Identification of Evolutionary Characteristics of Emerging Technologies: The Case of Smart Grid in Japan

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***Abstract*-Smart grid, as an emerging field, whose evolution is featured by radical innovation requires a great diversity of technologies from different disciplines. It has become rather difficult to figure out technological capability accumulation process throughout the evolutionary process. In order to unfold the "Buzzword", we try to explore: how technological capability accumulated throughout the evolutionary process and what is the current technological structure of smart grid. We newly combined Cluster analysis with Main Path analysis by conducting an empirical study over the period 1961 ~2014 in Japan using patent data retrieved with CPC (Cooperative Patent Classification) Code "Y04S" from European Patent Office. First, Centrality analysis was developed to identify the core inventions of smart grid. Second, community detection analysis was utilized to investigate the detailed technological structure of citation networks. Last but not least, Search Path Count (SPC) was designed to investigate the evolutionary trajectory of each cluster. Finally 3 different dimensions of knowledge pattern were obtained: the core invention, technological trajectory and cluster of smart grid inventions. We find Most of the innovative activities are happening in Clusters 3, 4 and 5. Especially, radical innovation is identified in Cluster 4. The result also provided strong evidence showing significant difference of technological capabilities among power companies.**

I. INTRODUCTION

Over the last decade, smart grid has experienced worldwide evolution. The technological features could be illustrated both by simple and complex ways[1]: 1) in simple term, smart grid could be featured as an intelligent grid; 2) in a relatively complex way, smart grid should be recognized as "platform to maximize reliability, availability, efficiency, economic performance, and higher security from attack and naturally occurring power disruptions"[2].It could be understood better when the concept was reviewed through the comparison between traditional power grid. Farhangi, H. [3] already made a comparison between the two different concepts. A general summary of difference between smart grid and existing grid can be depicted in Table 1.

However, smart grid, recognized as a "buzzword" like Big Data, is quite difficult to give a suitable definition to it, let alone outline the boundary and detailed composition. However, it does not mean smart grid has come from nowhere. They appeared as an answer to enhance the effectiveness and efficiency of the old power system [1], that technological advances must take place along some ordered and selective patterns in the potential paradigmatic shift of industrial evolution [2].

Technological paradigm and technological trajectory recognized as classical concepts from Innovation literature described the path dependent properties of technological change [4-6]. Although a great amount of reach has contributed to the analysis of technological change in different sectors, according to our knowledge, only a few literature investigated the evolutionary process of smart grid. We try to answer following questions: what are the most imperative technological capability accumulated throughout the evolutionary process and how is the current technological structure of smart Grid. The answers to these questions are quite relevant to policy makers, related companies and researchers, etc. The analysis of this systemic development is important in order to understand the state of the overall sustainable transitionary process by mapping the overall smart grid sector. Especially, in the infrastructure system, analyzing the technological trajectory by delineating the boundary of a country can provide valuable insights for understanding systemic change[7].

TABLE 1: THE DIFFERENCES BETWEEN TRADITIONAL POWER GRIDS AND SMART GRIDS(ADAPTED FROM FARHANGI, H. [3])

Traditional Power Grids	Smart Grid
Mechanization	Digitization
One-way communication	Two-way communication
Centralized power generation	Distributed power generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-healing
Manual checking equipment	Remote supervisory controlling equipment
Fewer user options	More user options
Finite control	Pervasive and intensive control system

The novelty of this paper is to fill the gap in the research by combining the Communities Detection method with Main Path analysis to map the technological capability accumulation underling the radical innovation process of smart grid. In order to investigate the technological evolutionary process from 1961-2014, patent citation networks was firstly built. Then centrality analysis by investigating In-degree centrality, out-degree centrality and betweenness centrality was developed to find the key inventions. Next step, in order to investigate the different dimensions of technological knowledge patterns, research investigating technological cluster and tracing technological trajectory was developed.

