then a decontamination step occurs in which the flake surfaces are coated with caustic soda (NaOH) at 150 °C. The surface including possible contaminants is etched away. Then volatile compounds are removed at temperatures of more than 200 °C. The flakes are extruded to pellets and a solid state polymerization is carried out in order to increase the recyclate's molar weight which may have been reduced by a number of causes. Firstly, during its life time, PET suffers from thermal, mechanical, and environmental stress; secondly, during processing, temperatures up to 300 °C are used which can cause a reduction in the molar weight; finally, mechanical influences and the presence of water might cause shortening of the chain length. Solid state polymerization restores the molar weight and improves material properties. The pellets derived from this process can be used for applications in contact with food.

11.5.2 Chemical Recycling

Even though bottle grade PET can be obtained by mechanical recycling, the deterioration of properties cannot be stopped in the long run. In general, PET recyclate has to be mixed with new PET in order to ensure the properties required. For this purpose, solvolytic processes are helpful for the recovery of monomeric materials from PET.

The reaction of PET with ethylene glycol is called glycolysis (when water is used, it is hydrolysis). Both are reverse reactions of the polymerization process, which we discuss here. The synthesis of PET relies today on the reaction of terephthalic acid with ethylene glycol in two steps. In the first step, terephthalic acid reacts with an excess of ethylene glycol to obtain BHET. Water is released and has to be removed from the system in order to avoid a back reaction. In the second step, PET polymer chains are formed by the polycondensation of BHET. Ethylene glycol that is released during this step is removed using temperatures of more than 200 °C and a vacuum. Since the chain length distribution is controlled by equilibria between the reacting compounds, effective separation of excessive ethylene glycol is required in order to obtain PET with the required properties.

Glycolysis is the reversed second step of PET polymerization. Before glycolysis, the used PET is ground, washed, and foreign materials are separated as described for the mechanical recycling of PET. The cleaned PET flakes are melted and then added to ethylene glycol. The reaction is carried out for several hours at temperatures about 200 °C. Metal salts like zinc acetate are frequently used as catalysts. The product consisting mainly of BHET, but with higher oligomers also present, is cooled down, precipitating the product. The solid product is then separated from the remaining ethylene glycol, which is purified by distillation and used again. BHET is recrystallized for purification and used as it is for the polymerization of PET (omitting the first reaction step). One disadvantage of this process is that impurities are not sufficient removed. Especially long heating times cause the formation of diethylene glycol, which is then incorporated in the polymer chain, changing the optical and mechanical properties.

The Teijin process (Fig. 11.7) uses the BHET for the production of dimethylterephthalate (DMT) by transesterification with methanol. Then DMT is used for the production of high purity terephthalic acid that can be used for the production of bottle grade PET.

The direct hydrolysis of PET requires high pressure water, making this process expensive. Temperatures higher than the melting point of PET at about 250 °C and a pressure of about 2 MPa are necessary. Such harsh conditions can be reduced by using alkaline or acid conditions. Sodium terephthalate is obtained in NaOH solution, making it necessary to recover terephthalic acid by adding additional acid

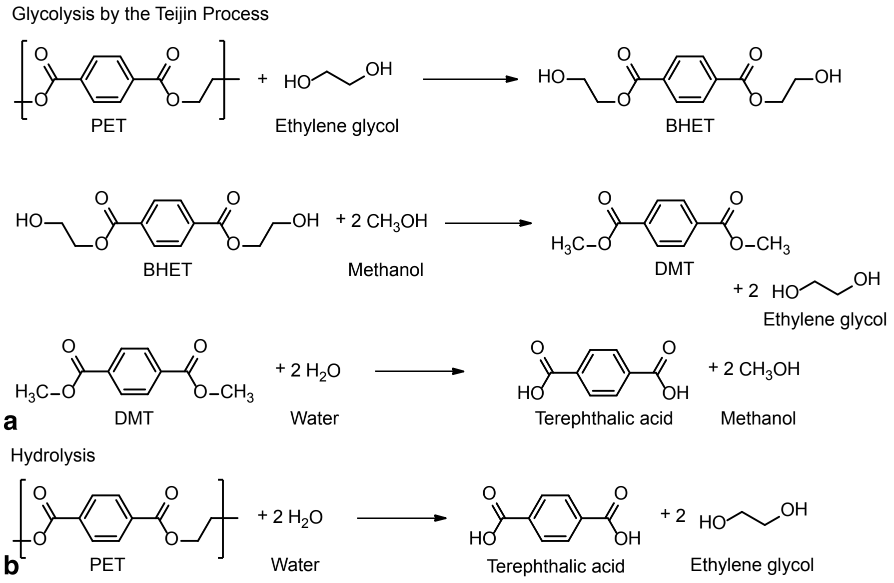


Fig. 11.7 Chemical reactions occurring during glycolysis and hydrolysis of PET

(hydrochloric acid or sulfuric acid). If sulfuric acid is used, high purity Na_2SO_4 can be obtained and sold, reducing the cost of the process. PET is readily dissolved in concentrated sulfuric acid. However, recovery of terephthalic acid and purification of sulfuric acid make this process expensive.

11.5.3 PET Composites

Composites are materials consisting of at least two different physically separated materials with different material properties. Examples of plastic containing composites are fiber reinforced plastics as they are used as light materials in plane and ship building, and PET/PVC composites, in which PET fibers are embedded in PVC sheets, giving strong weatherproofed tarpaulins.

Magnetic PET prepaid cards contain magnetite (Fe_3O_4) responsible for the magnetic properties of the card and rutile (TiO_2) as a white pigment. Both materials together improve the mechanical strength. They are incorporated to an amount of about 20% (by wt.) in the PET matrix. Incineration of such cards leaves a residue that is similar in composition to ilmenite, which is used as a basic ore in the production of titanium; these minerals can be used in existing metal producing facilities.

PET is of course lost during incineration and future research should focus on the recovery of organic materials as well as the inorganic components. Recycling techniques for PET as they were described above are not suitable for such composite materials since separation of small inorganic particles from highly viscous solvolysis derived solutions by filtration or centrifugation causes problems. However, hydrolysis in steam atmosphere at more than 400 °C offers the opportunity of decomposing PET without incineration. Gaseous terephthalic acid can be decarboxylated over a CaO catalyst and benzene is obtained as a basic material for the chemical industry.

11.6 PVC Recycling

Recycling of PVC faces various problems caused by its low thermal stability and the high content of additives. PVC degradation starts around 100 °C with the elimination of HCl, making the presence of stabilizers essential. Also other additives such as plasticizers and impact modifiers are present, making material recycling difficult. However, flame retardants are barely used, since the high chlorine content of 56 % (wt.) for pure PVC assures sufficient flame resistance.

Chemical recycling is hindered by the high chlorine content as well. The easy elimination of HCl does not allow monomer recovery. Although most of the chlorine is released easily, chlorine content in the oil remains unacceptably high during conversion into fuel requiring an additional dechlorination step prior to liquefaction and gasification.

11.6.1 Material Recycling

The Vinyloop process allows the recovery of PVC from PVC-containing waste streams. PVC materials are often composites containing metals or fibers. For the separation of these materials, the PVC waste is first ground and then dissolved in methylethylketone (2-butanone). Metals, cotton and PET fibers, as well as other contaminants are not dissolved and removed by centrifugation. Then steam is introduced into the PVC solution and methylethylketone is vaporized. PVC remains in the aqueous slurry and is separated from the liquid phase by centrifugation. Additives which are soluble in methylethylketone, but insoluble in water are precipitated with PVC and remain in the recyclate. This applies mainly to the plasticizer. The properties of the recyclate can be modified by the addition of additional additives.

The properties of recycled PVC can be upgraded by the chemical modification of the polymer. The chlorine atom in PVC has a high reactivity that can be used for introducing new functional groups into the polymer by nucleophilic substitution. In this way, the substitution of chlorine by isothiocyanate ($-N=C=S$) has antibacterial effects on the polymer. Long chain groups such as dodecathiolate ($-S-C_{12}H_{25}$) could replace plasticizer like phenolates, which pose a threat to human health and environment when leaching from PVC.

11.6.2 Chemical Recycling

Before PVC containing waste can be converted into fuels by liquefaction or gasification, dechlorination has to be conducted. Dechlorination can be carried out thermally by heating plastic waste at temperatures at about 300 °C when most of the chlorine is removed. If more efficient dechlorination is required, hydrogenation can be carried out. In the presence of hydrogen at elevated pressures and temperatures, heteroatoms such as halogens, oxygen, and nitrogen are removed as HCl, HBr, water, and ammonia. High quality paraffinic oil is obtained which is sold as syncrude.

Another possibility is wet dechlorination in aqueous or organic alkaline solutions. In aqueous solutions, high pressures are required, while the reaction can be carried out at atmospheric pressure in ethylene glycol at 190 °C. The residual dechlorinated PVC is a black rigid material that can be treated with other plastics in liquefaction or gasification plants. Chlorine is recovered as NaCl.

11.7 Energy Recovery

Today's energy supply relies on the fossil fuels natural gas, oil, and coal. It can be seen from Fig. 11.8 that natural gas provides the highest amount of energy during combustion expressed as heating value, followed by propane, petroleum products, and coal. This order can be explained by the elemental composition of these fuels: the combustion of hydrogen provides more energy than the combustion of carbon. As a consequence natural gas consisting of more than 90 % methane (CH_4) and an H/C ratio of 4 has the highest heating value. Lower is that of petroleum with an H/C ratio of 2. Coal consisting mainly of carbon has an H/C ratio of about 0.5. Vice versa, the highest emissions of the greenhouse gas CO_2 are generated by coal, since mainly carbon contributes to the combustion. CO_2 emissions of petroleum and especially natural gas are much lower, since the combustion of hydrogen makes a large contribution.

Most plastics are petrochemical products. Therefore, they also have high heating values. Polyolefins (PE, PP) and polystyrene are hydrocarbons with chemical structures also present in petroleum; these plastics can be seen as solid fuels. The heating values of heteroatom containing plastics such as PET and PVC are significantly lower. Because of the oxygen content, PET can be seen as a partially oxidized material. Since oxygen bonds do not contribute to the combustion, the energy released is reduced accordingly. PVC contains 56 % (wt.) chlorine as a non-burnable portion. It can be seen from this that the energy that can be recovered depends strongly on the elemental composition of the material.

Similar effects are observed in the combustion of bio-waste. Char coal which is derived from heating wood in the absence of oxygen at temperatures below 400 °C, exhibits heating values in the range of fossil coal. Heteroatoms especially oxygen

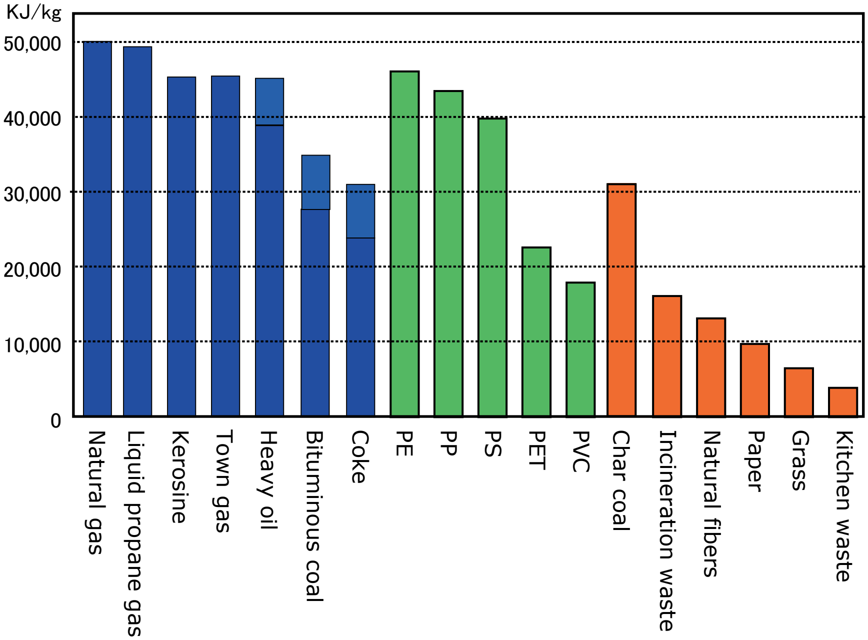


Fig. 11.8 Upper heating values of selected fuels: Fossil fuels (*blue*), plastics (*green*), biomass (*orange*)

are removed for the most part, leaving mainly carbon. Most biomass has a high water content resulting in a low heating value. Water has two effects: it is not burnable and its vaporization consumes additional heat. The higher the water content the lower the energy that can be recovered. The released heat of wet materials such as kitchen waste is so low that fossil fuels have to be added in order to maintain combustion.

Coal is commonly used as a reducing agent in blast furnaces (steel production) and heating medium in power plants and cement kilns (cement production). The partial replacement of coal by plastics causes a significant reduction in CO_2. If coal is completely replaced by waste plastics in cement kilns, a CO_2 reduction of 15 % is achieved. In Japan the partial replacement of coal by waste plastics in power plants and in the steel industry can reduce CO_2 emissions by 10 million t.

11.8 The Japanese Plastic Management System

In Japan, PET bottles and common packaging plastic waste are separately collected from other waste fractions, allowing their utilization after use. Also plastic parts from other waste streams such as cars and WEEE (waste electric and electronic equipment) are separated and treated. Although waste plastics are considered a

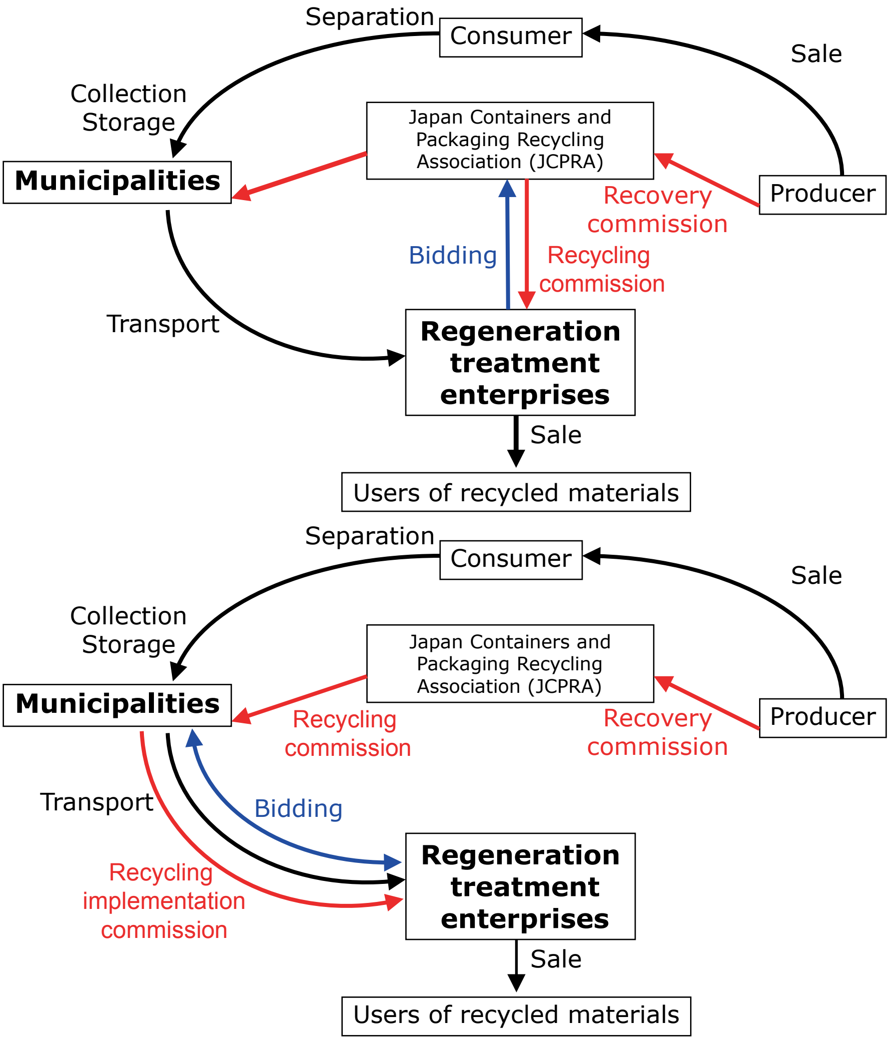


Fig. 11.9 Japanese packaging recycling system: *top* today's situation, *bottom* future modification

resource, the value of the materials is not sufficient to finance the treatment. The average cost for treating waste plastics is about 104,000 Yen/t. This money is collected from the producers (Fig. 11.9) in accordance with the polluter-pays principle—that the producer who is responsible for the design of his product has also the responsibility to take care for the treatment after use. Money is thus collected by the Japan Containers and Packaging Recycling Association (JCPRA) and used for paying recyclers. Companies which are capable of recycling plastic waste make offers to the JCPRA and the lowest bid wins.

Fig. 11.10 Disaster waste separation

After use, packaging plastics and plastic bottles are separated by the consumer and collected by local municipalities. The municipalities also receive money from the JCPRA for collecting and transport and forward the waste to the recycling companies which won the bid. The recycled materials are sold to companies which make use of them.

A newly proposed model transfers the responsibility for the bidding process from the JCPRA to the individual municipalities. The money required for paying the recyclers is then given to the municipalities, which conduct the bidding and pay the commission to the recyclers. This procedure would strengthen the contact between municipalities and recyclers, giving both the possibility to optimize according to the local situation.

