Network of Research and Policy Communities for Innovation: An Analysis of Co-evolution of Technology and Institution

YARIME Masaru
Graduate School of Frontier Sciences, University of Tokyo
Kashiwanoha 5-1-5, Kashiwa-shi
Chiba 277-8563, JAPAN

***Abstract*— This study examines how collaboration networks are formed between universities, industry, and the public sector and work for the creation of environmental innovation through global co-evolution technology and institution. The focus of this study is placed on the development of lead-free solders in the electric and electronic industry in Japan, Europe, and the United States. The structure of university-industry collaboration networks for lead-free solders is analyzed with the quantitative methods of social network analysis, based on data on the participants in research and development projects. Initiatives to regulate the use of lead in the United States influenced the formation of university-industry collaboration network for the development and adoption of lead-free solders in Japan. The network promoted cooperation and coordination among the relevant actors, including those working on chip implementation, solders, manufacturing equipment, parts, devices, printed circuit boards, and measurement instruments in implementing an effective transition to lead-free solders. The demonstration of technological progress in Japan in turn encouraged the introduction of a stringent regulation for the phase-out of lead-containing solders in Europe, leading to further formation of networks for technological development and adoption in other regions. Not involved in a domestic institutional network for regulating the use of lead, the university researchers in Japan, working from a relatively neutral position, took the initiative in creating international networks for the formulation of world-wide roadmaps for technological development and implementation, standardization of various specifications, and exchange and sharing of scientific and technological knowledge.**

***Index Terms*—co-evolution, network, university-industry collaboration, lead-free solders, Japan, Europe, United States**

I. Background

In this era of knowledge-based economies, rapid knowledge creation and easy access to knowledge bases are considered to make key contributions to innovation [1]. Since the utilization of knowledge has assumed greater importance in creating environmental innovations, collaboration across organizational boundaries has become more commonplace. In fields where scientific or technological progress is developing rapidly and the sources of knowledge are widely distributed, which is often the case for environmental innovations, no single organization has all the necessary skills to stay on top of all the various areas of progress and bring forth significant innovation [2]. Many of the recent studies suggest that inter-organizational networks play a crucial role in influencing changes, and the direction of those changes, in technological development. Reviewing the past findings of empirical research on the role of external sources of scientific, technical, and market information on innovation, Freeman pointed out the vital importance of external information networks and of collaboration with users during the development of new products and processes [3]. It is argued that dense ties between partners in technology collaboration networks foster information diffusion and knowledge exchange, enhancing the technological performance and collaboration opportunities of the partners [4-6]. Other innovation studies explain the benefits of inter-organizational relationships in terms of mutual and interactive learning through networks [7-8].

Traditionally assumed to be responsible for producing and disseminating knowledge, universities are now expected to be an essential institutional actor in pursuing economic and social goals, and governments in industrialized as well as developing countries increasingly regard universities as instruments for promoting innovation, rather than ivory towers devoted to the pursuit of knowledge for its own sake [9]. For this purpose, various attempts have been initiated in many parts of the world to foster the relationship of university-industry collaboration. In Japan, for example, the number of joint research projects between universities and companies in the private sector has continued to rise since the start of data collection in 1983, according to a study conducted by the National Institute of Science and Technology Policy [10]. In particular, since the 1990s, when laws and policies aimed at promoting university-industry collaboration, notably the Science and Technology Basic Law in 1995, the First Science and Technology Basic Plan in 1996, and the Law for Promoting Technology Transfer from Universities in 1998, were enacted or implemented, university-industry collaboration has been increasingly intensified across Japan.

University-industry collaboration produces output in different forms, including, among others, scientific and technological information and knowledge, equipment and instrumentation, prototypes for new products and processes, skills and human capital, a capacity for scientific and technological problem-solving, and networks of scientists and technologists [11-12]. While the transfer and utilization of intellectual properties, such as the licensing of patents via TLOs, has been emphasized recently, as evidenced by the passage of the Bayh-Dole Act in the United States and similar legislation in other countries, and has been analyzed extensively [9], intangible output like the formation and functioning of networks linking scientists and engineers in the private as well as public sectors has not yet been examined closely, although they will have an equally significant impact on the long-term capacity for innovation.