II. LITERATURE REVIEW

Scholars from various disciplines have contributed to researches on industrial evolution and economic growth by analyzing the technological advance process through the evolutionary theory [8-10]. Especially, evolutionary theory shed light on understanding of technological change from 3 aspects, namely: variation, selection and retention process. Identifying and tracing the emerging field, technological paradigm and trajectory[6]associated with technological advance which leads to industry-wide movement is very critical in making business strategy as well as economic and environmental policy[11] and it is very important for R&D managers, researchers, engineers, and policy makers[12]. Patent citation networks, when analyzed through the social network approach[13] provided fruitful result[14]. Furthermore, technological front and structure could be identified by clustering the citation network[15].

Inspired by growing importance of network approach for analysis of patents, we proposed a related methodology to analyze the “smart grid” which is an important field which can meet electricity system decarburization targets compatible with the Japanese governments’ goal, maximizing the use of renewable energy sources, such as photovoltaic and wind power. In this research we combined the community detection method with Main Path analysis to map the technological capability accumulation underling the radical innovation process of smart grid. The movement along the technological trajectory and detection of technological cluster implies the recent technological advance-i.e., evolution in smart grid- and in the underlying understanding of structure of technological cluster-i.e., configuration of smart grid.

III. DATA COLLECTION

Data were collected from the European Patent Office (EPO) Worldwide Patent Statistical Database, known as PATSTAT. The retrieving rule of patent collection in this research is based on CPC (Cooperative Patent Classification), a joint project launched by European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO) aiming at developing a classification which can be mutually used by both offices. Data were collected from the year 1961 to 2014. We searched the CPC –class Y04s1 on the EPO homepage to collect patents related to all types of smart grid technologies2. The final dataset covers 6171 patents from the year 1961 to the year 2014 in Japan.

IV. METHODOLOGY

The entire process of proposed methodology is illustrated in Fig. 1. After patents were retrieved from EPO database in step 1, patent network were built by using direct citation.

A. Patent Citation Analysis

Value of patent citation can be recognized from its function by conveying not just technological but also economical information and the information conveyed by patent citations can be summarized from two aspects[16]: firstly it can be served as an bridge linking among inventions, inventors and assignees; secondly, citation can be recognized as indicators of the “importance” of patents , so providing a way to measure the heterogeneity in the “value” of patents. In order to improve the effectiveness of investment of R&D resources in corresponding technological domain, citation network has been utilized quite often to illustrate technological trend, important technological issues, and technological front [17, 18]. However, key papers or patents sometimes may be missing in co-citation or bibliographic coupling based networks, especially when these documents are newly published[19]. By following previous studies [15, 20], direct citation is recommended in this paper to detect the emerging trend in smart grid. Therefore, we built the citation network by regarding the patents as nodes and direct citation as the linkage between nodes. Afterwards isolated nodes which have no linkage with other patents were removed, and a giant connected component is extracted.

B. Centrality Analysis

In step 2, centrality analysis is developed mainly from 3 different aspects: In-degree centrality, Out-degree centrality and Betweenness centrality

Degree Centrality, defined as the number of links adjacent to a node, is recognized as the simplest and popular method in the centrality measures.

The degree centrality of node i is given by the degree of the node:

$$C_i^{DEG} = \deg(i), \deg(i) \quad (1)$$

is degree of node i. In the situation of directed networks, linkages among different nodes have directions, two separate measures will be used to describe the degree centrality:

In-degree centrality: A node which receives many ties is characterized as prominent. The basic idea is that a number of neighbors seek to direct ties to them—and so this can be regarded as a measure of importance.

Out-degree centrality: Nodes which have high out-degree centrality are relatively able to disperse information quickly to many others. So nodes with high out-degree centrality are often characterized as influential.

[1] CPC=Y04s means Cooperative Patent Classification shared by EPO / USPTO to describe patents related to systems integrating technologies related to power network operation, communication or information technologies for improving the electrical power generation, transmission, distribution, management or usage, i.e. smart grids