11.9 Disaster Waste Management

The Great Eastern Japan Earthquake struck the Tohoku region on March 11th 2011 and caused a major tsunami. More than 20,000 people were killed and a whole coast line was devastated, leaving huge piles of things that became useless in minutes: disaster waste.

The disaster waste was collected and separated according to the materials involved (Fig. 11.10). Many materials such as glass and metal were recycled. Materials that could not be recycled were converted into energy. Over a period of 3 years, all materials that were demolished during the tsunami were utilized.

11.10 Conclusion

The quantities of plastic used in the modern economy make plastics a critical part of the challenge to move to a recycling-based economy. Many steps have been taken in Japan to maximise the extent of recycle—using laws, regulations and administrative systems in combination with advanced physical and chemical separation and recycling techniques. Nevertheless the sheer variety of plastic uses and compositions, as well as the economic challenges of collection, separation, cleaning etc., make this a field which continues to demand a high priority for future research.

Chapter 12
Recent Resource and Environmental Issues in the Steel Industry

Eiki Kasai

Abstract The theme of efficient use of resources is developed by looking at the resource and environmental issues raised by the extraction and refining of iron and steel. Recent resource and environmental trends in the steel industry are reviewed from the perspective of the mineral sources available, future population and economic trends and their impact on resources, and the potential for meeting demands for steel in an environmentally-friendly way. Approaches such as utilization of hydrogen-bearing fuels and/or biomass wastes instead of coke as reducing agents of iron ores to reduce carbon dioxide emission are described, and a vision of sustainable iron and steel making is proposed.

Keywords Iron and steel industry · Environmental impacts of steel production · Iron ore resources · Recycling of iron · Steel

12.1 Background to Iron and Steel

If we go back to its original source, iron is the final element produced through the nuclear fusion ongoing within stars. This has led to it being more widespread in space compared with other elements with atomic numbers close to iron, as shown in Fig. 12.1. Elements having larger atomic numbers than iron have mostly originated from supernova explosions in bigger stars and are thus found in lower amounts. The distribution of elements in the earth is thus the consequence of several generational changes of stars after the Big Bang and the existing ratio of iron within the earth's crust is relatively high at approx. 5.6 % (mass). Iron also is the main component of the earth's core.

This abundance, combined with its ease of extraction and working have made iron a cheap and most popular metal in human society. While iron was first produced in the Iron Age many millennia ago, after the industrial revolution it has become a core material which underpins industry to the extent that the amount of

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E. Kasai (✉)
Graduate School of Environmental Studies, Tohoku University, Sendai, Japan
e-mail: kasai@mail.kankyo.tohoku.ac.jp

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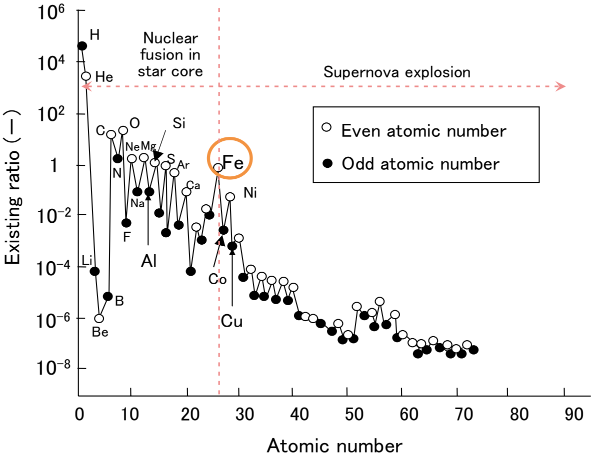
Fig. 12.1 Existing ratio of elements in space



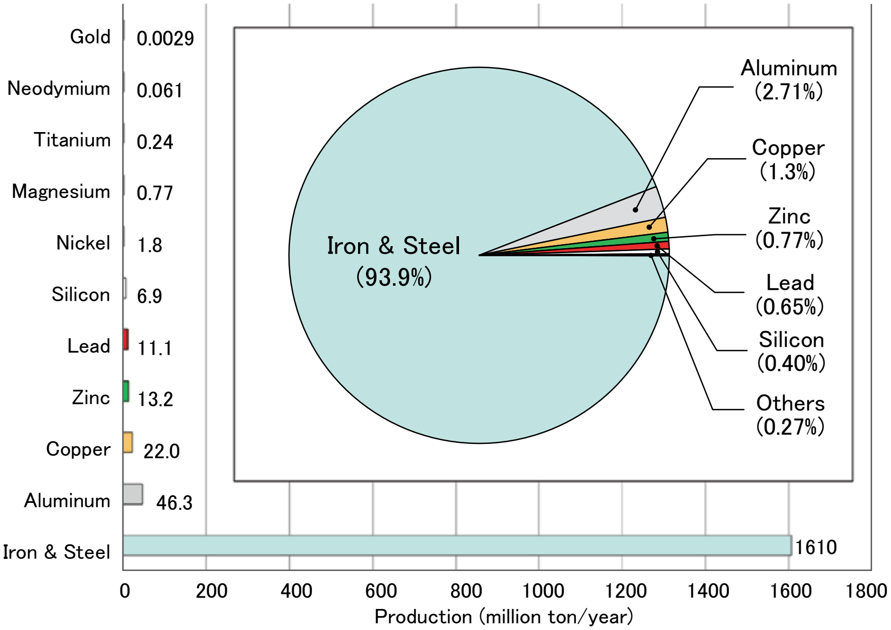


Fig. 12.2 Annual world production of metals

its production has been used as an economic criteria for a country. Even today, iron and steel are so far the largest metallic products that other metals are called collectively 'non-ferrous' metals. Figure 12.2 shows the global production ratios of different metals, and it can be seen that iron and steel comprise about 94% of the total. The reason why iron has become such a popular material is not only the plentiful availability of its resources and cheap price but also its unique characteristics

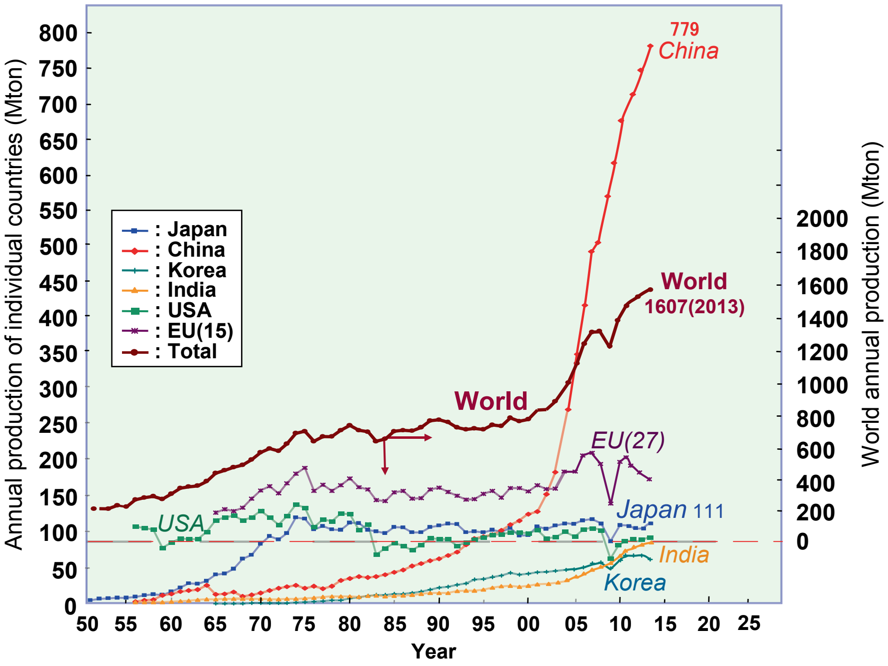


Fig. 12.3 Changes in world steel production

and properties. In particular, various properties can be provided by adding different alloying elements such as carbon. Further, the hardness and ductility can be easily controlled by heat treatment- even for steel having the same composition. Hence, it has been used for a long time as a fundamental material for cutlery and farming tools, and is also used in various constructional roles; for rails, pipes and many machinery parts. It has another important feature—the ease of its oxidation, relatively small environmental impact to human and ecological systems, and good recyclability due to its strong magnetism.

Figure 12.3 shows the changes in the amount of global steel production. Global annual steel production remained around 700–800 million t after the oil shocks of 1973 and 1979, but has recently started to increase rapidly. This is mainly due to increasing production in emergent countries and especially in China where production has drastically increased by 6.5 times from 120 million t in 2000 to 780 million in 2013. With such an increase in steel production, the prices of iron ores and coking coal, which is a major raw material for metallurgical coke, have rapidly increased several-fold and have maintained higher levels to the present day. In particular, the price of iron ore has increased rapidly, showing a peak in 2008 during the resources 'bubble period', and surpassing that peak since 2010 (see Fig. 12.4). When such changes in the resource price are compared to the changes in steel production over the same period, a degree of correlation can be observed, suggesting that the resource prices are responding according to its supply-demand relationship.

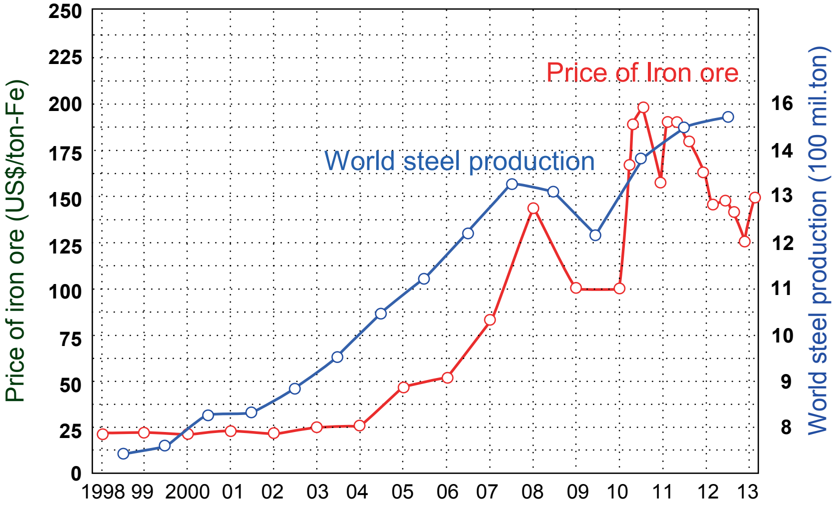


Fig. 12.4 Changes in Australian hematite ore price for Japan

12.2 Lifetimes of Metal Resources

Figure 12.5 shows the relationship between annual consumption of various elements and their proportion in the earth crust; that is a modified Clark Number[1]. In the figure, elements are sorted into three groups; chalcophile, siderophile and lithophile, according to the classification by Goldschmidt (1937). In this graph, the chalcophile elements which are aligned along the orange line (that is metal resources which are present at lower concentrations but are being consumed in larger amounts) are exhaustible. It is no surprise that gold and silver are included in such elements but it is also notable that common metals like copper and lead are located there. Iron is one of the siderophile elements; its consumption is extremely large but the quantity of resources existing is also large. Therefore, it is one of the elements where it is not necessary to be concerned about the resource's exhaustibility. It is also worthy of mention that another element, indium is classified as one of lithophile elements, whose resources are usually sufficient. However, indium has been mainly produced as a byproduct of the zinc refining process and supply is therefore determined by the demand for zinc. As the demand for indium for use as ITO (tin-doped indium oxide) materials has increased rapidly (for electrodes in liquid crystal panels and organic electroluminescence), demand has exceeded supply and indium broke the supply-demand balance in the short-term. Such imbalances can only be reversed by development of new resources, which may be stimulated by the resulting increase in the price of indium.

From the point of view of different availabilities and rates of consumption, some observations can be made on the ways in which the static lifetimes of several

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[1] Clarke's numbers express the average content of the chemical elements in the earth's crust and other geochemical and cosmo-chemical systems.

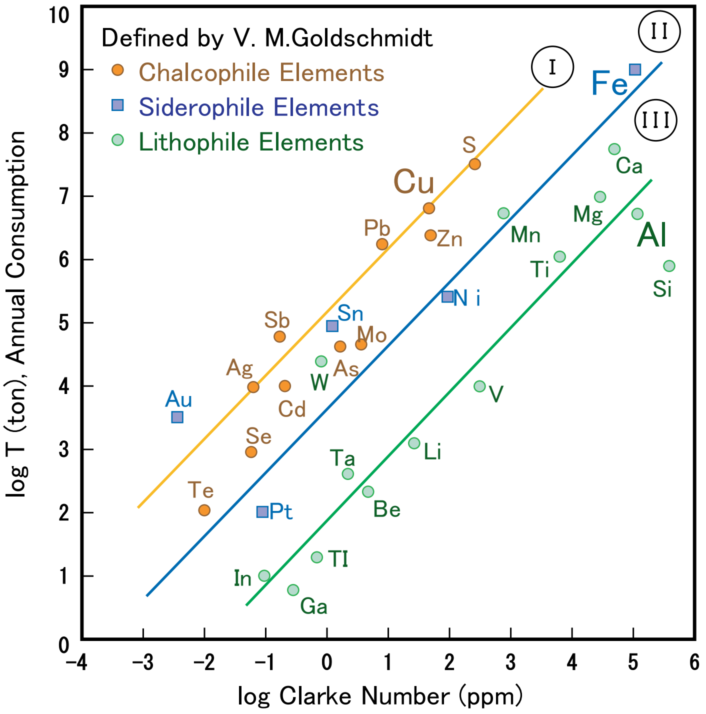
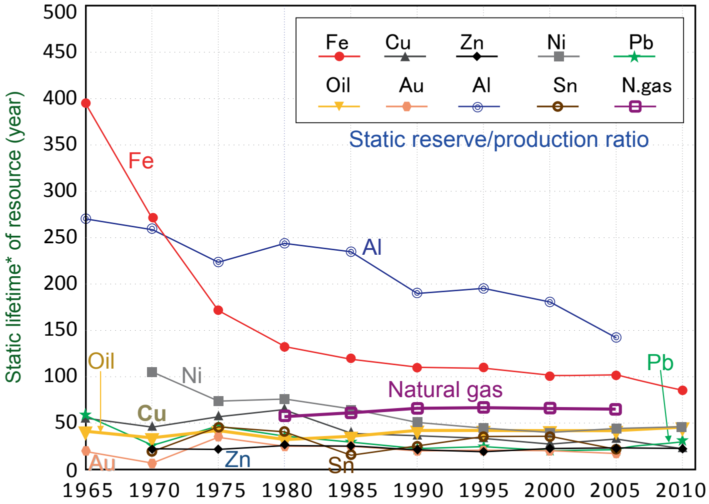


Fig. 12.5 Classification of metals by Goldschmidt (1937)

resources are changing. Here static lifetime is used as an indicator of the future availability of a specific resource, and is calculated as the quotient of 'Proved reserve/Annual usage'. Figure 12.6 shows the changes in static lifetimes of major metal resources and oil & natural gas. Metal resources other than aluminum, iron and nickel have varied within a rather narrow range between 20 and 60 years. The lifetime of crude oil has also been stable at about 40 years, despite claims that it would not last more than about 20 years at the time of the second oil-shock of 1979. The production quantity of base metals such as zinc and tin, and noble metals like gold and silver have generally increased over this period. In particular, their production increased drastically (along with steel production) in the resources' bubble years from 2000 to 2008. Despite this, large shifts have not been seen in their static lifetime estimates.

There are different hypotheses which can explain this apparent contradiction. For instance:

1. New mines and oil deposits have been discovered, enabling an increase in production;
2. The amounts minable from existing mines have been increased by new technologies; and
3. Information on the reserve estimates have been controlled; for example by major resource companies and/or mine-rich countries.



*Static lifetime = Proved reserves / Annual usage

Fig. 12.6 Changes in static lifetime of major metal resources and oil & natural gas

Today, the amount of a reserve which is minable has become one of the most important pieces of information for resource companies, and it is thus very difficult to collect reliable data. It is thus rather difficult to verify the above hypotheses, but the following suggestion can be made: The resource price usually increases with an increase in its consumption. It can thus be easily recognized that the costs available for mining, beneficiation and transportation can also be raised when prices of resource products are increased. Thus, lower grade ores (which may have been called soils or sands/rocks beforehand) will become utilizable as new resources. Furthermore, the criterion for mine closure will also change as larger amounts of resources will be capable of being economically produced from the same mine. These likely tendencies are closely related to the above hypotheses 1) and 2). Taking account of the above, the amount of the resource which is minable can be expected to vary depending on the resource price; and this in turn influences the static lifetime of the resource.

Despite the trend for some metal resources, the static lifetimes of aluminum, iron and nickel have decreased year by year (Fig. 12.6). Especially, that of iron greatly decreased from about a 400 year estimate in 1980 to about 150 years by 2005, followed by a further decrease to about 80 years in 2010's estimates. Such a change is very different to that for copper or zinc, and does not correspond to the changes in global steel production shown in Fig. 12.3. Global steel production in 1965 and 1975 were about 500 and 600 million t respectively, and increased only ~20 %; in contrast, the static lifetime of iron ore resource decreased in the same period from

400 to 175 years- by ~55 % (Fig. 12.6). This implies that a considerable quantity of iron resources has disappeared within 10 years! Such a trend was significant until 1975 but the changes have become smaller after 1980. So why did this proved resource disappear?