A historical study on the synthetic dye industry in the nineteenth century shows that the establishment of networks linking academia, industry, and the public sector led to differences in educational institutions and patent laws, the key factor in explaining the technological leadership of Germany over Britain and the United States [13]. Since a knowledge of synthetic organic chemistry was such a critical resource for firms in the dye industry, a strong connection to the keepers of this knowledge was a key variable in the long-term success of individual firms, and the network of ties that were created between academic scientists, industrialists, and government officials in Germany allowed them to build a stronger system of research and training. At the same time, the social network that connected individual players in academia, industry, and government was crucial in bringing about the changes in German patent laws concerning chemicals, for their own advantage. In this way, technology and institutions co-evolve through close interactions through networks linking academia, industry, and the policy sector in ways peculiar to national systems of innovation [11, 14-16].

The work of Murmann is significant in the sense that it examines in detail the importance of network formation among academia, industry, and the public sector in bringing forth successful innovation. Its analysis, however, is limited to qualitative aspects of innovation networks and does not benefit fully from utilizing the well-developed methods and applications of social network analysis [17-18]. In recent years, network analysis has been undergoing considerable progress, with significant contributions, theoretically as well as empirically, from natural scientific disciplines, especially physics [19-20]. Also the analysis of Murmann is basically limited to examining the influences of the domestic network on the co-evolution of technology and institution in Germany. Building upon the work of Murmann, who conducted a detailed case study with rich historical data, it is important to take a more quantitative approach to analyzing the structure and evolution of innovation networks in university-industry collaboration.

It is also necessary to consider the influences of domestic networks on networks in other countries and regions to fully examine the implications of global co-evolution of technology and institution for environmental innovation. In the past many studies have been conducted to examine the impacts of environmental policies and other institutional factors on technological change [21-26]. They mainly considered how environmental policies influenced innovation in the domestic context. As globalization of economic activities has intensified recently, however, international interactions between technology and institution have become common, and implications of their co-evolution beyond national or regional boundaries for environmental innovations require detailed examination.

In this paper, we examine how collaboration networks involving academia, industry, and the public sector are formed and how technology and institution are co-evolved leading to environmental innovations. A case study is conducted on the development of lead-free solders in the electric and electronic industry in Japan, Europe, and the United States. The structure and evolution of university-industry collaboration networks in Japan, Europe, and the United States are analyzed with expensive data on the participants in research and development projects and consortia as well as scientific papers, patent applications, and commercialization of products related to lead-free solders. Traditionally lead has been used extensively for solders in electrical and electronic products. Regulatory discussions in the United States promoted the formation of university-industry collaboration networks in Japan for developing lead-free solders. In making a transition to lead-free solders, close collaboration and coordination is indispensable among the relevant actors, including material suppliers, component producers, equipment makers, product manufacturers, and final users, as well as universities and public institutes. University researchers played a critical role in establishing research and development networks linking academia, industry, and the public sector in Japan. The structure of dense networks of university-industry collaboration contributed to bringing forth environmental innovation successfully. This technological progress in Japan in turn promoted the introduction of an environmental regulation for the phase-out of lead-containing solders in Europe, which further encouraged formation of networks for technological development in other regions. This study illustrates that university-industry collaboration networks promoted environmental innovation through global co-evolution of technology and institution.