2 The details for patent retrieval on EPO is listed below:

```
SELECT distinct(tls201_appln.appln_id)
FROM tls201_appln join tls224_appln_cpc ON tls201_appln.appln_id=tls224_appln_cpc.appln_id
where left(cpc_class_symbol,4) = 'Y04S' and applnauth = 'JP'
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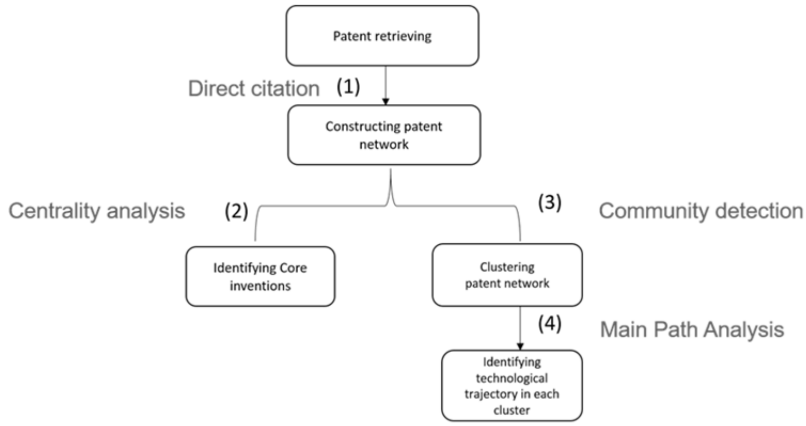

Fig. 1 Framework of the proposed methodology in this research

Betweenness centrality [21] [22] is a measure of the extent to which a node is connected to other nodes that are not connected to each other. It can be recognized as a measure of the degree to which a node serves as a bridge.

The betweenness centrality of node of i can be expressed as follows:

$$C_i^{BET} = \sum_{j,k} \frac{b_{jik}}{b_{jk}} \quad (2)$$

Where, b_{jk} is the number of shortest paths from node j to k, and b_{jik} be the number of shortest paths from node j to k that pass through node i.

C. Community detection and Main Path analysis

After obtaining the giant component of citation network, in step 3 technological communities are detected using the Louvain Method (within Gephi software), because it is not only suitable for fast unfolding of communities in large networks [23] but also one of the best performing algorithms for the directed network. Louvain Method uses iteratively repeated multi step based on a local optimization of Newman-Girvan modularity to achieve a hierarchical decomposition of the network.

After clustering the patent network via splitting the giant communities into sub-communities, we built the new directed networks by manually allocating direction to each pair of nodes which makes it possible to combine the Communality detection with Main Path Analysis. In step 4, Main Path Analysis were designed to identify the technological evolutionary process with each sub-communities by investigating dynamic technological trajectory. Main Path of a citation network a path from a “Source” patent which is cited but cite no other to “Sink” patent which only cites others but is not cited by any other patents[10]. Even Several methods are available for calculating the travel weights of Main Path, Search Path Count (SPC) was adopted by this paper to evaluate the importance of each citation path since it is commonly recognized as the first recommendation for analyzing the large and complex networks[24].

V. RESULT AND DISCUSSION

Worldwide Patent Statistical Database PATSTAT (version Autumn/2015) database served as the source for collection of patent documents. In all, a total of 6171 patent documents about smart grid were obtained with the reference period from 1961 to 2014. As shown in Fig 2 in the last decade, the numbers of patent applications have rapidly grown in a short time. This indicates that smart grid technologies are experiencing radical innovation in importance year by year but still at its emerging stage.

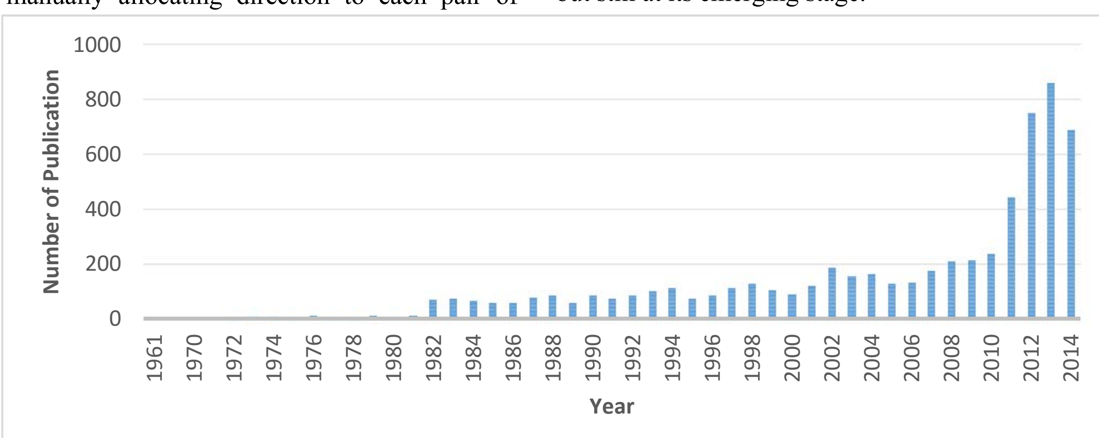

Fig.2. Development of annual patent publication of smart grid in Japan

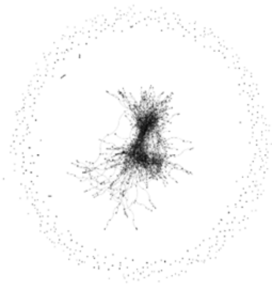

Fig. 3 Full citation network

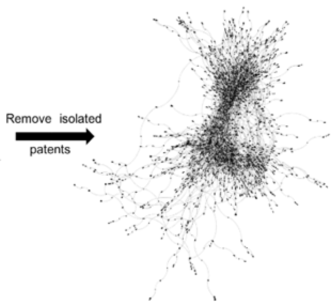

Fig. 4 Giant Component of Citation network

The relatively low number of patent publications in 2013 and 2014 can be explained that because it takes 18 months until an application is disclosed to the public. Taking into account the latest patents were collected into the PATSTAT data base by October 2015, the value for 2013, 2014 (October 2015 minus 18 months) is not completed.