One reason is that during the decades of 1960–1970, a major innovation occurred in the iron & steel industry. Until then, it was usual to locate the steel-works near to the mines of the main raw materials of iron ore or coal. But, a new business model (seaside iron-making) became established mainly by Japanese steel makers. Its new concept was to produce high-quality steel at low cost by importing high quality iron ores and coals, and by using large-scale blast furnaces. In order to perform efficient iron-making using a large blast furnace, it was necessary to ensure stable supplies of large quantities of high-grade iron ores and coking coals. This required a reduction in transportation costs for the raw materials from Brazil, India and Australia which led to economic use of large ships for the long distance transportation necessary. As such, seaside iron-making became popular, most of small pit-mines were closed, thus reducing the economically viable resources; for instance, the last iron ore mine in Japan was Kahaishi mine and was closed in 1993.

This illustrates the point that whether the material existing in nature is classed as a ‘resource’ or not is dependent simply on whether production using that natural material is economically justified or not. Thus, the same substance can be a ‘resource’ or just simply ‘rocks’, depending on the economic and geographical conditions, combined with technological progresses. It may thus be better to simply define ‘resource’ as follows:

1. Located at a minable place;
2. Containing useful substances and concentrations;
3. Gathered in sufficient quantity; and of course,
4. Being capable of being exploited economically.

These days, the utilization of waste materials through recycling is widely promoted. Such recycling materials are sometimes called ‘secondary’ resources but the technological and economic viability of their recycle can vary significantly. Used paper and steel scrap are representatives of secondary resources where their recycle is both technologically and economically viable. On the other hand, many wastes can be recycled only through significant additional expenses of preliminary selection, separation, detoxification and so forth by the waste generators and/or handlers. Such cases may be also regarded as broadly economically justified when the costs of recycle are compared with costs for the proper disposals of the wastes concerned. Not only iron & steel but also many base metals are used in large quantities by society and therefore collection of such metal scraps is relatively easy, so that base metals are suitable materials for recycling. It is thus important to balance the amounts of metal production from ores and scraps to mitigate the degradation of primary resources.

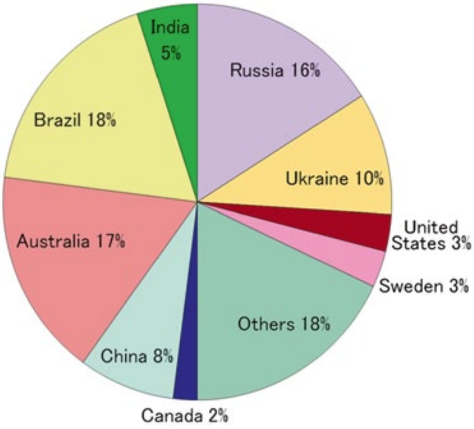


Fig. 12.7 Global distribution of iron ore reserves. (US Geological Survey 2014)

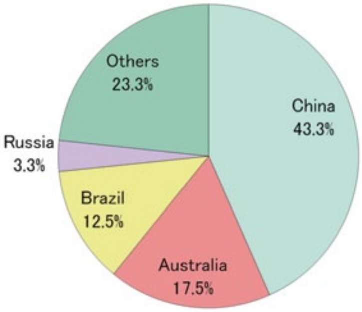


Fig. 12.8 Global distribution of iron ore production. (British Geological Survey 2014)

12.3 Distribution of Iron Ore Resources and Their Trading

Figure 12.7 shows the outline of global distribution of iron ore reserves. More than three quarters are held by a limited number of countries; Brazil, Australia, Russia, Ukraine, China and India in that order (US Geological Survey 2010). On the other hand, China accounts for more than 43 % of the current iron ore production and is followed by Australia, Brazil and Russia in that order (Fig. 12.8; British Geological Survey 2014). The distribution of iron ore exports are shown in Fig. 12.9 (ISSB 2013). Nearly 75 % is provided by two countries;- Australia and secondly Brazil. China is the biggest iron ore mining and steel production country but it does not appear here since Chinese steel production far exceeds its iron ore production, and it has thus become the largest importing country of iron ores.

The production of iron ores are influenced by very large several companies known as major resource companies, which were established by recent megamergers and restructuring. Figure 12.10 shows the shares of iron ore seaborne trading

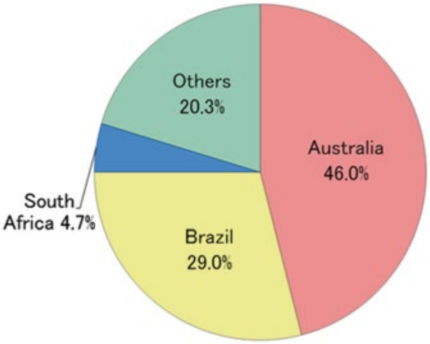


Fig. 12.9 Distribution of iron ore exports in the world (2012)

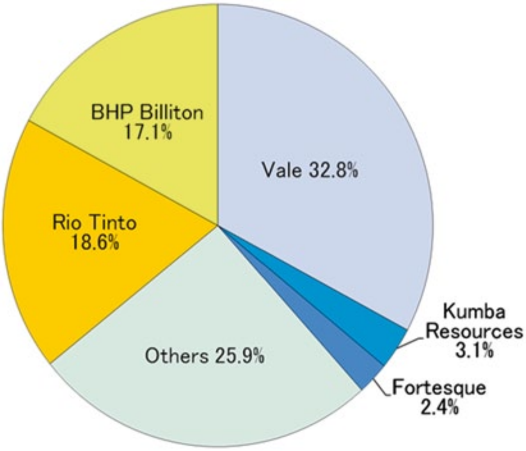
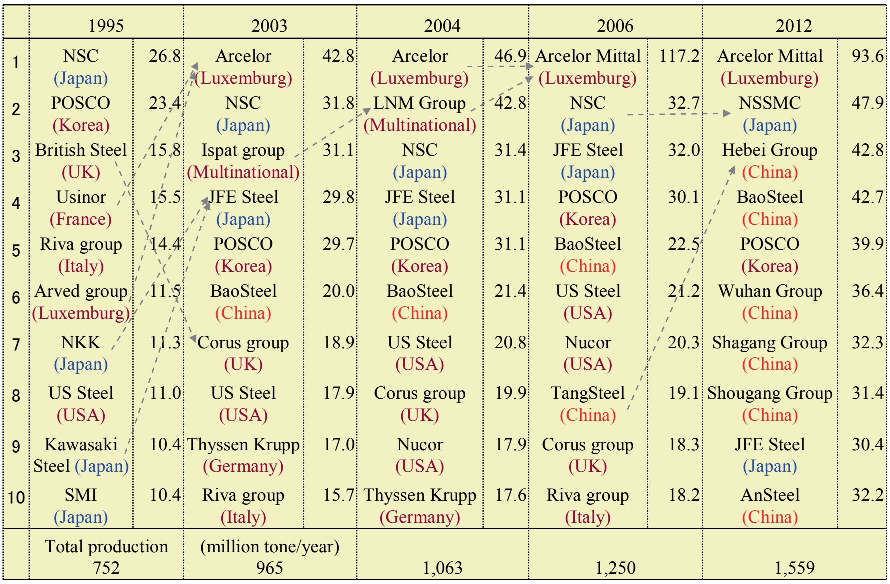


Fig. 12.10 Share of the seaborne trade of iron ores among resource companies (2008). (Reuters, http://www.reuters.com/)

for such major companies in 2008. An oligopoly situation is seen as three major companies, Vale, Rio Tinto and BHP Billiton, accounting for about 70 % of global trading. It can be suggested that such a situation is one of the reasons for unstable price fluctuations in iron ore resources. In addition, the influence of these international major companies is also large in terms of coal resources.

12.4 Restructuring of Integrated Steel Companies

As mentioned above, iron ore and coal resources are now in an oligopoly situation, held by a few massive companies. The negotiating power of the steel companies to the price and property of iron ores has thus become relatively small. To compete with major resource companies, international mergers and restructurings have thus also been made in steel companies and it has accelerated from the end of 20th



	1995		2003		2004		2006		2012	
1	NSC (Japan)	26.8	Arcelor (Luxemburg)	42.8	Arcelor (Luxemburg)	46.9	Arcelor Mittal (Luxemburg)	117.2	Arcelor Mittal (Luxemburg)	93.6
2	POSCO (Korea)	23.4	NSC (Japan)	31.8	LNM Group (Multinational)	42.8	NSC (Japan)	32.7	NSSMC (Japan)	47.9
3	British Steel (UK)	15.8	Ispat group (Multinational)	31.1	NSC (Japan)	31.4	JFE Steel (Japan)	32.0	Hebei Group (China)	42.8
4	Usinor (France)	15.5	JFE Steel (Japan)	29.8	JFE Steel (Japan)	31.1	POSCO (Korea)	30.1	BaoSteel (China)	42.7
5	Riva group (Italy)	14.4	POSCO (Korea)	29.7	POSCO (Korea)	31.1	BaoSteel (China)	22.5	POSCO (Korea)	39.9
6	Arved group (Luxemburg)	11.5	BaoSteel (China)	20.0	BaoSteel (China)	21.4	US Steel (USA)	21.2	Wuhan Group (China)	36.4
7	NKK (Japan)	11.3	Corus group (UK)	18.9	US Steel (USA)	20.8	Nucor (USA)	20.3	Shagang Group (China)	32.3
8	US Steel (USA)	11.0	US Steel (USA)	17.9	Corus group (UK)	19.9	TangSteel (China)	19.1	Shougang Group (China)	31.4
9	Kawasaki Steel (Japan)	10.4	Thyssen Krupp (Germany)	17.0	Nucor (USA)	17.9	Corus group (UK)	18.3	JFE Steel (Japan)	30.4
10	SMI (Japan)	10.4	Riva group (Italy)	15.7	Thyssen Krupp (Germany)	17.6	Riva group (Italy)	18.2	AnSteel (China)	32.2
	Total production 752		(million tone/year) 965		1,063		1,250		1,559	

Fig. 12.11 Change in the world steel production ranking

century (see Fig. 12.11). For example, Nippon Steel (NSC) ceded first place for crude steel production to Arcelor, which was established in 2003 by the merger of French and Luxemburg companies. After that, Arcelor was acquired by Mittal Steel Company and became the world biggest steel company; Arcelor & Mittal. In Japan, Nippon Kokan (NKK) merged with Kawasaki Steel to form JFE Steel in 2002. Furthermore, Sumitomo Metal Industry (SMI) merged with NSC to form Nippon Steel & Sumitomo Metal Corporation (NSSMC) in 2012. This merger has taken a Japanese steel company back to second place in crude steel production in the world, although the amount of steel produced is less than half that of Arcelor & Mittal.

In China, many middle- and small-scale steel companies have been built across the country from the 1990s. The central government started to introduce policies such as the abolishment of small-scale blast furnaces due to concerns over the downturn in the demand-and-supply balance for steel and environmental problems. It also promoted the merger of companies and many large steel companies were subsequently born in China. Six of the ten biggest steel companies of the world in 2012 are now Chinese.

At the same time, momentum towards the construction of integrated steel works has been gathering pace in ASEAN countries such as Indonesia, Thailand, Malaysia and Vietnam, and some of them have already been completed. Some of these countries possess their own iron ore resources although their amount and properties are not comparable to the major iron sources. However, such resources will become utilized as further degradation of current iron ore resources takes place.

12.5 Environmental Impact of the Steel Industry

Japanese iron- and steelmaking technology is at world-leading level in terms of energy efficiency and environmental protection. About 520 t of coke and pulverized coal are used to produce 1 t of steel. Such fuels are called a ‘reducing agent’, since they are used to reduce iron oxides to metallic iron. Gases formed in the coke oven (Coke oven gas, COG) and discharged from blast furnaces (Blast-furnace gas, BFG) are utilized as fuels in power generation and for heating various materials in downstream processes such as rolling. In total, about 2000 kg-CO_2 per ton of steel is formed in such a process. On the other hand, steelmaking by an electric arc furnace (EAF) process emits about 500 kg-CO_2/ton-steel, which is only a quarter of that from integrated iron- and steelmaking (Birat et al. 1999). From this point of view, it seems better to promote EAF steelmaking using scraps. However, the amount of steel scrap generation is limited to about 2.5 % of the steel stockpiles which exist in Japan as steel products and social infrastructures. Thus, about 3.5 million t of scrap are annually generated in Japan at present against the 1.4 billion t of steel in stockpiles (see Fig. 12.12). Japanese steel production has been a little above 100 million t/year, and therefore it is still necessary to use natural iron ore resources to keep this production level.

Figure 12.13 shows the CO_2 emissions from different sectors in the world. Total emissions from the industry sector are ~31 % and the steel industry contributes one quarter of this. After the introduction of modern iron & steelmaking technology, many efforts have continued to reduce the amount of reducing agents used. The reducing agent rate in 1950 was about 1000 kg/ton-steel but has been substantially

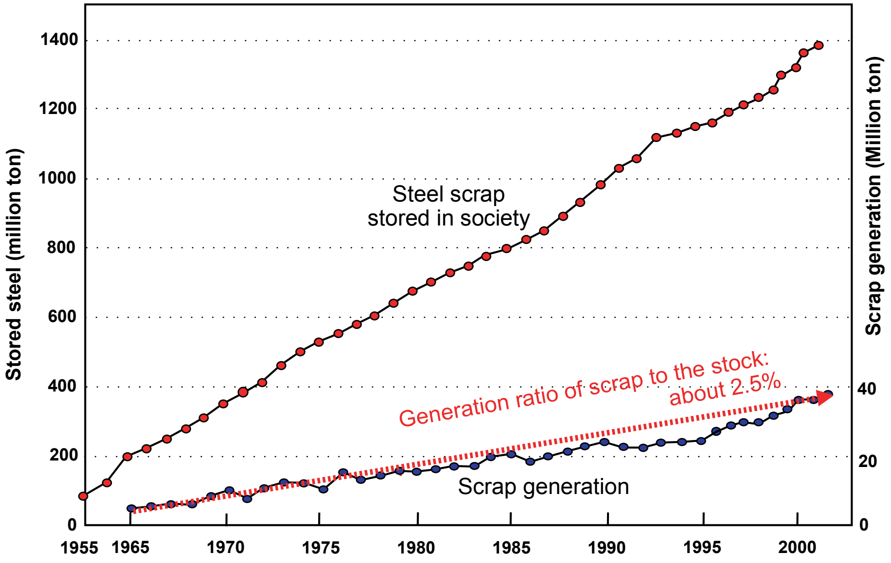


Fig. 12.12 Amount of socially-stored steel and scrap generation in Japan

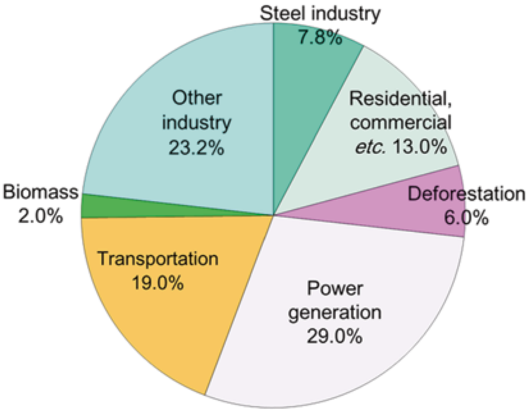


Fig. 12.13 CO_2 emission from different sectors in the world (Global emissions in 2011: 33.5 million t)

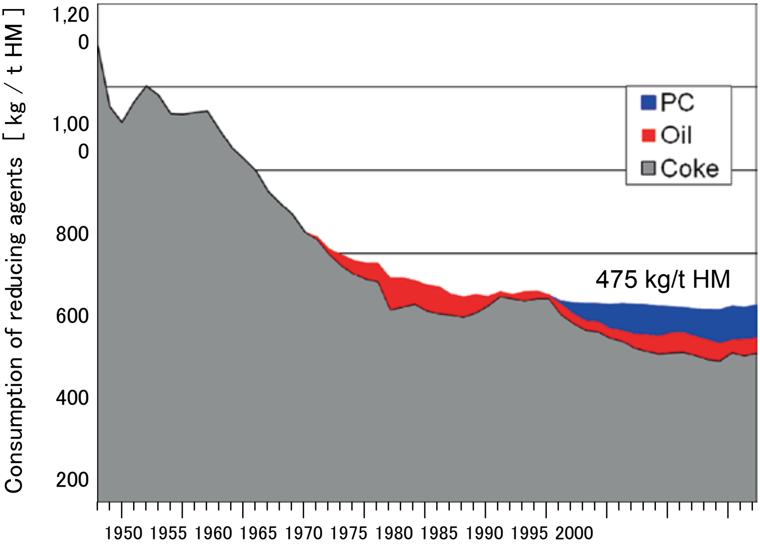


Fig. 12.14 Changes in the reduction reagent rate of the blast furnace ironmaking process

reduced to about 475 kg/ton-steel due to efficient improvements (Fig. 12.14). However, such a value is already close to the theoretically ideal condition when one considers the energies necessary for the reduction of iron oxides, and for heating metal and slag. Therefore a drastic innovation of the process itself is urgently required.