II. Regulations on Lead-Containing Solders in Electric and Electronic Products

Regulation on the use of lead was initiated in the United States, where lead was banned in the manufacture of paint in 1978 and for the solders used for joining domestic water piping in 1986. Then in the early 1990s, a series of legislations were proposed in the House of Representatives and the Senate to introduce a regulation to further minimize releases of lead into the environment and the development and implementation of a means to reduce exposure to existing sources of environmentally dispersed lead [27]. The first such proposal—S. 2637 Lead Reduction Act, Senator Reid (1990)—was intended to mandate that one year after the date of enactment, no one would be permitted to manufacture, process, or distribute in commerce any solder containing more than 0.1% lead. Although several studies were conducted on the possibility of using similar lead-free alloys in electronics, no process trials of lead-free alloys had been performed, and specific alloys tailored to the application had to be developed. This lack of technical data on alternative technologies allowed the electronic industry to lobby against the inclusion of electronic solders in the general ban on lead, based on the main objection that no suitable lead-free alternatives were available. Various questions were also raised with regard to the impact on product cost and competitiveness, as it was generally assumed that lead-free products were more expensive than those made using lead-containing solders [28]. Since an attempt to pass a revised Reid Bill (S. 729) failed in 1993, no further legislative proposals specifically affecting lead solders have been made in the United States. There are several states in which recycling efforts for electronics have been started, notably California, where manufacturers have to report information about reductions in the use of certain heavy metals, including lead, under the California Electronic Waste Recycling Act (S.B. 20/50). At the federal level, however, there is no legislation requiring the elimination of lead from electronic products.

Meanwhile, legislation directly affecting the solder and electronic industries began to be considered in Europe. The first draft of the Waste Electrical and Electronic Equipment (WEEE) Directive was published in April 1998. Three months later, this was followed by the publication of the second draft, which included the proposed ban on the use of lead in electronic assembly, with a schedule for the ban to be implemented by January 2004. Then, in June 1999, a draft proposal for a WEEE directive, including the restriction of certain hazardous substances such as lead, was submitted to the business test panel as a pilot project [29]. During the policy-making process, business groups and organizations lobbied for modifying, delaying, or removing the introduction of the material bans [30-31]. On the other hand, the provision on the substitution of substances was supported by environmental NGOs, asking for an extension of this requirement to other substances. In June 2000, the European Commission officially adopted the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive, along with the separate WEEE Directive [32-33]. The RoHS proposal required substitutions for lead and various other heavy metals, as well as brominated flame retardants, from January 2008. Following a conciliation process between the Council and the Parliament, in which a final implementation date of July 2006 was agreed upon, the RoHS Directive came into force in February 2003. Each member state was given 18 months to introduce the required national legislation. Some exemptions are allowed for the continued use of lead in essential applications, including lead alloys used for high-temperature soldering, and extended target dates are applied to high-reliability products such as network infrastructure.

The control of lead has been strengthened in Japan through various measures, including the review of water quality standards on lead, the strengthening of amendments to the Waste Disposal Law, and the enactment in April 2000 of the Home Appliances Recycling Law, which was originally introduced in 1998. Under this legislation, electronic devices containing lead can no longer be discarded, unless they are dealt with in a proper manner. Unlike in Europe, however, legislation to regulate the use of lead in solders per se has not yet been introduced. Although the Ministry of Economy, Trade and Industry (METI) is currently considering possible regulations with regard to lead-containing solders through discussions at a technical committee of the Council of Industrial Structure, it is likely that rather than banning the use of lead for solders, limiting its use in electric and electronic products for recycling will be given priority, according to a report published recently by METI [34].

III. University-Industry Collaboration Networks on Lead-Free Solders

Following the discussions in the United States Congress on legislation for regulating the use of lead-containing solders, many research and development projects and consortia were formed to explore lead-free alternatives in Japan and Europe, as well as the United States. These research and development projects included technical committees and working groups, in each of which scientists and engineers with specific expertise, from universities as well as industry, cooperated in working on various technical issues. Through these projects, the electronics community intended to gain experience with the performance of lead-free solders to begin addressing lead-free issues, including manufacturing yield, process windows for complex boards, and component compatibility.

To see the network structure of these research and development projects on lead-free solders, we conducted a network analysis of data on the participants in the projects. Initially, we obtained two-mode graphs in which two types of nodes are included, that is, square nodes that represent research and development projects or scientific papers and circular nodes that represent the organizations participating in them. Since the two-mode graphs did not explicitly show the ties between pairs of participating organizations linked by the projects, they needed to be transformed into one-mode graphs to see inter-organizational linkages [17]. To analyze the structure of R&D project networks in the United States, Europe, and Japan, we collected data on the participants in major projects on lead-free solders in the United States [35-37], Europe [38-41], and Japan [42-45]. Table 1 provides the number of research and development projects conducted in the United States, Europe, and Japan and the number of organizations participating in these projects.