Fig.3 shows the original patent citation networks which is composed by 8936 nodes and 10996 edges. Correspondingly, the giant network has been extracted by deleting the isolated nodes and the size has been reduced to 6306 nodes (71% remained) and 8971 edges (80% remained) as shown in Fig. 4.

A. Centrality analysis

As shown in Table 2, the top ranking patents are listed according to the value of in-degree and out-degree (value>18 for in-degree and value >17 for out-degree). Many important findings can be shown by investigating in-degree and out-degree tables. Patents with highest value in in-degree can be explained as technology contains most up to date information. Additionally, it can also help to clarify which patens or which cluster patents positioned in are the "absorbers" of highly impacted technologies. It can be verified from Patent 275684738 entitled "VEHICLUAR CHARGING UNIT" and published in 2009.This technology was aiming to promote population of Electric Vehicles by providing an easy charging Battery. On the contrary, out-degree centrality helps to identify most cited patents or clusters which are recognized as "source" of the many original technologies. The patents which are mostly cited by others are patent 291873470 with the title "POWER MANAGEMENT SYSTEM, 2001" which unlocked the value of power charging system of an EV car and make sudden going out operation possible even the car was originally charging in a house. The two evidence demonstrate that EV car related technology playing a key role during the evolutionary process of smart grid.

In addition to degree centrality, betweeness-centrality was also investigated in this paper. A node with high betweeness-centrality means it is located at the shortest path between two communities of chosen nodes. In other words, it can be served as "pivot points in the network"[25]. So patents performed as pivot points has the high possibility to bring high impact to other technological domains. Betweeness-centrally can also be used as an indicator of radical innovation[12]. In Table 3, the top 10 patents with high betweeness-centrality are listed with cluster number. The results show that most of the patents are related to systems supporting issues which are designed to improve the interoperability of EV cars. Additionally, by looking at the clusters where the patents located, we found that they are almost from the same Cluster 4. The results show that Cluster 4 is an important technology mediator which might bring high impact for technological advance in smart grid domain.

TABLE 3: TOP 10 PATENTS WITH HIGH BETWEENESS-CENTRALITY

Patent Publish ID	betweeness centrality	Cluster Number
319554877	668.7	4
275684738	261	4
278289365	259.5	4
276447635	239.5	4
331662113	220.5	4
335628707	183	4
276949795	175.5	4
278849846	165.5	4
281658069	162	3
275897438	149	4

TABLE 2: TOP 9 PATENTS WITH HIGH IN-DEGREE AND TOP 8 PATENS WITH HIGH OUT-DEGREE

Patent Publish ID	indegree (>18)	Cluster Number	Patent Publish ID	outdegree(>17)	Cluster Number
275684738	28	4	291873470	41	4
276224517	25	4	276494960	26	4
277132862	24	2	319554877	22	4
340342666	24	3	288872863	21	3
340394594	24	3	289811043	20	3
275857188	23	5	289321831	17	4