In order to further reduce CO_2 emissions from the iron & steelmaking process, it is necessary to employ fuel substitution to hydrocarbon gases like natural gas, which generates less CO_2, and/or biomass, which is currently classed as a carbon-neutral fuel. European Union nations started the ULCOS (Ultra–Low CO_2 Steelmaking) project in 2004, which aims to develop a new iron and steelmaking technology to reduce CO_2 emissions by more than 50% from the present value. It completed

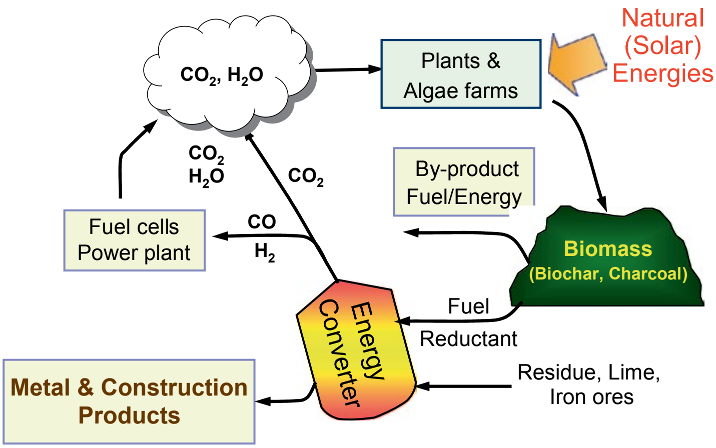


Fig. 12.15 An image for a sustainable iron & steelmaking process

the research phase and pilot phase and went into a demonstration phase in 2010 (ULCOS 2013). In Japan, the "COURSE 50" project (CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 (Japan Iron and Steel Federation 2013) is ongoing as a national collaboration project between the integrated steel companies and universities, aiming at the reduction of CO_2 emissions by 30% through utilization of more hydrogen in the iron-making process together with CCS (Carbon dioxide Capture & Storage) technology. It was initiated in 2008 and a pilot plant is being constructed at present.

Figure 12.15 shows an example outline of the co-production system of iron and energy. Further efficiency will be only made by the combination of cascade utilization of energy and coproduction. Various trials to develop new iron-making processes are being made including the recovery of surplus energy and its civilian supply.

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Chapter 13
Resource Recycling of Non-Ferrous Metals

Takashi Nakamura

Abstract This chapter focuses on non-ferrous metals, their resources, extraction and recycling. Mining of these metals (copper, zinc etc.) causes major environmental damage through open mining techniques, and thus improving recycling rates has major environmental benefits as well as potentially economic ones. This chapter thus looks at the recycling technology for these metals and ways in which they can be increased from sources such as dusts from steel scrap processing and electronic wastes. A number of recycling approaches applied to a range of industries are introduced, together with a system approach to increasing Japan's recycling of valuable metals.

Keywords Non-ferrous metals · Metal recycling · E-scrap · EAF dust

13.1 Introduction

While many use the term 'zero-emission', this perfect goal is both theoretically impossible in view of the laws of thermodynamics and also limited by the practicalities of engineering. The only way to achieve true sustainability on the planet therefore, is to regulate industrial activity so that it can operate within the equilibrium magnitude of energy supplied to the Earth by the solar system. Given the present rate of energy consumption, this would require a combination of an appreciable shrinkage in economic activity, a reduction in population and/or a substantial reduction in the standard of living in industrialized countries—none of which is particularly appealing.

Use of the term 'sustainable development' without any clarification of its scientific basis can thus give people a false sense of security. Implementing sustainable development requires engineers and scientists to first analyze the total mass-flow of energy and materials, estimate the local impacts on the environment as well as

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T. Nakamura (✉)
Institute of Multidisciplinary Research for Advanced Materials,
Tohoku University, Sendai, Japan
e-mail: ntakashi@sda.att.ne.jp

Graduate School of Environmental Studies, Tohoku University, Sendai, Japan

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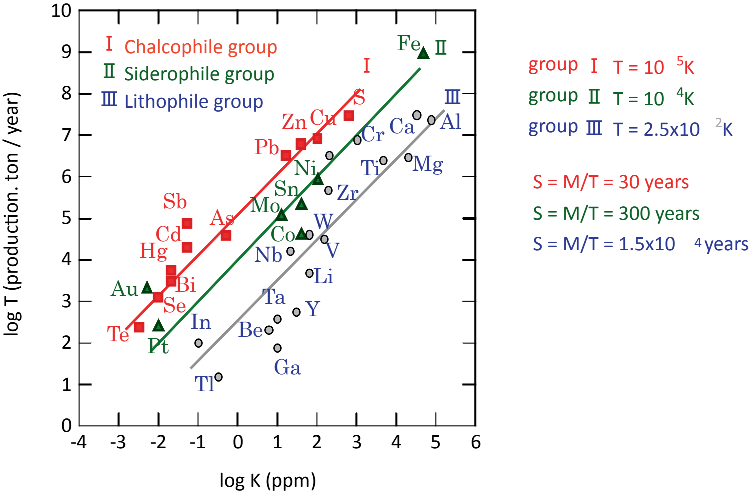

Fig. 13.1 Relationship between annual production amounts (T) and Clarke's Numbers (K)

the global impact of a particular industrial activity, before devising strategies to ensure sustainability on this planet. One aspect of this is to address the basic resource consumption of the key elements that are essential to support our current industrial society. The previous chapter addressed issues related to the iron and steel industry, and in this chapter we will turn to the non-ferrous metals and consider the potential for reducing their substantial environmental impact by increasing their rate of recycling.

Metal resources have been classified geochemically by Goldschmidt (1954) according to their preferred host phases into lithophile (rock-loving), siderophile (iron-loving), and chalcophile (ore-loving or chalcogen-loving) nature. These groups can be distinguished as shown in Fig. 13.1 where the annual production of metals is plotted logarithmically against Clarke's numbers[1] (Masuko 1994). The different groups reflect major differences in their distribution and chemical behavior with implications for their environmental impact. For instance, Siderophile elements are the high-density transition metals which dissolve readily in iron, and sink towards the core so that they are rare in the Earth's crust. Lithophile elements combine readily with oxygen so remain near the surface but require energy-intensive electrolysis for extraction. Chalcophile elements also remain close to the earth's surface because they combine readily with sulfur and thus their refining requires reduction with coke to remove the sulfur with its associated pollution.

The detrimental environmental impacts of metal extraction and refining can be illustrated by the case of copper (chalcophile group) extraction. Firstly, copper mining has direct impacts on the environment through mining. Secondly, non-ferrous

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[1] Clarke's numbers express the average content of the chemical elements in the earth's crust and other geochemical and cosmo-chemical systems.

metal production in general is a complex process comprised of a series of sequential operations aimed at the separation of the metal fraction from the mined ore. The first step is the separation of the desired principal mineral from the native one- in the case of copper, this is chalcopyrite. Here, at this first stage some 99.5 % of the material processed becomes waste mineral almost immediately. Second, the separated concentrate then is subjected to selective refining. For copper, iron sulfide is partially oxidized to produce a slag phase and a waste gas stream bearing sulfur dioxide. The melt (referred to as a matte), is then sulfur-oxidized to copper metal. The waste gas from further oxidation contains additional sulfur dioxide together with oxides from less noble metals known as fume. Finally, the impure copper is purified in an electro-winning process and separated from more noble metals contained in the mineral including precious metals such as silver and gold.

The local environmental damage of smelting has affected many parts of the world (Chapter 2 mentioned some of the earliest cases in Japan of such gross pollution from sulfur dioxide at the Ashio mine) and emissions include the minor toxic elements arsenic, mercury, selenium and tellurium. The overall resource balance from a single copper smelter in a year producing 20 million t can be summarized as follows:

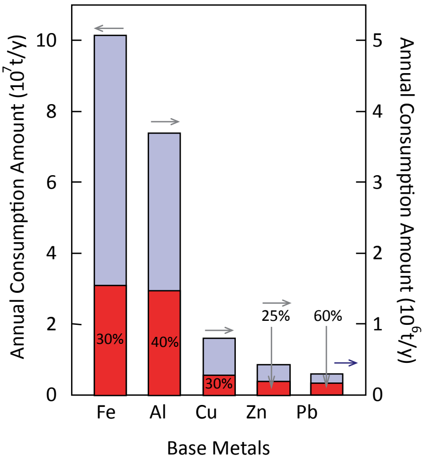
- discarded minerals: 40 billion t;
- sulfur, 20 million t;
- iron oxide, 20 million t;
- smaller amounts of other metals;
- electricity and fuel.

Considering such figures shows that recycling of metals should be seriously considered both to preserve limited resources, and to minimize emissions of the hazardous elements which accompany the refining process. In contrast to the large impact of mining and refining, recycling these metals has the advantage of avoiding mining operations and also avoiding the concentration of potentially undesirable elements left on the surface of the earth. Recycling does, however have the challenge of how to obtain the raw materials for recycling and the potentially high costs associated with collection of the materials to be recycled and separation from other waste materials. We will now consider some current issues related to recycling of non-ferrous metals.

13.2 Recycling Non-ferrous Metals- the Current Position

As mentioned above, the use of virgin ore has a strong negative impact on the environment from both a geographical point of view (destruction of landscape and production of large amounts of tailings, etc.) and in terms of global emissions of carbon dioxide (from energy use) and toxic gases. Also the potential economic difficulties of recycling materials have also been mentioned; in particular relatively high labor costs may make recycling economically unfavorable. It is thus important

Fig. 13.2 Recent total consumption and recycling of base metals in Japan



to consider the environmental impact of recycling of materials that is being done at present. Here an important aspect is the implications of the cascade effects of recycling, because in reality, where a material undergoes multiple recycling, the steady build-up of contamination leads to a cascade decrease in quality from first to second grade, then second to third grade, and so on until it becomes so contaminated that it is unusable. In a sense, the recycled material undergoes a re-mineralization, that will require at some point a primary-type processing step in order to again produce a pure and useable material. This primary-type processing step will have associated with it high consumption of energy resources and emissions.

Aluminum (Al) metal is an excellent candidate for recycling because of the high energy consumption in its production. If aluminum scrap could be recycled to its original purity by simple remelting, more than 90 % of the energy could be saved compared to production via smelting from bauxite. Metallurgists, however, know that the development of a commercial process for purification of molten aluminum from scrap hinges on being able to remove iron (Fe), which is difficult. Thermodynamically, removal of the chalcophile and siderophile elements Cu and Fe from aluminum is extremely difficult. Most secondary aluminum used is therefore a very low grade, such as source for cast products or as a deoxidation reagent in the steel-making process. From a LCA (life cycle assessment) point of view, alloying of chalcophile elements to siderophile metals and siderophile elements to lithophile metals must be limited; even though such alloys are in wide use because of their better performance. To facilitate recycling therefore, the paradigm for metal processing needs to change.

The recent amounts of base metals consumed and recycled in Japan are shown in Fig. 13.2. Since the amount of iron and steel consumption is much higher than that of the non-ferrous metals, the left vertical axis in the figure shows iron and steel and the right vertical axis the other base metals. The bar height shows the annual consumption and the darkened portion of the bar shows the recycled amount. The recycling ratio for iron and steel is about 30 %, and most iron scrap is treated by the

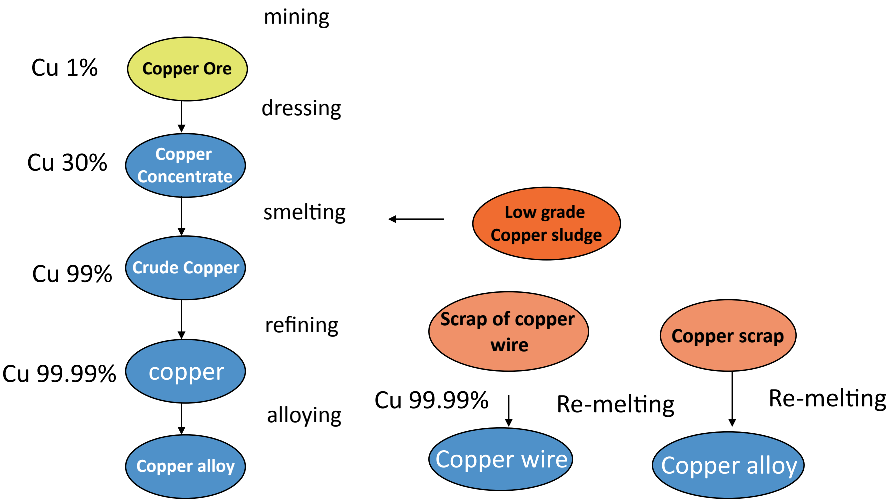


Fig. 13.3 Material flow of copper from copper ore to Cu alloy

electric arc furnace process (EAF). One major technical problem in iron and steel is the removal of tramp elements, especially copper and tin (Sn), which are thermodynamically more stable than Fe. Several processes to eliminate these tramp elements from scrap iron have been proposed but no economical method has yet been found. There is also an important economic problem involved: steel obtained by EAF using scrap is cheap due to its lower grade quality.

As mentioned above, Al is a good metal to recycle because the energy consumed in the metal's production is extremely high compared with remelting (Kellogg 1977), and the recycling ratio of Al is about 40 % in Japan. However, since Al is a very active metal, most impurity elements cannot be removed by remelting with the exception of alkaline and alkaline earth metals. This means that impurities must be removed before melting by washing or other laundering techniques (Masuko 1994).

A simplified flow diagram for Cu recycling compared with primary smelting is shown in Fig. 13.3. The advantage of Cu recycling is that even very low grade copper waste can be recycled to high grade copper using a primary copper smelter. Cu is an easy metal to recycle if it is possible to collect radiators and wires which are made of high purity Cu. But the recycling ratio of Cu is only 30 %, because it is used in small motors and electric circuit boards with LSI circuits which makes the Cu hard to separate from other materials. The recycle techniques for Cu are thus remelting for high grade Cu scrap and returning to a Cu smelter for low grade scrap.

The consumption of lead (Pb) is not large but the recycling ratio is very high, more than 60 %, because a system for recycling Pb from batteries has been well-established in Japan. Recycling of Pb-based chemicals is still a problem, however.

The Zn recycling ratio is around 25 % which is the lowest of the base metals because its main use is in plating on steel to protect corrosion. EAF dust has to be recycled not only to recover Zn but to keep the environment clean. EAF dust has

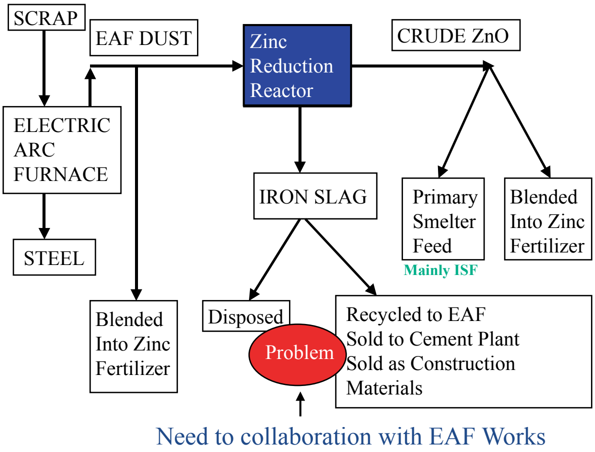


Fig. 13.4 Generalized materials flow for EAF dust treatment

been designated as a harmful industrial waste in Japan because it contains small amounts of heavy metals such as lead and also a very small amount of dioxins. Although numerous treatment processes have been proposed, only three have been employed commercially in Japan. We now discuss recycling of Zn from EAF dust recycling in more detail.

13.3 EAF Dust Recycling

Steel production from electric arc furnaces has been increasing and this trend is likely to continue. As a result, increasing quantities of EAF flue dust containing high zinc content will have to be treated and more zinc will become available for recycling. A schematic material flow for zinc-coated steel scrap is shown in Fig. 13.4. When steel is being produced from scrap, the zinc remaining on the feedstock is volatilized and captured in the flue dust which is filtered out from the furnace gases. A substantial quantity of this dust is upgraded and then used as feedstock for the production of primary zinc. This treatment is not economic however, and most EAF dust has historically been landfilled. However, as the dust has become listed as a hazardous waste and has to be disposed of in more highly regulated sites, the attraction has grown for technical improvements towards highly efficient recycling. Industry is aware of the potential for further recovery of zinc from EAF dusts, and the amount of these materials that are treated to recover the zinc content is increasing.

Today's EAF dust treatment processes are summarized in Fig. 13.5 which includes both commercial operation processes and pilot plant operation processes (but excludes processes still at the laboratory scale). Pyrometallurgical processes such as the Waelz kiln process have been commonly used to recover crude ZnO from EAF

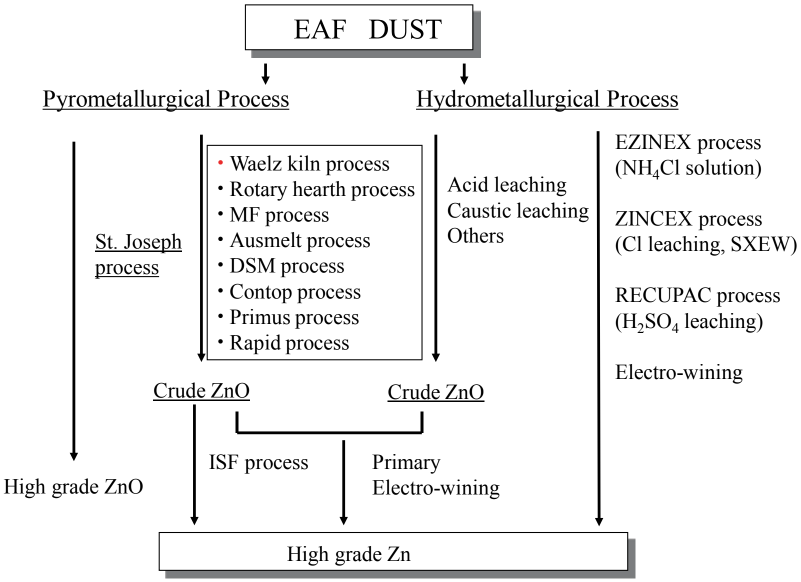


Fig. 13.5 Schematic presentation of EAF dust treatment

dust in the past. There are a number of pyometallurgical processes that have been operated and such processes are effective in treating large amounts of EAF dust at one time. However, only crude ZnO can be produced, since the reaction of ZnO in a pyrometallurgical process is just from (ZnO) in EAF dust (with a concentration of ~30%) → (ZnO) high grade(with a concentration of over 90%).