Figure 1 to Figure 3 show the one-mode graphs of the research and development network on lead-free solders formed in the United States, Europe, and Japan by 1999. The blue circle nodes represent universities; the green square nodes, public research institutes; and the red triangle nodes, private companies. While each company or public research institute is represented by one node, each research laboratory, which is normally headed by a professor, is represented by one node in the case of universities, because it can be considered to have a relatively high autonomy, compared with companies or public research institutes. A link between two nodes shows that the two organizations participated in the same project. The thickness of a line represents the strength of the relationship between the two nodes. Hence, if two organizations participate in many research and development projects together, the line linking them becomes thicker.

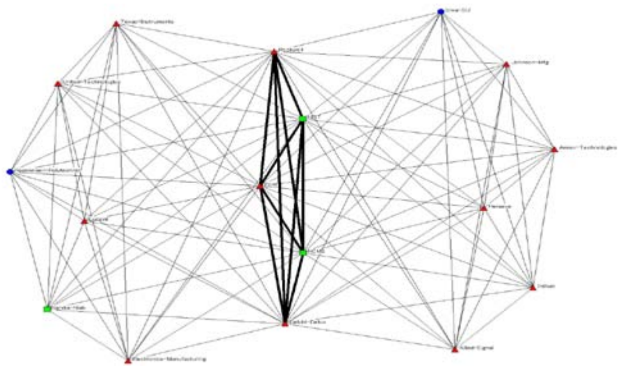

Figure 1. Network Structure of R&D Projects on Lead-Free Solders Formed in the United States by 1999

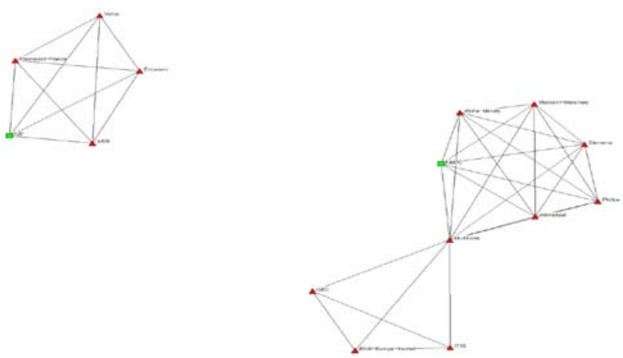

Figure 2. Network Structure of R&D Projects on Lead-Free Solders Formed in Europe by 1999

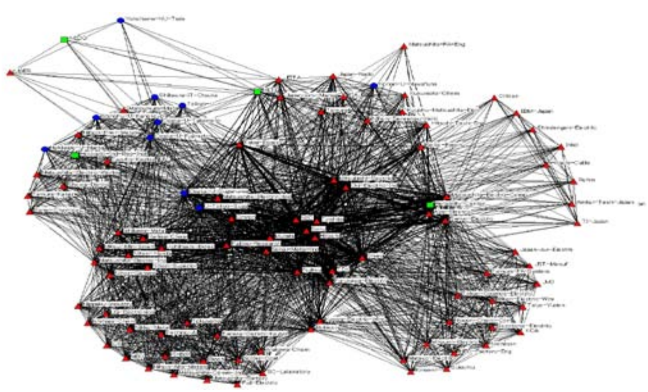

Figure 3. Network Structure of R&D Projects on Lead-Free Solders Formed in Japan by 1999

The structure of the network formed for research and development projects in Europe is fragmented into two components, with no linkages between them, whereas that in the United States is connected, but the links among the nodes are relatively sparse. In contrast, the structure of the Japanese innovation network is dense, and the number of the nodes included in the network is by far the largest. They are also well connected, with many more ties between them than the U.S. or European networks. These figures for network structure suggest that a dense network, involving relevant actors in academia, industry, and the public sector, was formed at a relatively early stage in Japan, compared with those in the United States and Europe.