275841331	20	4	286556176	17	4
301794143	19	4	277015111	17	4
380516365	19	3			

B. Community detection and Main Path analysis

Clustering the direct citation network is formed using the Louvain Method [23]. Five Clusters are identified by inputting the Resolution variable with the value of 6 as shown in Fig 5 with different colors. Subsequently, each clusters' theme is identified by combing the Main Path Analysis and work flow is shown in Fig 6.

Cluster ID	Cluster Theme
Cluster 1	power protection& power quality management
Cluster 2	Supervisory Control Power System
Cluster 3	Systems supporting renewable power generation, transmission or distribution.
Cluster 4	EV charging system
Cluster 5	Home Energy Management Systems (HEMS)

Fig.5 Constructed Clusters of patent citation networks

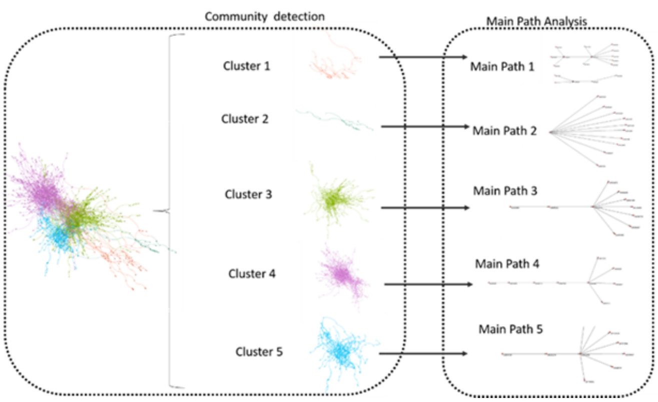

Fig. 6 illustration of relation between community detection and Path analysis

Cluster 1

Cluster 1 consists of 371 nodes and 403 Edges. The Main path analysis indicates technological trajectory starting from left hand and ending on the right hands. The arrows represent technological advances between different technologies. It is different with other clusters, two different branches which depict the evolutionary process of cluster 1 are shown in Fig 7. The divergence of trajectory indicates: the two different trajectory still did not find the joint place which can be served as crossover of two ideas. The patents in upper trajectory of Main Path 1 indicates protection control system technologies which are of great importance for the whole security and stability of the electricity system. Toshiba has a dominated contribution towards problem solving process of power system protection issues and it can be demonstrated by strong share of patents in the path (12 in total, 7 from Toshiba). The bottom trajectory consist of patents related to power quality data collection, power quality monitoring device, etc. which can be summarized as "power quality management". So the overall themes which direct Cluster 1 can be summarized as "power protection & power quality management". The overall result of main path analysis shows that, only one power company (Chugoku Electric Power) participated in the innovative actives. Compared to the power companies' lack enthusiasm in general, IT, electronic and electric companies had quite different attitudes who are currently actively participating in the innovation process.

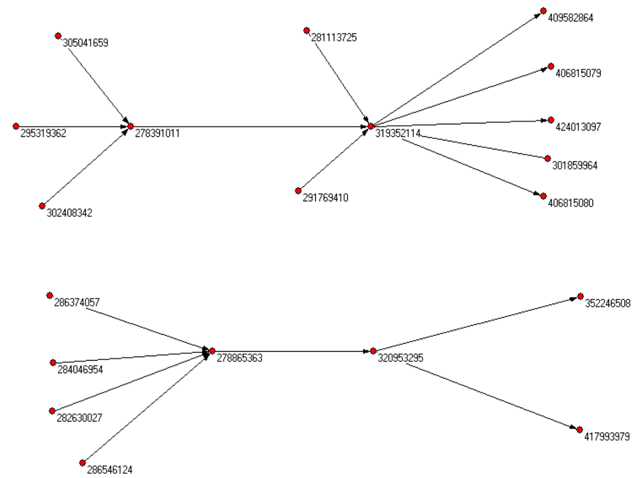

Fig 7 Main path 1

Cluster 2

Cluster 2 include 171 nodes and 139 edges. This development direction of Cluster 2 is still at quit diversified stage and we still could not find clear or complete trajectory as shown in Fig 8. When analyzing the patents in the main path, we found that most of the patents tackle supervisory control system issues. Since the whole cluster is not yet developed, more R&D resources are needed to promote the new technological advances in supervisory control system domain. Companies like Hitachi, Toshiba played quite an important role during the early development stage of Cluster 2.

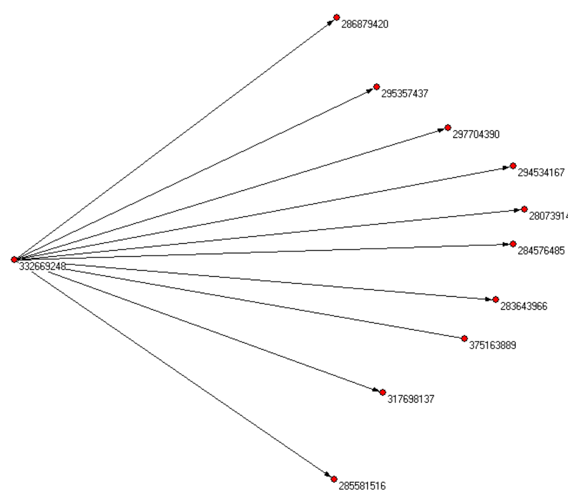

Fig 8 Main path 2

Cluster 3