During the pyrometallurgical process, ZnO or Zinc ferrite ($ZnFe_2O_4$) is reduced and metallic zinc vapor is formed but this metallic zinc is oxidized again during cooling, following thermodynamic principles. Several trials to recover metallic zinc directly have been made, but no viable process has yet been developed. This is because cooling of metallic zinc gas to a liquid state without oxidizing is one of the most difficult of metallurgical techniques.

The pyrometallurgical recycling processes used in Japan are summarized in Table 13.1. Each method has a distinguishing feature. The Waelz kiln process is most popular and the leading technology for treating EAF flue dust and is continuously being optimized for energy input, product and off gas quality.

The rotary hearth furnace process has been developed and operated commercially (McClelland and Metius 2003). High quality crude zinc oxide is obtained in the rotary hearth furnace process and the residue is recyclable as an iron source, although the initial capital investment is relatively high. A schematic process flow is shown in Fig. 13.6. Pellets consisting of EAF dust are reduced with pulverized coal, and zinc is evaporated and also cooled down in the rotary furnace. This furnace is used to treat blast furnace dust in steelworks in Japan.

Table 13.1 Comparison of pyrometallurgical processes for EAF dust treatment in Japan

Process	Furnace operation	Energy	Product	Raw material flexibility	De-lead process
Waelz	Large/complex	Coke, carbon, oil	Crude ZnO sinters	Low	Chlorinated roasting
Rotary Hearth	Large/complex	Coal, natural gas	ZnO, iron	Low	–
MF	Small/simple	Coke, oil	Crude ZnO, slag	High	–
St. Joseph	Large/complex	Electricity	ZnO, sinters	Low	Chlorinated roasting
DSM	Small/simple	Coal	Crude ZnO	Low	–

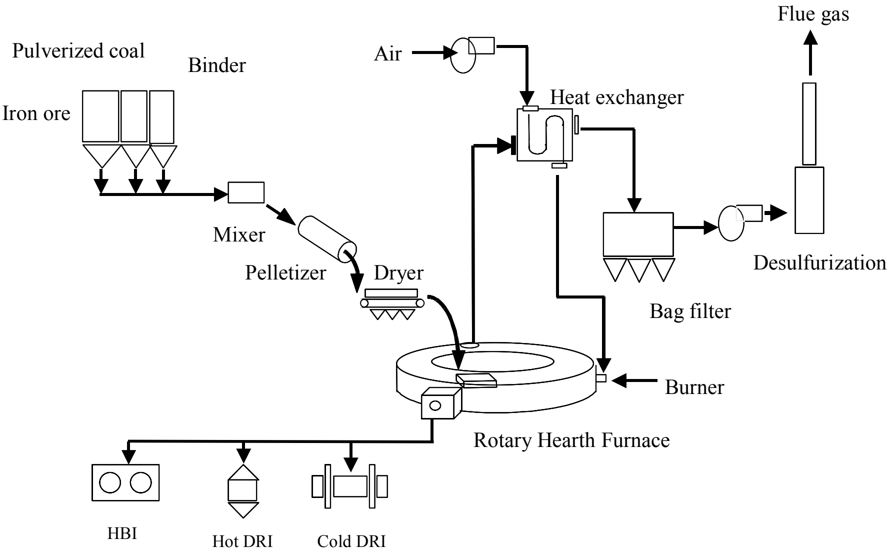
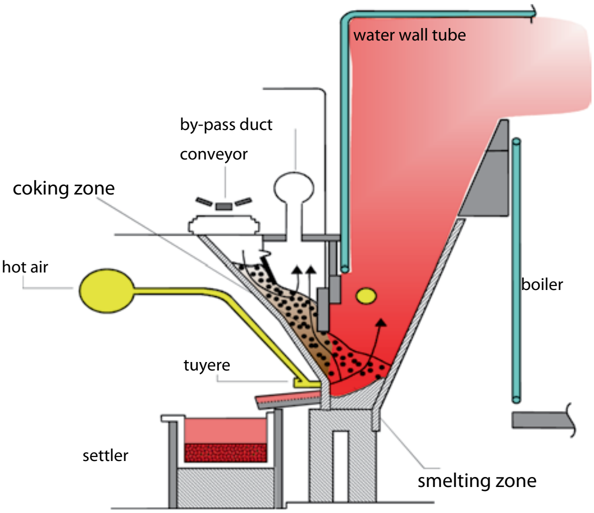


Fig. 13.6 Schematic illustration of Rotary Hearth Furnace process

The Mitsui Furnace (MF) originally developed by Mitsui Mining & Metals, Ltd. is a unique short blast furnace type as shown in Fig. 13.7. Briquettes of EAF dust and cokes are put into the furnace from the top, and hot air is blown from a tuyere as used in a blast furnace, and ZnO and $ZnFe_2O_4$ are reduced to zinc gas by cokes in the furnace. This process produces crude ZnO and molten slag. Making molten slag has merit because it is easy to use for construction minerals; however iron cannot be recycled.

One technical problem of EAF dust is that the pyrometallurgical processes are not the final stage required to supply metallic zinc but only the middle stage, since they produce only crude ZnO. One more step such as the ISF (Imperial Smelting Furnace) process is necessary to refine the crude ZnO into zinc.

Fig. 13.7 Schematic illustration of MF furnace



13.4 E-scrap Recycling

13.4.1 Current Situation

We now turn to the potential for the recovery of metals from 'E-scrap' or 'Waste Electrical and Electronic Equipment (WEEE)' in Japan (Shiratori and Nakamura 2007). An approximate estimate of the amounts of metals in WEEE in Japan is shown in Table 13.2. Iron and steel scrap is of course, highest value and second is aluminum. Copper scrap in WEEE was estimated by Shiratori and Nakamura (2007) at around 150,000 t, which also has a good potential to be recycled. Amounts of precious metals like gold and silver are less certain, but it is considered that a few tons of these could be recovered if all WEEE in Japan were collected.

There are the following three types of actions for recycling of WEEE in Japan.

1. Basic Laws
   - Home Appliance Recycling Law (air conditioner, washing machine, TV-set, refrigerator, clothes drier). This covers about 1/3 of all WEEE in Japan, and over 6 kg/capita of WEEE have been treated under this scheme.
2. Voluntary actions by manufacturers
   - There is a 'Mobile Recycling Network' for recycling mobile phones which received 7,343,000 units (total of 696 t in 2010); this comprised about 20 % of the units sold in 2010.
   - The 'PC-3R' scheme for computers handled 367,564 units in 2010; this was less than 10 % of the units sold in 2010.
3. Uncontrolled reuse and recycle, which includes:
   - Reuse as secondhand goods (in Japan and Southeast Asia).
   - Export to Southeast Asia (for recycling).
   - Illegal Disposal.

Table 13.2 Amounts (tons) of metal estimated in man-made resources in Japan by Shiratori and Nakamura (2007)

Metal	Category	Total amount	Recycle ratio (%)	Amount not recycled	Amount estimated in WEEE	Remarks
Au	Electronics/machine	134	40	80.4	42	
Ag	Electronics/photo	672	30	470.4	670	Except battery
Pt	Electronics/catalyst	1.9	30	1.33	1.5	
Pd	Electronics/catalyst	7	30	4.9	3.7	
Cu	Electronics/wire	1,530,000	90	153,000	110,000	
Pb	Battery/solder	39,000	30	27,300	10,300	Includes pigment
Sn	Electronics/solder	12,400	30	8680	5300	
Zn	Galvanizing/battery	6800	25	5100	11,900	Galvanizing not considered
Ni	Electronics/battery	4800	25	3600	7000	Superalloys not considered
Cd	Battery	600	25	450	220	
Co	Magnet/battery	11,070	20	8856	Unknown	
Ga	GaS, GaP	53	20	42.4	23	
In	ITO, solder	486	90	63	46	
Ge	Fluorescent materials	7700	20	6160	Unknown	
Ta	Condenser	205	20	164	133	
REE(Nd, Sm, Dy, L)	Magnet/battery	4000	20	3200	Unknown	

E-scrap generated by local government is mainly landfilled and also part of the E-scrap collected by small traders is shipped aboard both legally and illegally.

Small domestic appliances were not widely collected before a new recycling law was enforced from April 2013. Overall, the potential weight of WEEE generated per capita in Japan has reached 20 kg—similar to other well developed countries. However, the collection rate is below 50 %. In particular, the collection rates for high grade WEEE such as PCs and cellular phones are small and hidden flows for these products still exist. This is despite E-scrap being an excellent source of minor metals so that E-scrap recycling should be one of the key measures to ensure a stable supply of minor metals.

The recycling flow for non-ferrous metals in Japan is shown in Fig. 13.8. E-scrap containing non-ferrous metals is finally recycled in non-ferrous metal smelters

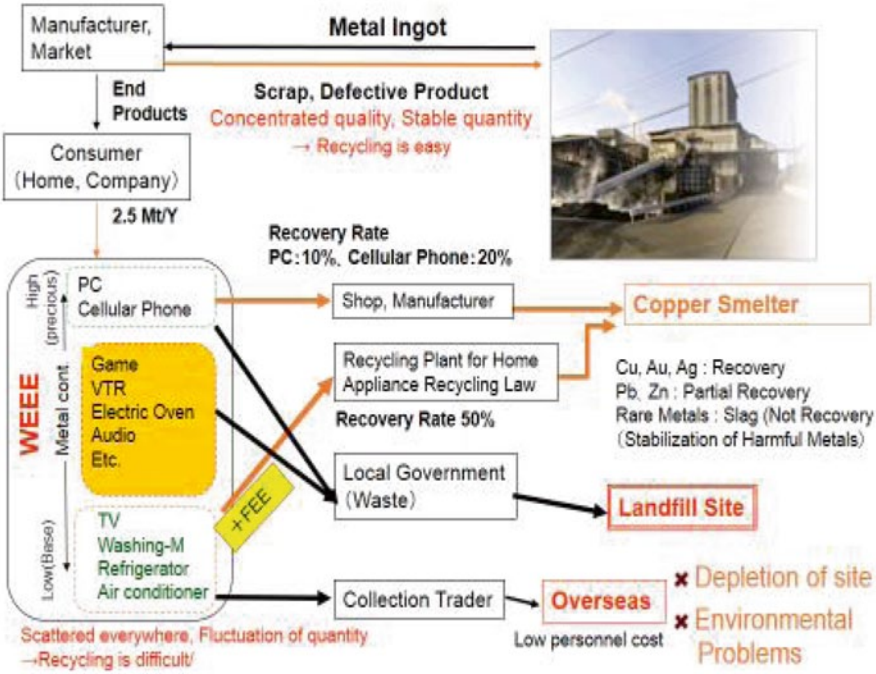


Fig. 13.8 Recycling of non-ferrous metals

through several routes. In the case of WEEE, when copper, gold and silver are collected for recycling, minor metals can also be gathered with them. If minor metals are separated from WEEE by proper techniques and are accumulated for recovery, they can be considered as resources. However, recycling of rare earth elements (REE) from WEEE is still a long way from meeting the demands for them. Why is the recycling of REE so difficult and what are the essential problems which are blocking progress in recycling?

There are indeed problems both in the social system and in technologies. The highest barrier to overcome is to build up a good economical collection system for WEEE. In the EU, a WEEE directive was established and recycling laws for home electronics applicants were also established in Japan. However, no strategy to recover minor rare metals was considered in either of these actions. A second bottleneck for recovery is the difficulty of recovery technology, especially dismantling parts containing REE. Most REE-containing parts are small and involve complex shapes which must be dismantled. For instance the neodymium-iron-boron magnet has a very strong magnetic force and is sometimes used with steel. A difficulty is thus separation of REE from other metals like iron. A separation process for dysprosium from neodymium after leaching is not so difficult however.

Precious metals and platinum group metals (PGM) are readily recycled in nonferrous metal smelters. Most of recycling resources are put into smelting furnaces such as copper converters, and they are finally recovered from copper slimes after copper electro-refining. Some pre-treatments processes may be required to adapt the furnaces.

Other minor metals have been also been recovered in copper, zinc and lead smelters. Recently Nippon Mining & Metals, Co. has developed a new factory to recover not only PGM but other rare metals in a Hitachi refinery (Jx-Group 2014). Indium, nickel, cobalt, antimony, bismuth, selenium and tellurium are recovered in this plant as well as precious metals. Almost the same treatment manner is found in other non- ferrous smelters. Non- ferrous metal smelters thus play an important role for minor rare metals recycling- especially since most minor metals must be imported into Japan, for refining, conversion and use.

A new concept for a metal recycling system (RtoS: “Reserve to Stock”, “artificial ore deposit design”) was introduced by Shiratori and Nakamura (2006), and based on the concept of the “Urban mine” (Nanjyo 1988). If effective recovery systems are not taken into consideration, rare metals will dissipate all over the world in the future. In particular, established procedures for collecting, recycling and extracting Cu, Au, and Ag from WEEE presents the opportunity to also gather rare metals at the same time. If minor rare metals are separated from WEEE by proper techniques and are accumulated for recovery, we can consider them as resources. A possible system for minor rare metals recycling has been suggested which could be self-supporting economically by devising a collection system and introducing commercial transactions into the recycling system (Shiratori and Nakamura 2006).

13.4.2 Recycling Technologies for E-scrap

Metal production from natural ore has had a long history- more than 200 years since the start of the industrial revolution. The first step is the exploration of ores, followed by feasibility study (FS) for mining, mineral dressing and extraction. Man-made resources (metal scrap and/or waste containing metals) have also been treated in the same way; and the differences between both approaches can be found in the early stages as shown in Fig. 13.9. The exploration, FS and mining correspond to the material flow analysis of target metals, the collection system and collection of

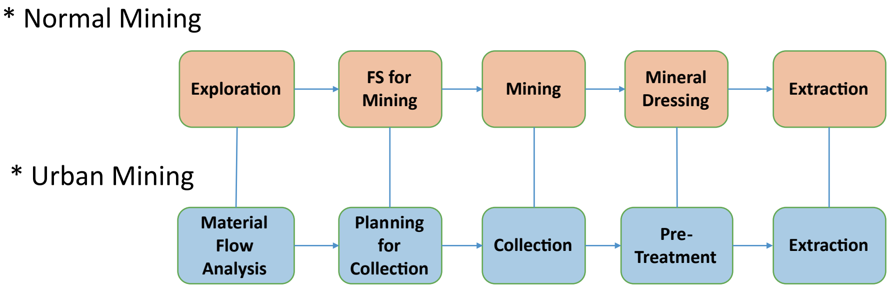


Fig. 13.9 Comparison between urban mine development and normal mine development

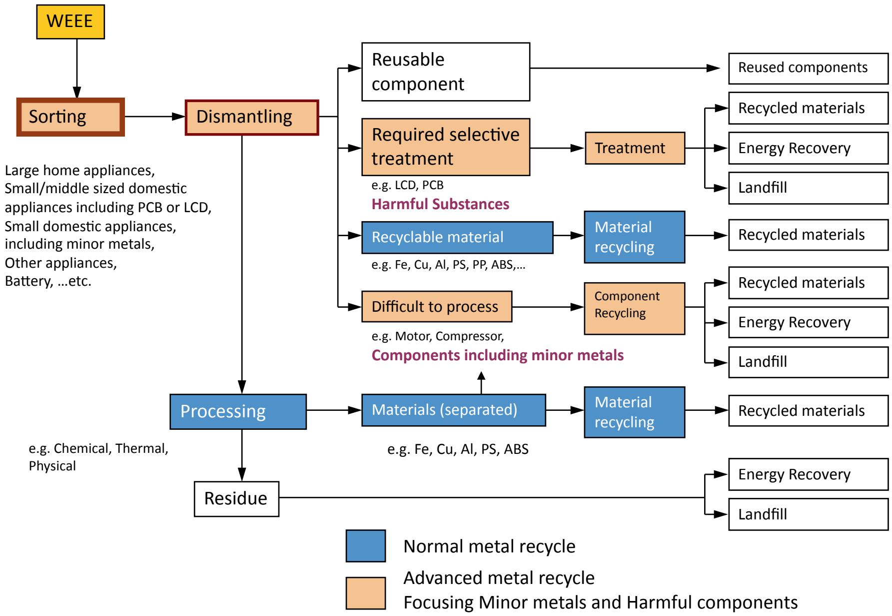


Fig. 13.10 Whole flow diagram for the processing of E-scrap

scrap, respectively. Establishment of an effective collection system is an essential prerequisite for developing urban mining economically.

A whole flow diagram for the processing of E-scrap is shown in Fig. 13.10. This shows the flow of E-scrap after collecting and the main pretreatment stage for E-scrap where WEEE are dismantled and crushed to various parts in the first step after collection. There are many methods for dismantling such as hand-picking, and crushing or shredding. Sorting techniques are applied to separate materials like iron & steels, non-ferrous alloys like aluminum and copper, and plastics. These sorting techniques include gravity separation, magnetic separation and so on, which are mainly used in the old mineral processing industry. Metallurgical production, with its intrinsic potential in smelting, extraction, enrichment and separation methods, related technology and process flow sheets, each with their own selectivity and yield, plays an important role in the context of minor rare metals.