In terms of betweenness centrality, research laboratories headed by university professors—namely, Professor Suga of the University of Tokyo and Professors Suganuma, Takemoto, and Fujimoto of Osaka University—occupy important positions in the Japanese network. This would suggest that these actors in academia, along with large electronic manufacturers such as Toshiba, Sony, NEC, Hitachi, and Fujitsu, have functioned as information hubs or coordinators among relevant actors. In the case of the United States, on the other hand, public institutes/organizations such as the National Center for Manufacturing Sciences (NCMS) and the National Institute of Standards and Technology (NIST) are positioned at important places in terms of betweenness centrality.

We also analyzed research and development project networks on lead-free solders that had been formed by 2004 in the United States, Europe, and Japan. As in the case of the networks formed by 1999, two-mode graphs are transformed into one-mode graphs, which are shown in Figure 4 to Figure 6.

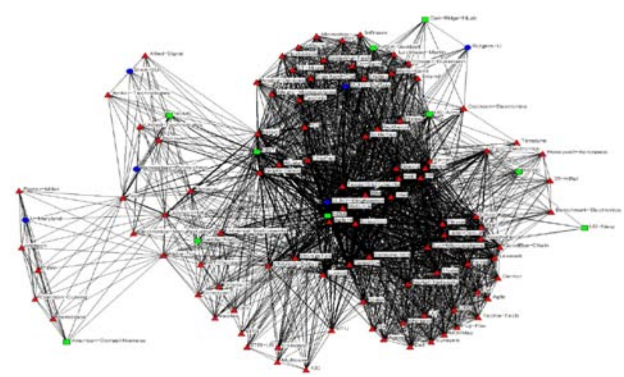

Figure 4. Network Structure of R&D Projects on Lead-Free Solders Formed in the United States by 2004

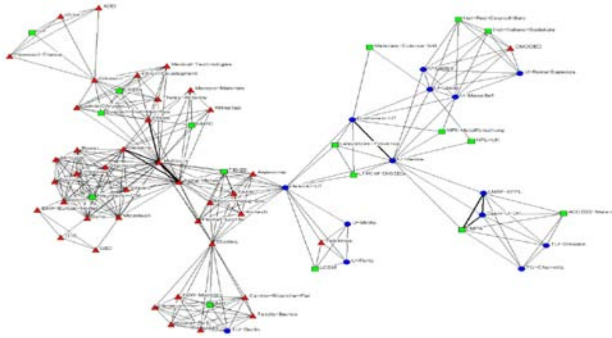

Figure 5. Network Structure of R&D Projects on Lead-Free Solders Formed in Europe by 2004

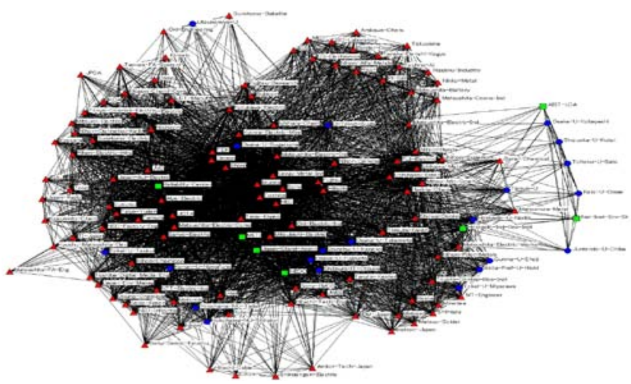

Figure 6. Network Structure of R&D Projects on Lead-Free Solders Formed in Japan by 2004

In the case of the U.S. and Japanese networks, the majority of the participants are companies, with several well-connected universities and public research institutes, whereas in Europe the number of companies, universities, and public research institutes that participated in the network are almost equal. These innovation network figures suggest that the United States had almost caught up with Japan in terms of the entrance of participants in the R&D community and the density of linkages among them by 2004. In Europe, although the network has grown since 2000, there are basically two parts, which are relatively separate, with companies mostly participating in one part and universities in the other. Since innovation on lead-free soldering technologies would require close and delicate coordination among solder materials, production processes, measurement equipment, and final products, the lack of industry-wide cooperation could have resulted in inadequate and delayed development and adoption of lead-free soldering technologies in Europe.