The third cluster including 1923nodes and 2566 edges are the second biggest one compared to other 4 clusters. Cluster 3 is related to renewable energy, especially Systems supporting renewable power generation, transmission or distribution. As shown in Fig 9, some patents are related to green power certificate transaction method, method for efficient use of green premium, power generation data managing method in solar power, etc. Regarding the technological development, it describes a process from supervising system for self-consumed electric energy to green power generation devices to power delivery/reception system. This cluster is quite important, since the integration of renewable energies into traditional grids causes a problem. Smart grid can solve these problems by preventing outage and allowing consumers to manage their own energy consumption. Overall the technological advances in this domain can demonstrate the value of smart grid. The assignees on the main path are mainly Sony Corporation, Tokyo Electric Power Company, Chugoku Electric Power and Mitsubishi Electric. Another power company (Tokyo Electric Power Company) appeared in this cluster.

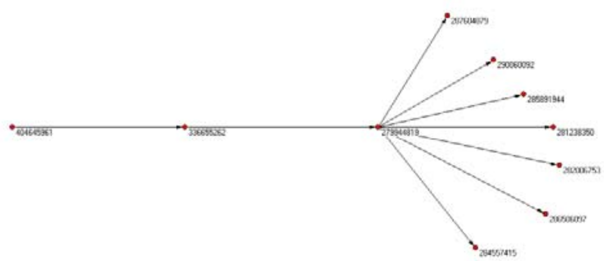

Fig. 9 Main path 3

Cluster 4

Cluster 4 consists of 2980nodes and 2566 edges are the biggest cluster. Most patents deal with power charging issue of EV cars. As we can see from Fig. 10, the trajectory is relatively fully developed compared to other cluster. The technological advances in the cluster start from power charging related hardware for EV to charging system which can connect the EV to power grid. Vehicle-to-grid (V2G) is a of great importance issue in smart grid, since it can fulfill the function of communicating with power systems and also can sell own power back to the grid. Even we witnessed fast technological advances towards the evolution of EV charging system, V2G still left quite big room for improvement. More innovations should be encouraged towards this issues. Panasonic Electronics, Toshiba, and Chugoku Electric Power played a key role for evolutionary process of EV charging system.

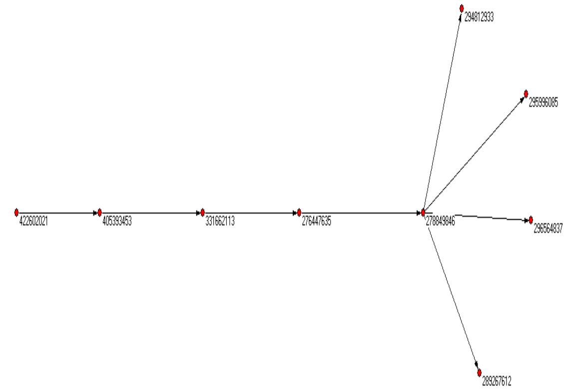

Fig. 10 Main path 4

Cluster 5

Cluster 5, consists of 890 nodes and 1108 edges. The overall cluster theme is Home Energy Management Systems (HEMS). HEMS is an ICT based solution to control energy supply and demand. Technological change in this cluster is mainly focusing on advancement in energy saving function as shown in Fig 11. It is without doubts that saving energy is a key feature of HEMS and which also contribute significantly to the full achievement of smart grid. However, demand response should not be missed as well since it is an imperative option used by both system planner and consumer to balance the supply and demand. Furthermore, this option depicts the obvious difference between conventional power system and smart grid system. So R&D resources and more practical efforts should also be allocated in this domain.

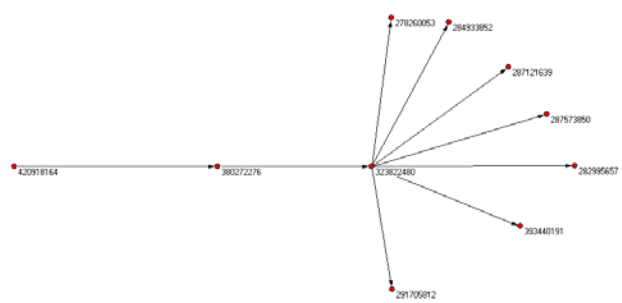

Fig. 11 Main path 5

With the new companies entering this domain, the composition of assignees changed a lot on the main path and they are occupied by ICT companies like Yahoo Inc., Panasonic Corporation, and Fujitsu Ltd. The overview of 5 different trajectories is showed on Fig. 12 which provides us a clear picture of image for evolutionary process of smart grid.

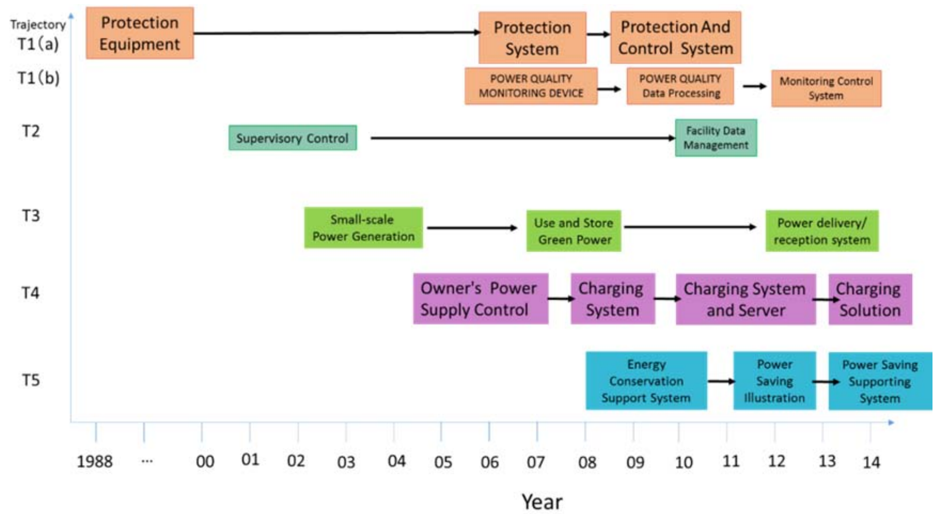

Fig. 12 Overview of 5 different trajectories

VI. FINDINGS AND DISCUSSION