The integrated iron & steel industry is relatively straightforward: starting with iron ore mining, ore sintering and/or pelletizing, production of metallurgical coke, quarrying of limestone, it continues with a fixed sequence involving blast furnaces, convertors, hot and often cold rolling. Nonferrous metal industry is much more diversified than steel production. Almost all plant is unique, adapted to either the composition of specific and often complex ores, or to certain ranges of metal scrap and/or residues. Particular processes and plant lay-outs are determined by (1) ore composition, including the amount and nature of its intrinsic accompanying impurities and their own markets and value, and (2) the required purity of the resulting products and other technical or environmental specifications. Depending on the process principle and flow sheet, the occurrence of accompanying elements is either beneficial—since their separation is easy and their contribution to turnover substantial – or pernicious, where the opposite is the case. This leads to highly diversified flow sheets and operating conditions, in which some plants recover a wide range of additional elements, separating these one by one, and other plants merely removing these as undesirable impurities, e.g. in the slag. Such choices are made on the basis of economic, logistic, as well as technical reasons.

Copper is a valuable element, and silver even more so. Yet, during electrolysis silver is precipitated willfully with the slimes, since it is separated easily, sold profitably, and moreover its continued presence lowers the quality of electrolytic copper. Nickel similarly is highly valuable and yet its presence in a copper smelter may become a real nuisance: when it appears, it cannot be separated so easily and still has to be sluiced out, together with a considerable amount of copper co-entrained in the bleed stream in order to safeguard copper specification standards. Of course, some dedicated smelters operate schemes that allow separation of these two valuable metals, but these smelters may be situated far away and not too much interested in custom co-treating such an occasional mixed copper/nickel stream. Extracting value for less usual or more complex flows is not so evident and the picture of supply and demand for such services is often unfavorable and continuously evolving.

13.5 In Conclusion

We have considered the impacts on the environment of base metals from a resource perspective. Environmental problems will continue to be important, but so will natural resource security. Creating a zero-waste society will help to combat both these issues and promote sustainable development. Natural resources depend on the land in which they are found, and can therefore become easily involved in politics. Environmental sustainability is next to impossible without bold political leadership. Thus, we need to consider both the environment and natural resource security when formulating national strategy. Especially in countries like Japan where advanced technology is everywhere but there are few resources, there is a need to thoroughly debate the use of technology to create a zero-waste society and then to create such a society.

Non-ferrous metals recycling is vital to maintaining a supply chain for minor rare metals in Japan. Non-ferrous smelters are important to advance recycling of basic and minor rare metals. A new system is necessary for this and greater development of recycling technologies for non-ferrous metals and minor rare metals. This would have considerable impacts on the environment from a resource perspective. Environmental problems will continue to be important but natural resource security will also become as important. Creating a zero-waste society aims to combat both of these issues and promotes sustainable development.

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Chapter 14
Strengthening Scientists and Engineers Appreciation of the Real World

Shunsuke Managi

Abstract This introduces the increased emphasis on society's relationship with academic research and how to strengthen students' experience outside the research laboratory. This is already one of the objectives in the ELTP, but is also expected to gain importance as the new approach to international global environmental change under Future Earth gains momentum. This will require researchers to improve communications with society and its stakeholders, requiring researchers to hone their communication skills and ability to envisage the interests and viewpoints of different stakeholders. The field of environmental economics brings together many aspects of sustainability and its compatibility with the economic system, and this chapter raises a number of questions (including those emerging after the 2011 tsunami and Fukushima nuclear disaster) designed to encourage students to apply a more system-wide and lateral thinking.

Keywords Fukushima · Tsunami · Economic costing · Valuing life · Future Earth · Stakeholders

14.1 Science Engineering and Society

This book has originated from a series of lectures given in the postgraduate Environmental Leader Training Program (ELTP) at Tohoku University, where most of the students are conducting research for their PhD or MSc in various fields of science or engineering. The various lectures, and the associated chapters in his book, provide additional knowledge and insights into a range of energy and resource problems. In some cases these will be in fields close to the student's own research area; in other areas it will add a breadth to his/her knowledge and contribute to their 'bird's eye view' of these problems, which is one of the ELTP's objectives.

Most young researchers will still be in a position where they are learning the art of research which is based on strict objectivity, rationality, openness and debate

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S. Managi (✉)
Graduate School of Environmental Studies, Tohoku University, Sendai, Japan
e-mail: managi.s@gmail.com

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over accuracy and relevance. The methodology of research requires the detailed examination of previous literature, results and theories, and a strong determination to build on that foundation to discover new knowledge. Although the primary purpose might well be to provide material for a thesis or publication, most students in the science and engineering field are also well aware of the extent to which Society is entirely dependent on previous scientific and engineering research and development. They may well have a simplistic view therefore that scientific results are always acted upon, are generally capable of being communicated as objective information (or even facts) and that society will wish to use and act on the latest scientific information.

However the more astute students will already have realized that this is not always the case. In the sustainability foundation course (see Chap. 1) on the history of most major pollution problems, society has traditionally gone through a phase of rejecting early scientific evidence on environmental damage, and both governments and industry have tended to go to substantial lengths to avoid dealing with such problems (see the various case studies in Norton (2012), EEA (2013)). In the ELTP they will have also have seen how extensively special-interests have and continue to deny, distort, and manipulate the science related to global warming and climate change.

Students may also be conscious that governments consistently refuse to adopt policies to improve the sustainability of society. Failure to agree carbon reduction targets at successive international negotiations under the UN Framework Convention on Climate Change reveals how governments prioritize short-term economic interests over longer term sustainability. Even over the economic ‘rules of the game’ governments appear unable to move to a more sustainable path- even where such reforms have been recommended for decades by business itself. For instance, the World Business Council on Sustainable Development (WBCSD 1992) emphasized the importance of internalizing environmental externalities, removing perverse subsidies (such as to fossil fuels or fishing) which encourage overconsumption, strict application of the polluter pays principle and other economic reforms designed to level the playing field between sustainable and non-sustainable business. Yet 20 years later at the Rio+20 Summit on sustainable development, little progress on these core recommendations could be reported since 1992[1].

14.2 Future Earth

One response of the global research community to this situation has been the adoption following the Rio+20 Summit in 2012, of the international collaborative research programme called ‘Future Earth’. This major international collaborative initiative involves a significant redesign of research on sustainability problems- in

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[1] For instance Koplow (2012) reports that fossil fuel subsidies in G20 countries remain; indeed some G20 countries (e.g. Canada) actively sought to protect them at Rio+20, so that a proposed commitment to ending fossil fuel subsidies was erased from the final text of the Rio declaration.

response to the lack of societal action despite the wealth of scientific information on the way human activities are altering the Earth system with significant impacts on the environment at local, regional and global levels. Despite the changes in the Earth's climate and loss of biodiversity, which are undermining improvements in human well-being and poverty alleviation, the world is no more on a sustainable path (UNEP 2012) than it was before the definition of sustainable development was even invented in 1987 (WCED 1987).

Future Earth will address the issues critical to poverty alleviation and development including food, water, energy, health and human security (ICSU 2013). It will provide and integrate new insights into areas such as governance, tipping points, natural capital, the sustainable use and conservation of biodiversity, lifestyles, ethics and values. In particular, it focuses on the need for a more holistic approach and the interactions between natural and human drivers of change, and to achieve this aims to apply deeper integration between natural and social sciences, economics and humanities. A new approach and operational model to research has been proposed and is now being implemented whereby the groups conducting research seek to engage much more actively with stakeholders- from the initial research project design phase to the final dissemination of results, and in influencing subsequent actions following the research. Stakeholders in this case include research funders, governments, development organisations, business and industry, civil society, media and organisations at the interface of science and policy.

14.3 Implications for Future Earth of Japan's Environmental Leader Programs

One question which faces us is how this new thinking might influence the approach taken under the environmental leader programs. In particular, how Japan should anticipate the impact of Future Earth over its projected 10 year period on the skills needed for researchers into global environmental challenges. At the time of writing this chapter, Japan is bidding to host either the global headquarters or an Asian 'regional hub' within the overall global Future Earth programme. This has led to some reflection on how compatible the existing environmental leader program is with the demands of Future Earth for this 'new type' of researcher, and whether Japan should develop its own activity related to education and training to support the regional education and capacity building required for a Future Earth agenda. Let us consider this aspect here.

14.3.1 Future Earth Educational Needs

Future Earth (FE) is a 10 year initiative to provide scientific support for the many challenges facing society and for the sustainable development goals (SDG) process agreed at the Rio+20 summit in June 2014. FE's emphasis is the integration of natural and social science and humanities to address real problems of society, and the early engagement of stakeholders in defining problems and in communicating solutions which can lead to transformation to sustainability and the necessary institutional, economic, social, technological and behavioural change. A key concept is to encourage 'trans-discipline' research which means that research is not just across disciplines (inter-discipline or cross-discipline) but engages societal stakeholders in design, implementation and dissemination of the research. Section 5 of the Future Earth Design Report (ICSU 2013) recognises that education and capacity building is necessary to provide human resources capable of the necessary 'trans-disciplinary' approach. Resources will thus be needed to strengthen the Asia region's capacity to develop the next generation of researchers on global environmental change and sustainability, enhance institutions' capability to participate internationally, develop innovative approaches to stakeholder engagement and co-design of trans-disciplinary-oriented education and training.

14.3.2 Japan's Relevance to Future Earth

Japan's policy history also has much synergy with the needs of FE. Japan's 21st Centennial Environmental National Strategy adopted in 2007 aims to establish a Japanese model for achieving a sustainable society based on three components-low carbon usage, high levels of material cycling, and natural symbiosis- all critical steps in achieving a sustainable society. This strategy also recognized that Japan can, through this industrial paradigm, contribute to both its own and the rest of Asia's sustainable prosperity. As described in Chap. 1, both the Ministry of the Environment (MOE) and the Ministry of Education and Science (MEXT) established environmental leader programs. These programs support a wide range of curricula and teaching approaches aimed at a broad range of environmental leaders, and appear compatible with the trans-disciplinary, young researchers prioritized in the Future Earth initiative. In addition the international links already established within Asia in the environmental leader programs provide a good foundation for adaption and expansion within Asia to provide the education and capacity building envisaged in FE.

The distressing experience of the Great East Japan Earthquake is also relevant. The earthquake and tsunami destroyed whole communities, and the aftermath of the tsunami damage triggered the Fukushima nuclear disaster. These events illustrated the challenges of applying science, technology and public policy to a crisis with huge environmental and public health implications- in many ways analogous at the local level to some of the challenges envisaged in Future Earth. Post-disaster response also revealed many failures in the way institutions deal with science and stakeholders; in the way established organizations fail to take an open approach in seeking scientific advice, informing the public, and seeking co-creation of viable solutions. These experiences are very relevant to the application of natural

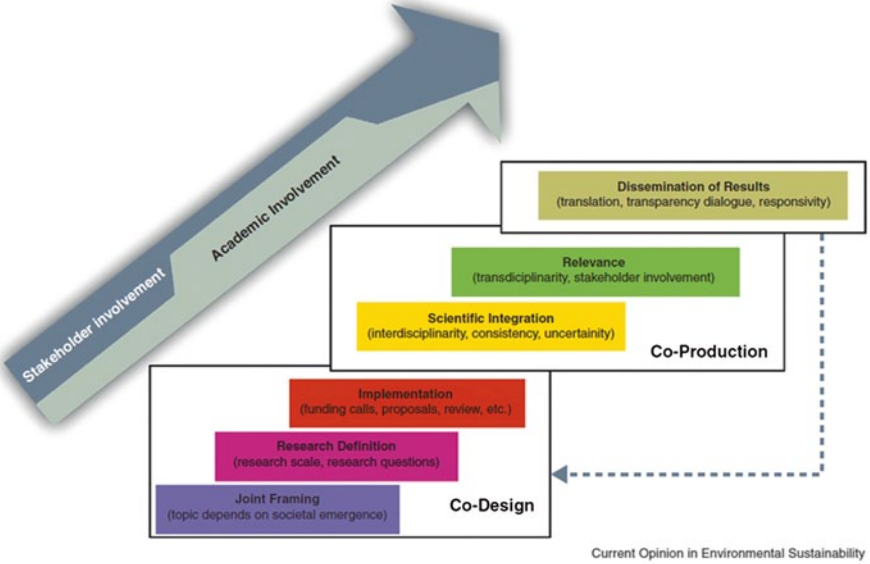

Fig. 14.1 Framework for trans-disciplinary research showing the stages of interaction between the research community and stakeholders. (Mauser et al. 2013; open access)

scientists, social scientists, humanities and stakeholders to the real world challenges envisaged in FE.

Challenges since 2011 have also provided the Graduate School of Environmental Studies at Tohoku University experience of a ‘trans-disciplinary’ approach in its response to the regional recovery to the earthquake and tsunami. As one example, in order to define the future research agenda to promote a sustainable local community, the Graduate School consulted key stakeholders in the areas affected (including the local administrations and Mayors) in order to define the components of the new energy and smart community project (NET 2012). Each project has been designed to respond to different local stakeholder priorities and thus conforms to the initial FE co-design phase envisaged in the trans-disciplinary research model described by Mauser et al. (2013) as shown in Fig. 14.1. The GSES also has strong inter-disciplinary research teams where engineering, physical and biological sciences, economics, social sciences and humanities research and teaching programs interact. Aspects and issues in sustainable development and research targets are related to many of the targets of Future Earth itemized in Mauser et al. (2013) and listed in Table 14.1. Trencher et al. (2013) see the co-creation of knowledge for sustainability envisaged under Future Earth as involving “*collaborating with government, industry and civil society to advance the sustainable transformation of a specific geographical area*” which is an appropriate way of describing the response of Tohoku university to the urgency of adapting and responding to the catastrophic local impacts of the 2011 earthquake and tsunami.

Table 14.1 Research challenges identified in Future Earth. (From Mauser et al. 2013)

Grand challenges for research	Forecasting- improve the usefulness of forecasts of future environmental conditions and their consequences for people
	Observing- develop, enhance and integrate the observations system needed to manage global and regional environmental change
	Defining- determine how to anticipate, recognise, avoid and manage disruptive global environmental change
	Responding-determine what institutional, economic and behavioural changes can enable effective steps towards global sustainability
	Innovating- encourage innovation in developing technological, policy and social responses to achieve global sustainability
Research questions associated with the Grand Challenges	How can humanity feed a growing world population within sustainable boundaries of the Earth system? How can governance be aligned with the opportunities for global sustainability?
	What risks is humanity taking in the Anthropocene, from negative implications on development, to tipping points with catastrophic implications for human societies?
	How can the world economy and available technologies be transformed to stimulate innovation processes that foster sustainable development?
	In a rapidly urbanizing world, how can humanity design and sustain liveable and sustainable cities?
	How can humanity succeeded in rapid global transition to a low carbon economy that secures energy access for all and preserves the remaining biodiversity on Earth?
	How can societies adapt to the social and ecological consequences of warmer world and what are the barriers, limits and opportunities in adaptation?
	How can natural capital, ecosystem services, and environmental processes on Earth be shared in a fair way among all citizens of the world?
	What lifestyles, ethics and values are conducive to environmental stewardship and human well-being and how might these evolve to support a positive transition to global sustainability?
	How does global environmental change affects poverty and development, and how can the world eradicate poverty and create rewarding livelihoods while achieving global sustainability?

14.3.3 Asian Integrated Education and Training for Future Earth

At the time of writing, debate is continuing on how best to meet the FE requirements for "capacity building among the scientific and other stakeholder communities to strengthen integrated research for sustainability and the uptake of this research in decision-making processes". One option could be to build on the environmental leader programs to form collaborations between Japanese universities such as Tohoku University and other centres with similar expertise and objectives within Asia.

Although this is still at an early conceptual development stage, such an initiative could develop, apply and promulgate innovative education which internalises the expertise and practical wisdom of stakeholders in a trans-professional and trans-discipline approach, encouraging mutual learning among natural and social science and humanities, and responding to social needs. It could:

- establish processes for early engagement of stakeholders (including national, regional and local governments, industry and voluntary groups) in mutual learning and co-design of the centre's priorities and activities;
- apply co-design to broaden the existing environmental leader focus of current initiatives to the global sustainability and SDG agenda;
- co-design, develop and promote educational materials, teaching and training methodology to support the implementation of training programs at participating centres,
- formalise and strengthen existing Asian regional links with specified education programs (or plans) in each collaborative center;
- strengthen mutual learning within other Asian Environmental Leader programs and Higher Education for Sustainable Development networks.

The objective would be to stimulate interest among young researchers (postgraduates and postdocs) in the trans-disciplinary approach of FE, and provide them with an opportunity to hone their trans-disciplinary perspective and understanding of the issues which FE is seeking to address. At the same time, education programmes may also be offered to stakeholders (e.g. local government, local companies) to provide knowledge and understanding of the rationale and need for Future Earth, thereby strengthening their role as stakeholders.

While this debate over the longer term response to Future Earth is continuing, it does appear a likely trend that environmental leader program students will need to have greater insights into the relationship between science, engineering and society and its stakeholders at large.

In an attempt to help towards this objective and also to shed light on the apparent conundrums listed earlier on the failure of society to accept and act on some types of scientific knowledge, the lecture on which this chapter is based used a range of experiences after the 2011 earthquake and tsunami to pose a series of questions to the students. These are designed to illustrate the point that many scientific insights are open to different interpretations, that the message conveyed may depend on the method of communication and the attitude of the scientist conveying the message, and that responses to scientific information include extensive subjective and psychological elements.