The network structure for research and development projects on lead-free solders in Japan is very dense. As there is only one component in the graph, all the nodes included in the network are connected. These findings suggest that information and knowledge could be shared effectively through the multiple linkages among the relevant actors, including universities, solder suppliers, component producers, and electronic equipment manufacturers. Since the development and implementation of lead-free soldering technologies would require close collaboration and coordination among solder materials, production processes, measurement equipment, and final products, the existence of a broad degree of cooperation worked effectively in developing and adopting lead-free soldering technologies in Japan.

Large electronic companies in the private sector, such as Hitachi, Fujitsu, Oki Electric Industry, Toshiba, NEC, Sony, Mitsubishi Electric, and Matsushita Electric Industry, have relatively large values of betweenness centrality, suggesting that they are major players working between solder manufacturers, metal makers, and component suppliers. It should also be noted that the list includes the same university laboratories as in the network formed by 1999, along with several other laboratories led by professors in other universities. Among the organizations with large values of betweenness centrality are METI and NEDO in the public sector. Thus, we could argue that the network structure of research and development projects in Japan, which included major players in the public as well as private sectors at relatively central positions, has contributed to facilitating close public-private partnerships for implementing innovation on lead-free soldering technologies.

The structure of the U.S. network exhibits characteristics that are similar to those in the Japanese network in terms of the number of nodes and linkages. The list of organizations with large values of betweenness centrality indicates, however, that universities play a relatively minor role in the United States. Instead, public research institutes, notably NIST and the National Electronics Manufacturing Initiative (NEMI), are major actors, centrally positioned among mostly large private companies, including Texas Instruments, IBM, Motorola, and Intel. In the case of Europe, while the network contains numerous universities and public research institutes with relatively high values of betweenness centrality, such as the Helsinki University of Technology and the University of Vienna, its structure, which is basically separated into two parts, implies that communication and coordination between university laboratories and private companies would not be implemented effectively. Although large companies, such as Philips and Siemens, were achieving implementation of lead-free soldering in Europe, there was no pan-European industry forum involving small- and medium-sized enterprises (SMEs), and coherent information networks, or technology or research provider networks, did not exist in Europe and the United States at that time.

IV. Global Co-Evolution of Technology and Institution beyond Regional Boundaries

As discussed above, although control of lead has been tightened with various measures, the use of lead has not been explicitly banned in Japan. That means that while strong regulations have not been introduced on lead-containing solders, innovation on lead-free solders has been promoted. Why that have happened can been seen by looking at how the network on regulatory formation is separated from the network on technological development.

Environmental regulations on hazardous substances in Japan are basically discussed at the Ministry of Economy, Trade, and Industry (METI) and the Ministry of the Environment (MOE). The framework for regulating the use of lead-containing solders in electric and electronic products is examined at the Working Group on the Advancement of Product 3R Systems of the Committee on Wastes and Recycling of the Environmental Division of the Industrial Structure Council of METI [34]. This working group consists of 20 people coming from universities, public research institutes, industry associations, non-governmental organizations, and mass media, as well as observers of the Ministry of the Environment. Most of them are experts on recycling of products. The conclusion of the working group was that it is not absolutely necessary to ban the use of lead as introduced by the Directive on the Restriction of Hazardous Substances (RoHS) in the European Union and that it would be more desirable to establish a system to monitor and control hazardous substances including lead contained in products through improved supply chain management and open disclosure of information. Based on this recommendation, the Law for Promotion of Effective Utilization of Resources was revised in 2006, which required that the use of hazardous substances such as lead in electric and electronic appliances should be displayed.