Various findings can have different implications by starting from different analytical aspects.

Generally in-degree and out-degree identify the “absorber” and “source” among the original technologies. Betweeness centrality recognized as “pivot points in the network” implies the high potential to bring impact to other surrounding patents. More over betweeness can be used as a metric of radical innovation. Social Network analysis and Cluster analysis combined with the Main Path analysis figure out:1) the emerging technological themes 2) the important technological themes 3) technological themes related to radical innovation. Details are given as below:

First, Radical innovation are identified in cluter4-EV charging systems. Patens in cluster 4 not only have high value in betweeness but also in in-degree and out-degree. In another words, it means cluster 4 is not only sourcing new ideas to other clusters but also it is absorbing high impact technologies. All of these information indicate that EV charging system related technologies are currently undergoing a rapid development and its development also has huge impact on other clusters.

Second, by comparing the size of different clusters, we found cluster3, 4, and 5 are obviously bigger than cluster 1, 2 which can be explained that most of the innovative activities are happening in these 3 different clusters: systems supporting renewable power generation, transmission or distribution, EV charging system, and Home Energy Management Systems (HEMS) domains. Current situation in Japan confirmed our findings. The electricity supply system in Japan has already been very “smart” as far as electric transmission and distribution[26], it is normal to observe little innovative activities in Cluster 1, 2. Active innovative performance in cluster 3, 4 and 5 is consistent with Japanese government’s strategy for the prior development of technological domain which can be recognized from four “smart community” social experiments.

Third, Chugoku Electric Power Company displayed strong technological capability in many technological domain which is quite different with other power companies. Power companies’ lower technological capability is consist with our interview result3, which shows that as a natural monopoly industry, power companies are reluctant to participate into the smart grid related innovation process. Since they do not want to take the risks to lose their customers in case of customers’ indifferent reaction to new technology. On the other side, Toshiba, Mitsubishi electric, and Hitachi, Ltd revealed strong technological capability in specific domain.

Fourth, emerging field such as power protection& power quality management and supervisory control system field need very intensive and political attention. Investors could also go for funding the projects related to this field which could offer high returns on high risk.

The proposed methodology of this paper could help governmental officials and R&D managers who are working on smart grid sectors to figure out the current technological trend and plan the precise decision making according to their current position in this sector. For example, electronic company and IT related firms are entering fast especially in Home Management System field. Moreover managers should pay attention to EV charging not only because it is a sector which is undergoing the most radical change and but also it is an important technology mediator which might bring high impact for technological advance in smart grid domain.