14.4 Using the Experience of the 2011 Great East Japan Earthquake and Tsunami as a Stimulus for Analysis and Debate

14.4.1 Background to Current Issues

The Great East Japan Earthquake and Tsunami caused severe damages especially along the coastal area. As a magnitude 9.0 earthquake, this has been recognized as the most powerful earthquake in the country's history and was one of the world's five strongest earthquakes since modern record-keeping began in 1900. Most buildings inundated by the tsunami were destroyed, and the world was shocked to see the extent of devastation which spread throughout the region and transmitted through tragic TV pictures and internet videos. In terms of quantitative impact, National Police Agency report 15,883 deaths, 6150 injured, and 2643 people missing, as well as 129,225 buildings totally collapsed, with a further 254,204 buildings 'half collapsed', and another 691,766 buildings partially damaged. The damage spread across 20 prefectures. On the other hand, there were also many areas that were only slightly affected, and the impact by the disaster was not as severe as in previous major earthquakes, reflecting the effectiveness of the current standard of infrastructure and architecture in Japan in providing resistance against even the strongest of quakes.

The tsunami flooded the Fukushima Daiichi nuclear power plant of Tokyo Electric Power Company (TEPCO) and led to core meltdown, hydrogen gas explosions and major release of radiation. Evacuations of the local population within an initial radius of 30 km were required affecting around half a million people. Even though the evacuation radius has been reduced some 100,000 residents remain excluded from their houses, work or farms and do not yet know if or when they can return.

With regard to the response to the nuclear power disaster, a number of organizations and associations have been involved, and the information provided by them has often been confusing and missing the main points. This has led to much confusion over terms such as 'safe', 'acceptable risk', 'no significant effects' and so on. Often scientists and public relations sources may differ; also differences have emerged between experts within Japan, or involving international organisations. What we have also learned from the experiences of the nuclear disaster in Fukushima is that it is crucial to have a variety of energy sources, since Japan is now dependent on fossil fuels for over 90 % of its electricity due to the complete shutdown of its nuclear power plants.

Developing a future policy on energy is complicated by the fact that public sentiment on nuclear power is very complex. When the climate issue started attracting people's attention in the late 1990s and 2000s, the government promoted nuclear power energy as a means of reducing greenhouse gas emissions, and this attracted broad public acceptance. However, after the accident in Fukushima, the public reacted strongly against nuclear and interest moved from climate change to renewable energy. On the other hand, people have also reacted negatively to the 20 % rise of energy cost expected if all the nuclear power plants are stopped permanently. In other Asian countries, the debates and discussions on nuclear power have been very active, and their attention to the future action and decisions by the Japanese government is high.

Another key point is that in order to accelerate the pace of economic recovery in the local affected areas it is crucial to avoid an outflow of the population. From survey results, it is found out that if people can expect a high income and if others will remain in the area, then they too will be willing to continue staying in the same area. The fishery is one of the most important industries in Tohoku and thus there is no recovery and re-establishment of Tohoku without the re-establishment of its fishery. Even before the tsunami, the production of the fishery had decreased in the last 20 years due to over-fishing, and the income of fishermen is now much lower than 20 years ago. Currently, this industry thus depends heavily on subsidies from the government. Moreover, the fishing industry has been heavily damaged by Fukushima's nuclear power plant accident and the prospect of radiation contamination- especially by caesium. This raises questions on how to allocate the reconstruction budget; this may be more effective if it is used for reconstruction of fabrication facilities, not to reconstruct ports as they used to be. If the subsidy can be used more effectively, it will provide job opportunities and benefit other industries through generating income.

It is clear even from this very brief and general introduction on this issue that it is important for us to learn from this experience as many lessons as possible, and to transmit and share the information to the public in easy-to-understand ways for the future. We thus list some topics and questions below which can be posed to the class and trigger debate and encourage the broader outlook and thinking which is compatible with Future Earth.

14.4.2 Questions Posed by the Current Situation Following the Disasters

14.4.2.1 The Frequency of Tsunamis

Tohoku University experts included those with detailed knowledge on historical tsunamis, and as part of the university's local outreach, experts would give lectures and briefings to local communities in potentially vulnerable areas. Data on tsunamis in the last hundred years was very good, but there were historical records of extreme wave heights of 600 years ago and also at roughly thousand-year intervals. How should such information be communicated? Clearly peoples' usual life span is less than 100 years and this is therefore the natural period most people consider as a life time event. There may be a tendency for experts to limit themselves to that period from concern over either talking outside their audience's expectations or in triggering unnecessary worries among some. Indeed many will expect an expert to concentrate on the higher and more immediate risks when they are engaged in outreach for educating citizen. On the other hand, over 1000 years or more, there might be high chance of a much higher disaster affecting significantly vulnerable areas. Even though the reliability of such scientific data is weaker than recent data, it might be that citizens would want to know to avoid them misjudging the issue of tsunamis as just a short term issue. The question is how that information should be transmitted to potentially vulnerable populations.

14.4.2.2 Economic Valuation

The 2011 tsunami caused just over 18,000 dead or missing. Another 24,670 were injured on account of this disaster. Furthermore, 1.2 million buildings were destroyed or damaged across a wide area.It is not the largest fatality of such natural events (the death toll from the Sumatra tsunami, and the typhoon Nargis in Myanmar were much larger) but the Japanese damage was the highest economic cost ever recorded. The reason was not just the high value of buildings and infrastructure in a developed country but also because the *economic value of life* is much higher since it is related to the income of the person affected. This introduces the extent to which economics is applied even to life and death and can be a useful source of debate.

The World Bank estimated in March 2011 that the economic damage associated with the eastern Japan earthquake was in the vicinity of US$ 235 billion. Actual damage to infrastructure such as roads, railways, dams, harbours, airports, and power plants was so extensive that accurate estimates are difficult to obtain. Because of these, accuracy matters too in addition to ethical criteria to judge in valuing human life in terms of disaster for future sustainability.

14.4.2.3 Balancing Risks

Tokyo Electric Power Co. (TEPCO) as Fukushima nuclear power plant's operator announced that 900,000 terabecquerels of radioactivity were released from the troubled reactors in the first few weeks of the crisis. This is more than double that of previous estimates. The destruction of the Fukushima nuclear power station was due to the flooding of the backup generators and could have been avoided had the company merely shifted them from the basement to a higher level. This is so obvious with hindsight that the question is why this was not done. The reasons include the costs and an innate resistance of institutions to suffer avoidable costs. Also critical was the uncertainty over the level of risk. Even accepting evidence of rare extreme events, the probability of such an event occurring within the lifetime of a single power station (40–50 years) would have been seen as low.

This simple analysis can be a source of discussion not only on the validity of balancing costs against risks, but also on aspects of responsibility; whether the company, and government or society should be responsible for such 'safety insurance'. If safety cannot be guaranteed, government intervention might be needed. Government intervention adds more costs to the power company and if this is known to a company, it may decide it is wise to start cooperative action before being criticized by the government or stakeholder. The question is why this did not occur in this case- was it through too weak demands by the government on behalf of the safety of its people? It may be that energy companies have been subjected to less of these potential market pressures than other businesses.

14.4.2.4 Effects of the Disaster on Attitudes to Nuclear Power

The Fukushima disaster has led to a surge in opposition to nuclear power. In April 2011, a month after the accident, 10 % of the population still supported increasing the use of nuclear power. Then this backing fell to 2 % by October 2011. The number in favour of decreasing or phasing out nuclear power increased from 41 to 68 % in the same period. However such shifts in public opinion have occurred before (Froggatt et al. 2012). After the oil shock in the 1970s, nuclear power became popular to reduce dependency on imported oil. After some scandals in falsified safety checks and hiding information on safety, nuclear power became less popular. However concern over global warming and carbon dioxide emissions from the time of the Kyoto protocol increased appreciation of nuclear power. Now a combination of the Fukushima disaster and unresolved issues on disposal of waste has led to unpopularity again. However there are many associated questions; what risk are we excepting by increasing CO_2 emissions? With a dependency of over 90 % on fossil fuels, what are the implications for energy security? With the power station already built and representing a huge investment cost, can we really afford to write that off and not use it? There are many questions to encourage students to take more holistic approach.

14.4.2.5 Energy Security

The shutting down of the nuclear power plant removed thousands of megawatts from Japan's power grid. To offset the loss of domestic energy supply, Japan requires import from outside because only 4 % of energy is domestically produced if we exclude nuclear power. Thus gas and coal is being imported more than before. For example, imports of LNG in 2012 were 11 % higher than before. This is $ 27 bn or 8 % of Japanese imports. As a result, fuel costs for electric power companies increased by 94 % from their pre-Fukushima levels of $ 36.2 bn in 2010 to $ 70.9 bn in 2012's fiscal year. Supporters of using nuclear power say nuclear power is required because of energy security. The people who argue against say the increase in fuel cost by import is costly but still less than 1 % of GDP of Japan. This can be a critical issue- even leading to wars as happened as WWII for Japan. Can we really afford to be complacent about the current 4 % rate of energy security?

14.4.2.6 Food Risks

After the Fukushima disaster the public became very sensitive to the potential risks of radiation contamination in food. Despite monitoring programmes and the ease of checking radiation levels using a Geiger counter, psychological impacts make selling vegetables or fish from Fukushima extremely difficult. Despite the scientific observation that levels are lower than in some states in the USA (due to natural radiation), this concern is not easily overcome. Recent surveys show that the radiation levels in fish from the closed area around Fukushima are only 20 % higher than fish from unaffected areas. Scientists tell us that it does not affect health. However, listening to the same message, journalists may choose to say the opposite and write an article saying it is not safe. So how should such information be communicated? And will the scientist communicating that information expect the audience to accept fish from Fukushima or continue to reject it? This can be a useful exercise in the critical issue of science and risk communication.

14.4.2.7 Disposal of Debris

Normally, the media shows only the areas where damages are very striking and severe, and as a result, this information can create misunderstanding among the public concerning the overall situation in all affected areas. For example, the tsunami left a large quantity of debris, and soon the problem of where to dispose of the debris arose. The initial information and message was that the quantity was too much to dispose of only in the Tohoku region and that support from other areas was needed. Therefore, the government requested other prefectures and cities to help in its disposal by providing a subsidy to those who would agree to accept some of the debris. A number of cities raised their hands in respond to this request, but in others it led to substantial local opposition and much argument. In fact, when a survey was conducted one month after the disaster, it was found that the quantity of debris was much less than estimated by the government. Estimating the magnitude of material stock which has lost its social function as a result of a disaster allows the quantities required for reconstruction and help to be better understood (the volumes of waste flows generated by that disaster). Tanikawa et al. (2014) showed that the material stock losses of buildings and road infrastructure were 31.8 million and

2.1 million t, respectively. These are large amounts but not large enough that they need help from outside. However for political reasons the request to other areas was not reversed.

It often happens that the actual situation is different from the one that has already been reported by media and governments. It is crucial to provide the right information to the right person; otherwise it may lead to development of a wrong plan and strategy. This is another example of inadequate information and public responses. Information disclosure to media and public has again been found to be difficult and the adjustment process in policy making needs to be better established. How these decision-making can be improved is another question to discuss.

14.4.2.8 Free trade

Although not directly related to the Fukushima disaster, issues such as energy security, food security, environmental protection (among others) link in with the issue of free trade which is currently under negotiation under the proposed Trans-Pacific Partnership. This can also be a source of informing the students about broader issues? When certain resources are possible to purchase by imports, question arises how large a share of that resource can be practically imported. There are different views—some see no problem in importing 100 % of that resource, while others prefer to try to increase domestic supply as much as possible from the point of view of security of supply.

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Chapter 15
Environmental Leadership Training—Effects on Students' Future Environmental Leadership

Michael Norton, Yu-you Li and Yasumitsu Tanaka

Abstract This book is based on the experience of developing and applying environmental leadership education and training at Tohoku University, where learners are masters and doctorate researchers in sciences, engineering and humanities. This book's focus is on a range of issues in energy and resources, but is just one part of the wider curriculum outlined in Chap. 1 aiming to strengthen motivation and provide the necessary knowledge and personal skills to support environmental leadership in the student's future workplace. This final chapter thus assesses how far we have achieved that role based on student feedback, their decisions in selection of future jobs, and limited feedback from their employment after graduating. This is set against a theoretical framework of leadership in sustainable development.

Keywords Environmental leadership · Education for sustainable development · Sustainability

15.1 Introduction

This book addresses a range of subjects related to energy and resources which are included in the environmental leadership training program available at Tohoku University for Masters and Doctorate researchers. As described in Chap. 1, the ELTP curriculum provides knowledge (environmental sustainability, sustainable business, water and urban environments etc.), strengthens personal skills in an international framework (Environmental Leader Training and International Environmental Leader Symposia), and offers practical experience (through fieldwork and internships) to

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M. Norton (✉) · Y.-y. Li · Y. Tanaka
Environmental Leader Program, Tohoku University, Sendai, Japan
e-mail: norton@mail.kankyo.tohoku.ac.jp

Y.-y. Li
e-mail: yyli@epl1.civil.tohoku.ac.jp

Y. Tanaka
e-mail: tanaka@mail.kankyo.tohoku.ac.jp

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strengthen motivation and provide the necessary knowledge and personal skills to support environmental leadership in the student's future workplace.

In this final chapter we assess the impact of the ELTP on the learners based on their own feedback and assessments, and also consider ways in which they can apply their acquired knowledge and skills in their workplace after graduation[1]. This is placed against the backdrop of theoretical approaches available on environmental leadership.

15.2 Environmental Leadership—Theoretical Framework and Current System Conditions

Before considering the impact of the ELTP, we consider what theoretical framework exists for analysing how 'environmental leaders' can apply their skills and motivation. The ELTP and similar programs (Table 1.2) may well produce motivated graduates knowledgeable about the many challenges of sustainable development, but they need to apply their enhanced knowledge and leadership skills to effect change in society. Despite much research on the role of leadership in business, there is little academic work on *environmental* leadership. Business models of leadership (such as responding to adaptive challenges, dominant and aggressive leadership, responsible leaders etc.) do not address leadership for the environment and sustainability. Business leadership focuses on functionality, rationality, linear thinking and utilitarianism, and economic objectives. In contrast, *environmental* leadership has to work within the social system and external limits of environmental impact and resource availability, as well as often to go against the established order of thinking under the present economic system in order to develop sustainable models of business and consumption (Hawken 2007).

One theoretical framework for environmental leadership is the concept of 'eco-leader' introduced by Western (2010), which emphasizes the system approach, connectivity, interdependence and harnessing the creativity and leadership potential of participants in the system. In particular, leaders need to have 'systems' intelligence which includes seeing patterns of interdependency and looking into the future (Senge 1990). Ability to develop a vision of the future which will be shared by the (leader's) group and stimulate a shift to more sustainable and future-oriented behaviour, is a prime factor. The 'eco-leader' approach recognizes that sustainability needs to be introduced into complex social and ecological systems, and a form of leadership developed which can motivate and encourage creativity and competencies in actors within the current system.

Many environmental challenges have never been confronted by humankind before; they thus require new and untried strategies to address them. In particular, the

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[1] The ELTP only started in 2011, so there is limited data set on the jobs and post-employment feedback of ELTP graduates.

theory of environmental leadership places priority on leadership **diversity**, rather than seeing the challenge from one single leadership perspective. This 'eco-leader' generates a system which decreases dependence upon individual positional leaders, increases input from organizational expertise, involves the entire organization in environmental scanning, subjects decision to review and criticism by members, enhances organizational diversity, and ensures that sustainability has a strong multifaceted voice (Western 2010).

In particular, environmental leaders have to recognize the contrast and tension between the current industrial-based leadership approach and a future sustainable (ecological approach); and understand the complexities of the system being led (for example a company's priority and decision making structure). Such leaders face challenges which are different from those in the standard industrial model. This may include:

- applying a global perspective in life and work;
- living within the limits of the natural environment;
- converting the increasing flow of new information into useful knowledge;
- coping with science and technology advances in a socially constructive manner;
- coping with fast changing social ecology.

An important factor is to ensure a diversity of genuine input into decision-making processes so that this encourages the emergence of leadership from within the system itself. A key component of environmental leadership is thus communicating to individuals how each could apply their knowledge and skills. One personality variable called the 'consideration of future consequences- CFC' (Redekop 2010) is a critical factor influencing whether a certain individual will be motivated towards more sustainable behaviour. Those high in CFC are able to connect current behaviours with future (adverse) consequences in such a way that this influences their actions. Leaders needs to encourage and empower this aspect; to explain to people how proposed solutions to environmental problems will benefit them in both the short and long-term.

Research has also shown that effective leaders need to introduce positive emotional states which convey hope for the future (Redekop 2010). One of the main tasks of leadership is thus to articulate credible visions of the future that embody and encourage the hopes and aspirations of the group. A careful balancing act needs to be struck between the need to clearly define the threats to our future, while not triggering levels of fear which may increase future anxiety and negative expectations of ability to find solutions (defeatism). Psychological analysis of what is required to encourage constructive responses to future concerns (rather than rejecting or ignoring knowledge on the seriousness of sustainability challenges) suggests that important aspects are (Moser 2007):

- a sense of personal risk (from the environmental threat involved);
- there should a sense of self-efficacy (I can do something about it);
- a sense of response efficiency (what I do will make a difference);
- clarity in what needs to be done;

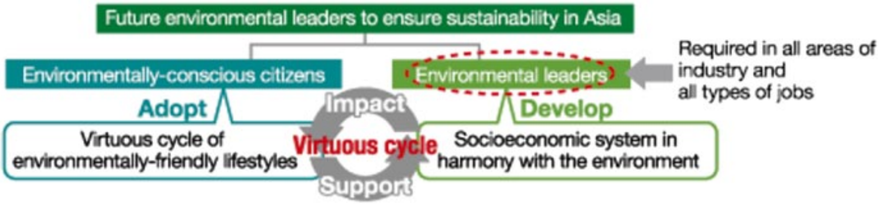

Fig. 15.1 Virtuous circle of environmentally-friendly businesses and consumers (MOE, 2008)

- social support for taking prescribed actions;
- trust that there is no manipulation.