What is interesting to note is that those university researchers who promoted the development of lead-free solders did not participate in the working group for discussing environmental regulations. That means that the network for regulatory formulation is established separately from the network for technological development without much information exchange. Knowledge on scientific findings and experiences gained through long-term technological development were not shared with the regulatory network, which influenced the decision not to introduce a more strict regulation on the use of lead-containing solders in Japan. The co-evolution of technology and institution, in the sense that the introduction of a strong environmental regulation encourages the development of clean technologies, which in turn induce more stringent regulatory arrangements, did not proceed smoothly within the context of national networks in Japan.

On the other hand, mutual influence between technological and institutional changes can be observed beyond regional boundaries. The professors who made significant contributions to the development of lead-free solders through university-industry collaboration networks in Japan also initiated activities for establishing technical specificities standards at the international level. The technological roadmap which was created with the initiative of these university researchers specified the timing of introducing different parts and components functioned as a proposal leading innovation in other regions of the world. With this roadmap for technological development and introduction, the First World Summit on Lead-Free Solders was held in 2001 with the participation of relevant industrial associations in Japan, Europe, and the United States, namely, the Japan Electronics and Information Technology Industries Association (JEITA), Soldertec of the International Tin Research Institute (ITRI), and the National Electronic Manufacturing Initiative (NEMI), respectively [46]. At the Second World Summit on Lead-Free Solders held in 2002 the three industrial associations agreed to work on creating a world roadmap for technological development and introduction of lead-free solders in the three regions [47].

During this process researchers at Japanese universities industries played a major role in promoting innovation through international dissemination of technical knowledge and experiences. Among them, Mr. SUETSUGU Kenichiro of Matsushita Electric Industry (currently Panasonic Electric Industry) was given the first Lead-Free Award, an award given by Soldertec to individuals and organizations that made a significant contribution to the development and diffusion of lead-free solders around the world each year. The second award was given to Professor SUGA Tadatomo of the University of Tokyo and the third award to Professor SUGANUMA Katsuaki of Osaka University in Japan [48]. The active involvement of these researchers from universities and industries made it possible to establish international standards of technical specificities and to create world roadmap for technological introduction. That facilitated further innovative activities in each region. Moreover, the accelerated progress in the state of technological change prompted policy makers in other regions to adopt strong environmental regulations. China, for example, has introduced a similar regulation to EU's RoHS Directive, by which the use of lead in electric and electronic products is banned in principle.

The process of global co-evolution of technology and institution for innovation on lead-free solders can be illustrated in Figure 7.

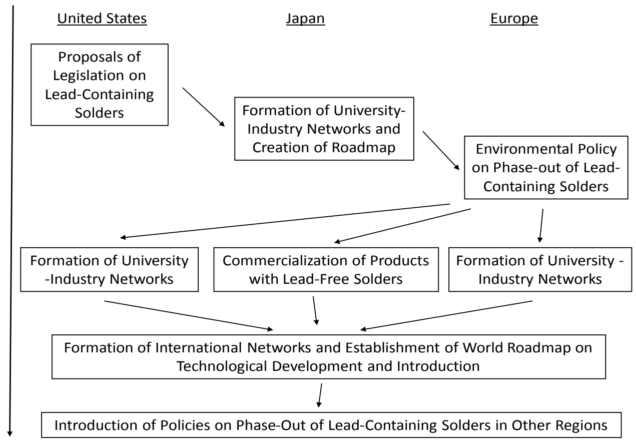

Figure 7 Global Co-evolution of Technology and Institution for Innovation on Lead-Free Solders

V. CONCLUDING REMARK

In this paper we examined how university-industry collaboration networks are formed and how they function for the creation of environmental innovation through global co-evolution of technology and institution. The case of lead-free solders was analyzed by looking at the technological development and public policies for the regulation of lead. Network analysis was conducted on data on the participants in research and development projects and consortia. This study illustrates that university researchers could play an essential role in establishing research and development networks among academia, industry, and the public sector for coordinating the behavior of different actors.