This study has limitations. We were not able to overcome the fundamental problem of patent analysis. As the aim of this paper is to investigate the whole technological capability accumulation process throughout the evolutionary process by utilizing the main path analysis, so any deleted patent will

[3] Interview was conduct with official in Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry on May, 2014

have the possibility to affect the integrity of technological trajectory formation. In order to get a complete technological evolutionary image of smart grid, we had to lay the truncation issue outside the scope of in this paper.

VII. CONCLUSION

As radical innovation of smart grid requires a great diversity of technologies from different disciplines, it has become more difficult to figure out technological capability accumulation process throughout the evolutionary process. In order to help managers and government to have a clear understanding of the historical evolution of smart grid as well as the potential for the future development, a novel method was proposed by combining the cluster analysis and Main Path analysis. The main objective of this paper was to investigate the evolutionary characteristics of smart grid based on patent citation network analysis. Centrality analysis identified the key invention of smart grid. By community detection and Main Path analysis, five clusters were identified in this paper, Cluster1 power protection & power quality management, Cluster2 Supervisory Control Power System, Cluster 3 Systems supporting renewable power generation, transmission or distribution, Cluster 4 EV charging system and Cluster 5 Home Energy Management Systems (HEMS). Within the 5 Clusters, Cluster 3, 4 and 5 contribute more to the whole technological evolution of smart grid. Especially, Cluster 4 recognized as radical innovation has significant impact to other domains. With a more clearly systematic view of technological evolutionary process of smart grid, it will be possible for making potential implications of the findings for various target groups.

Our proposed methodology has implications for technology strategy and public policy aiming at stimulating innovation in emerging technology sector domain: 1) Adjacent companies can contribute indirectly and directly to sectoral evolution by combining the knowledge from their own sector and novelty they created. ICT and electronic companies, e.g. Toshiba, Mitsubishi, Fujitsu and Sony etc. displayed stronger role than the incumbent power company by observing the whole evolutionary process; 2) The second implication related to literature related to technological positon and competitive advantage. Since the evolution of system depends on a variety of technological domains, opportunities for firms with knowledge in adjacent sectors can arise along the trajectory, if they have related knowledge accumulation and they are willing to contribute to the innovation of this sector. In others words, the timing of entry and firms' knowledge composition will have a great impact to the final success when a firm move into a specific sector.

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