Leaders also have to deal with the psychological difference between 'avoidance' goals and 'approach' goals (Snyder et al. 2006). This means that rather than seeking to avoid something (typically environmental collapse), leaders need to emphasize a target on which peoples positive thinking can focus. For instance environmental degradation being restored (ecological regeneration) is a useful concept.

One theoretical framework for environmental leadership was proposed in the Japanese Government's rationale for establishing the ELIAS and ELTP initiatives (see Chap. 1). This offered the conceptual model in Fig. 15.1 of a virtuous circle between environmentally-friendly consumers and green businesses eager to supply these consumers with more sustainable products and services. Environmental leaders are a mechanism for speeding this process, so that instead of the current small minority of consumers and businesses who are motivated by sustainability, this would expand to be the dominant paradigm in the economy. However as mentioned in Chap. 1, surveys of the state of sustainability in business show that business solutions to the sustainability challenges are not at a speed and scale necessary to avert widespread environmental, social and economic disruptions. Moreover, there is little evidence of rising sustainable consumer behavior since 2008. Furthermore, public concerns over a range of environmental issues (including climate change) have stagnated or declined, further reducing pressure for businesses to respond more actively (Chap. 1, Fig. 1.1).

This situation reinforces a message which has been given by sustainable businesses ever since the formation of the World Business Council on Sustainable Development (WBCSD) in 1992- that is to say that business can only become more sustainable if given appropriate signals by the market. To this end, the WBCSD has repeatedly called on governments to remove perverse subsidies, apply the polluter pays principle, implement economic reforms (pollution tax, cap and trade, certification etc.), include resource use in GDP goods and services, and incorporate the costs of externalities (starting with carbon, ecosystem services and water) into the structure of the marketplace. Yet over 20 years after the formation of WBCSD, the majority of these requests remain unanswered and the 2012 Earth Summit (Rio+20) failed to make progress in resolving such inherent conflicts between economy and environment.

As described in Chap. 1, the thinking underpinning the environmental leader programs was that Japan's leading role in environmental standards and technology would also create business in helping Asia and Africa develop more sustainably. However such 'win-win' scenarios are not inevitable and governments still need to decide between environment and economic priorities in many areas. As one recent example, we refer to measures to avoid 'locking in' developing economies to a high carbon future in the way they install new power sources. From 2013, the World Bank, the European Development Bank and other international lenders, together with the USA, UK and other national aid programs, stated that they would no longer fund coal-fired power generation in developing country projects and instead favour renewable or low carbon alternatives. Japan, as the world's largest funder of coal-fired power stations[2] has the power to reinforce these policy shifts or undermine such global efforts to reduce emissions; a conflict between the global environment and the economic interests of companies producing equipment for coal-fired power stations and coal mining. Such issues are perhaps beyond the likely role of environmental leaders from the JST ELTP, but illustrate that environmental leaders are not just required in the research laboratory but in management and political fields as well.

System failures, continued tension between economics and the environment, and the lack of environmental leadership at the political level all act as barriers to a more sustainable society and make applying environmental leadership skills more of a challenge! Against this background, let us now consider how far the ELTP has contributed to meeting this challenge.

15.3 Overall Assessment of the ELTP

Features of the ELTP have been assessed against the above theoretical leadership criteria (Norton et al. 2014). The inclusion of active (or problem-based) learning in courses helped in exploring ideas, gathering knowledge and forming personal judgements. This helped increase personal motivation, deepen understanding, develop critical thinking, and develop reflexive abilities (MacVaugh and Norton 2011). Some of the active learning projects directly addressed the above theoretical needs (visions of the future). Others placed the emphasis on finding solutions to strengthen students' 'approach goals' (sustainable innovation proposals; evaluation of leading examples of corporate sustainability), while presentations and debates strengthen the inter-personal skills required to persuade and motivate others, and promote the 'diversity in leadership' and 'inherent creativity' in environmental leadership theory outlined above.

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[2] Japan has been the largest investor in overseas coal projects since 2007 ($ 19.7 billion), followed by the U.S. ($ 8.9 billion), Germany ($ 6.0 billion), and South Korea ($ 3.1 billion). http://switchboard.nrdc.org/blogs/jschmidt/way_too_much_public_funding_is.html.

Specific examples of parts of the ELTP with direct relevance to the theoretical aspects of environmental leadership include:

- Effects of the course on individual thinking are revealed in course projects. For instance, Project 1 of the 'sustainability foundations' course requires students to consider which aspects of sustainable development they believe to be most important. Student priorities ranged over environmental, social and economic aspects of sustainable development, and a strong ethical base was demonstrated in some student comments:
  - "*The earth has reached its carrying capacity to support a quality human life"; "we have a responsibility for all other living things*".
  - "*Today's economic activities are not just about working and gaining money, increasing the company's profit, pursuing a high GDP or National economic growth, but it's actually beyond the 'classical' definition of economy itself. Today's economy is an emergence of new 'social value' that has gradually dominated and shifted another social life values such as, tradition and cultural values, moral-ethics values, social norm and religion values, etc.*".
  - "*We are facing so many problems and we also know what we need to do, but somehow it seems very hard to act. In my opinion, one of the most important factors is the lack of "LEADERSHIP". We need a person who really can inspire, motivate, and encourage us to act together*".
- Student responses to the second project focused on envisaging the future have been published (Norton et al. 2014) and suggest this project supported the abilities for forward thinking which are essential for an environmental leader.
- Preparing students to apply environmental leadership in businesses (where a majority are likely to find jobs after graduation[3]) was the role of the 'sustainable business' course which enabled graduates to evaluate the strengths and weaknesses of an organization's performance regarding sustainability; envisage what impact a more sustainable way of thinking would have on an individual's job and the company's business; consider case studies of successful sustainable businesses and strategies; and see sustainable societies and businesses as innovation targets for more sustainable goods and services. Through this course and associated project work, students are introduced to some of the basic approaches they may need if they are to think 'environmental leadership' in their future workplace. Students could also consider how to reconcile the tensions between business goals and sustainability imperatives.
- Practical experience relevant to business was also provided through fieldwork, which comprises group visits to environmental businesses, waste treatment facilities, and the like. Internships also offer an opportunity to bring together environmental issues with the specialism of the individual student (Chap. 1).

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[3] JST data across the ELTP programs show that of the Japanese students, 66 % entered companies after graduation.

Table 15.1 Student comments

Student nationality	Comment
Japanese	"*I'm honored to have been a member of basic course from last July. This experience has provided me a wonderful chance to improve my expertise and communicative ability. During these eight months I have enriched my professional knowledge focused on sustainable development and environmental management. I have also participated in lively fieldwork. The opportunities for communication provided during the fieldwork could not be achieved in my daily courses.*"
Chinese	"*Thanks to this program, I have realized the responsibility of being an environmental leader, and because my native China is a developing country, such study and training have great significance to our work of environmental protection.*"
Indonesian	"*These studies were also helpful to my research, the removal of antibiotics in the wastewater, which has a close relationship with this program. My research aims to reduce the negative effects of antibiotics to the ecosystem and solve the related environmental issues, which is also the purpose of this program. With the wide vision this program supplied, I have a new way of thinking about my research field.*"

Student feedback on the main curriculum courses has been positive. In addition there have been a number of individual comments on the value of the program and its value to individuals (Table 15.1). Particular value has been placed by Doctorate students on internships which provide a valuable interface between the environment-related knowledge acquired in the course and potential applications in real organizations. While it is too early to make quantitative assessment of the influence of the program on the career choices of students, there are several cases where individuals state that their choice of job was influenced by the ELTP.

15.4 Case Studies of Individual Graduates

Since the start of the ELTP to the time of writing (Summer 2014), 34 researchers have graduated from the Regular Course (18 were Japanese, 11 Chinese, 2 Indonesian and single students from Mexico, Egypt and Brazil). If activities after graduation are examined, many of the Masters graduates entered a Doctorate course (14 of the 25) which continues research in environmentally-relevant areas at the Graduate School. About half of the Doctorate graduates also found employment at the university as postdoctoral researchers or junior lecturers. The others left academia to take on jobs elsewhere, and a majority of these proved to be in environment-related businesses, companies with a high environmental and sustainability reputation, or organizations involved in other aspects of sustainable development. Overall, over 80 % of graduates continued their work in areas related to the environment or other aspects of sustainability. Some individual case studies to illustrate specific job-related experience follow:

Case A. One Japanese doctorate student researched high temperature behaviour of silicate materials- with an obvious relevance to scaling and corrosion in geothermal energy systems. On graduation this student took on a position at a Japanese National Laboratory working specifically on geothermal energy geochemistry, and will also be involved in the new Fukushima Renewable Energy Institute established after the Fukushima nuclear disaster in 2011.

The student had been interested in the problems of environment and energy since junior high school, and the ELTP was one of the factors considered during her Ph.D course. The ELTP featured in the job interview and the ELTP qualification added to the candidate's attractiveness to potential employers. In terms of specific benefits to the current job, the knowledge gained on economic and social problems and solutions to environmental problems has proved useful as a general foundation highly relevant to the role of national laboratories, whose objective is to translate basic research into useful technology for society. The general strengthening of communication and explaining skills was also cited as useful.

Case B. This student graduated and returned to her native country China, and is now working for a financial services company. During more than 2 years participating in the ELTP, she comments that the knowledge from the ELTP influenced her choice of future career, which evolved from an initial assumption of continuing research, to a strengthened motivation to contribute to society by providing professional environmental solutions and working for environment-related industrial development.

She notes that the knowledge learned from the ELTP (particularly interdisciplinary environment-related knowledge and research investigation approaches) are very helpful for the current job, since they allow her to enlarge the current range of business and provide more professional advice to customers. Personal skills were also greatly improved on communication with people from different backgrounds and nationalities. While most customers are Chinese, they are from different professions so the company can get closer to customers and solve more financial problems if well equipped with communication skills.

Case C. This student graduated from the ELTP and moved to a research position with an energy company. His current job is R&D on renewable energy from biomass, waste heat recovery etc.; technologies that can, in addition to economic benefits also contribute to energy security and to reducing environmental impact by improving conversion of fossil fuel and/or saving energy and resources. The current research focus had evolved from university research on fuel cells through the broadening of knowledge about energy and resources in the ELTP. The student cites the ELTP as informing his view of the future through learning about environmental issues and, in the job interview, was able to convey enthusiasm for environmental issues in his own words thanks to this experience. In particular, such experience increased attractiveness to the company because corporate responsibility for the environment has become important, and this company was thus looking for new staff with environmental knowledge. Another reason cited was because we are in a period when diversity and breadth is important. The ELTP, which has academic fields that integrate science, engineering and the humanities, enabled students to understand different values and obtain a bird's-eye view of the many facets of environmental and sustainability issues.

In terms of application in the current job, the ELTP helped by learning different approaches to solving environmental problems, and in increasing knowledge and expertise on energy and resources on the global scale. Furthermore, the broad knowledge of international affairs and legal frameworks is expected to be useful in working abroad in the future. The importance of human relationships was also appreciated through encounters with students from different backgrounds, nationalities, cultures, ages and positions. Moreover, not only were English skills improved but also the ability to act in the wider international context. Such experiences helped in facilitating cooperation with others.

Finally, this student expresses his ultimate goal as to solve global environmental problems, along with building a sustainable society. He learned in the ELTP that it was difficult to ensure a good balance among environmental, social, and economic pressures for building a sustainable society, because it relates to factors such as politics, economics, history, lifestyle, ecosystems and so on. However, he would like to continue to work on this complex challenge, taking full advantage of much valuable experience from the ELTP.

Case D involves an ELTP graduate who is now working on evaluating the potential for biomass energy in tropical countries such as Indonesia, with the aim of supporting low-carbon sustainable development. He notes the value of the International Environmental Leader Symposium he attended in Indonesia. This revealed the challenges in developing countries, the value of seeing first-hand the linkages between environment and culture, and insights obtained from cultural exchange with international students. He cites the ELTP as having provided an international and global perspective on environmental problems, which stimulated his interest in the environment, and this also allowed him to demonstrate an international perspective at the job interview. The ELTP also helped engineering and science researchers become aware of social sciences such as economics in thinking about environmental issues.

The ELTP added value to his basic research at Tohoku University into wastewater treatment and explained why especially in Asia, Africa and other developing regions, development of energy, resources and use of water creates a difficult balancing act between economic development as a primary goal and the preservation of the environment. In addition, the ELTP helped develop personal skills and to acquire the confidence to express opinions and ideas, and to communicate with others. The relationships formed in the ELTP with others could also help expand knowledge and contacts to other areas of environmental expertise.

Case E followed graduation from the ELTP by obtaining a temporary position as Assistant Professor at Tohoku University teaching on wastewater/waste management, and conducting research in bio-hydrogen fermentation from wastewater/waste resources. His teaching role builds on some of the cross-disciplinary perspectives obtained in the ELTP- for instance the relationship between the concepts of sustainability practice and community in areas of water quality surveillance and monitoring, water supply and pollution control technology, environmental impact of toxic substances and hazardous waste, environmental legislation, air quality, ambient standards and control of emissions in both urban and industrial areas. Aspects of the ELTP were effective in providing practical knowledge and insights, particularly in the field of sustainable environmental planning and management.

In Japan, many organizations work on advancing solutions to global problems for water and energy shortage. Personal experience included long-term operation for an integrated seawater desalination and sewage recycling system, which is of potential value not only for Japan but also for arid and semi-arid regions such as the graduate's own country (Egypt). Another important experience gained from the ELTP was in the area of recycling and energy production from wastewater/waste management, where links with one Japanese company provided a continuous system from collection and transportation to intermediate treatment and final treatment. This process combines applicable disposal management with ensured traceability that enables customers to avoid the risk of improper treatment.

Thanks to the ELTP, this graduate commented that it was possible to meet many ambitious and motivated people from whom different tactics and strategies in environmental protection and management could be learnt. The integration between sciences and the new interdisciplinary scientific branches covered in the ELTP is important in finding creative and cost effective solutions for environmental problems. Moreover, integration between natural sciences and human and social sciences is needed to apply solutions to some well-known environmental problem in different regions The experience from the ELTP is also expected to assist this graduate in working creatively and for a challenging future career. It will help its participants to become 'great leaders' and to make a difference in today's work environment.

The above case studies are qualitative evidence that the ELTP has succeeded in achieving some of its core objectives, although at this early stage it is not possible to foresee whether any individual will, in their later career development, assume the mantle of case study E's 'Great Leader'. The business world has many examples of such individuals who became personally highly motivated and steered their companies to a more sustainable model. Examples mentioned in the ELTP 'sustainable business' course include such names as Interface carpets, Nike and its 'North Star' vision, Puma, Unilever, Ricoh, Panasonic and many others.

15.5 Extending Environmental Leadership beyond Japan

As described in Chapter 1, the Japanese initiatives on environmental leadership are focused not just in Japan but other countries, especially Asia and Africa. One mechanism through which this can be achieved is through overseas students who have graduated in the ELTP returning to their own countries to apply their new skills, and we presented some examples of this in the previous section. In parallel however, the Tohoku University ELTP includes specific initiatives to support the development of environmental leader initiatives in other universities in other countries. Joint international symposia on environmental leadership have been held in collaboration with Ho Chi Minh City University of Technology (Vietnam), Xi'an University of Science and Technology and Shanghai Jiao Tong University (China), Gadjah Mada University and Bandung Institute of Technology (Indonesia), and Universiti Teknologi Malaysia.

These joint symposia allow students from partner universities to share their research related to environmental and sustainability issues as well as the general theme of environmental leadership. In this way the focus provided in Tohoku University on the holistic approach to tackling environmental problems, can be communicated and act as a model for other institutions to adopt if they so wish. These initiatives have led to deepened exchanges on environmental education and research, and a number of the partner universities have established their own 'Environmental Leader Program Regional Office' to facilitate future coordination with the Tohoku University ELTP. These liaison offices currently operate in China, Indonesia, Malaysia and Vietnam. We expect that students and future students from universities supporting environmental leadership programs will have the expertise to understand environmental issues and think about the world and its future. The future will be determined and created by such young people. They have a duty to undertake this task for the sake of their families, their children, their descendants, and for a sustainable earth.

15.6 In conclusion

This book has brought together a wide range of issues related to a sustainable future, reflecting the complex and inter-related issues and their associated areas of expertise. Here you will have seen presentations on specific technologies, underlying technical and scientific analyses, policies and strategies in the general field of energy and resources. These bring together science, engineering and social sciences such as economics into one volume- reflecting the ELTP's aim of providing a comprehensive and birds-eye view of the many challenges of achieving a sustainable future. We, the editors hope that some of the issues addressed in this course and book will stimulate others to join the quest for environmental leaders and apply their personal skills and knowledge to achieving a safe and environmentally sustainable future. We wish to express our appreciation to all the people who have worked together to make this happen—the cooperating universities and organizations all over the world, stakeholders, Tohoku University staff, and especially the students.

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