Proposals to regulate the use of lead for soldering in products, including electronic equipment, were initially made in the United States. While the proposed legislation was not enacted in the end, the move to develop lead-free soldering technologies was started at the industrial level in Japan, through the initiative of university professors, who set up a working group on lead-free solders within academic society. Since then, several research and development projects have been established, with the later ones receiving financial support from the public sector. These have involved not only large manufacturers of consumer electronic products but also small firms producing materials and equipment for solders, as well as universities and public research institutes. Through these projects, technological development and evaluation were conducted cooperatively, with the formulation of roadmaps headed by university professors being particularly effective in coordinating the views and behavior of the diverse actors, with clearly specified milestones towards the development of lead-free soldering technologies. The establishment of extensive collaboration networks in Japan, linking academia, industry, and the public sector, was critical in promoting innovation on lead-free solders.

On the other hand, although a legislative move toward regulating the use of lead was made earlier in the United States than in other regions, the formation of networks between universities, companies, and public institutes did not proceed quickly, as discussions on regulation ceased, although the U.S. networks have been growing rapidly, with several public institutes centrally positioned along with large electronic companies. Compared with Japan and the United States, the formation of networks in Europe has been delayed. While there are several European universities that have been very active in conducting scientific research on lead-free solders, the European networks have been created with universities and companies positioned in separate parts of the networks, which could have contributed to inhibiting close collaboration between universities and industry for the development of lead-free solders. One of the reasons for the delay in forming networks in Europe and the United States could be that university researchers in Europe and the United States did not play the critical role of taking the initiative, at least at an early stage of technological development, to create networks linking academic researchers, public institutes, and companies producing materials and equipment in industry for cooperation and coordination in technological evaluation and standardization.

Technological progress which was promoted through the formation of university-industry collaboration networks, however, did not induce corresponding institutional changes in Japan. The university researchers who played a major role in the technological network for developing lead-free solders were not involved in the institutional network for discussing environmental regulations. This separation of technological and regulatory networks can also be observed in Europe and the United States. In that sense, technology and institution did not co-evolve through overlapping domestic networks. On the other hand, technological and institutional changes influenced each other beyond national or regional boundaries. The initiatives to introduce stringent regulations on the use of lead in the United States encouraged university-industry networks for technological development in Japan. The demonstration of the feasibility of lead-free solders through university-industry collaboration in Japan prompted the introduction of strict regulations in Europe. This regulatory development in turn encouraged further innovative activities in each region. In that process, the university researchers who made significant contributions to the development of lead-free solders through university-industry collaboration networks in Japan also initiated creating international networks for establishing technical specificities and standards at the global level.

In the case of innovations in the Germany chemical industry in the 19th century as discussed in Murmann, the networks connecting academia, industry and the public sector facilitated technological and policy developments favoring innovation. There networks are basically limited to domestic actors, and their impacts are mainly within the national boundaries. That is, co-evolution of technology and institution proceeded in the context of national conditions. In contrast, the case of the innovation on lead-free solders suggests that the networks for technological development and those for policy making did not overlap within a country or region, and research and development activities and regulatory formulation were implemented rather independently. On the other hand, there were clearly strong interactions between technology progress and institutional change beyond national or regional boundaries. In that sense, global co-evolution of technology and institution was observed in the innovation on lead-free solders.

Since this study is just an analysis of a specific innovation, we need to be very careful in drawing general implications. Nevertheless, this case study suggests that while university-industry collaboration networks could be formed for research and development activities, it would not be easy to create networks covering technological communities and regulatory communities in promoting environmental innovations. That probably reflects the reality that actors in the private sector do not necessarily favor strong regulations for environmental protection, which would be quite different from the case of strengthening intellectual property rights vis-à-vis other countries. Under the circumstances, university researchers would play a crucial role in establishing and maintaining close networks involving relevant actors with diverse interests and backgrounds within and beyond national or regional boundaries. Being in a relatively neutral position, they could lead efforts for the evaluation, verification, and standardization of emerging new technologies at the international level. Although the analysis of this study is limited to the case of lead-free solders, further study would generate valuable findings on the formation and functions of university-industry collaboration networks and their implications for environmental innovations through global co-evolution of technology and institution.

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