International Journal of Energy Technology and Policy

ISSN print: 1472-8923 ISSN online: 1741-508X
2016 Vol. 12 No. 1

Detection and introduction of emerging technologies for green buildings in Thailand

Tanunya Visessonchok*

Department of Technology Management for Innovation,
Graduate School of Engineering,
The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Email: tanunya.v@gmail.com
*Corresponding author

Masahiro Sugiyama, Hajime Sasaki and Ichiro Sakata

Policy Alternatives Research Institutes,
The University of Tokyo,
7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
Email: masahiro@pari.u-tokyo.ac.jp
Email: sasaki@pari.u-tokyo.ac.jp
Email: isakata@ipr-ctr.t.u-tokyo.ac.jp

Abstract: Energy efficiency in Thailand remains low despite the escalating energy consumption. Moreover, Thailand's energy security situation is risky and unsustainable due to its large proportion of energy import and heavy dependency on natural gas for electricity generation. In this paper, a comprehensive citation-based approach employing academic and patent data are utilised in order to detect the emerging technologies for green buildings in tropical countries like Thailand. Rapidly growing and overlapping areas of paper and patent clusters have been identified as emerging technologies. As a result, the clusters related to solar cooling have been identified as a promising technology that satisfies the two conditions. Solar cooling possesses great potential since it closely fits the environment in Thailand where there is abundant sunlight all year round and air conditioning consumes roughly half of the total electrical usage.

Keywords: bibliometrics; citation network; green building; renewable energy; renewable technology; emerging technology; solar cooling.

Reference to this paper should be made as follows: Visessonchok, T., Sugiyama, M., Sasaki, H. and Sakata, I. (2016) 'Detection and introduction of emerging technologies for green buildings in Thailand', *Int. J. Energy Technology and Policy*, Vol. 12, No. 1, pp.2–19.

Biographical notes: Tanunya Visessonchok completed her graduate studies in Technology Management for Innovation from the University of Tokyo in 2014. She is now a Senior Associate working in the Business Development Division in a Thai renewable energy firm.

Masahiro Sugiyama is an Assistant Professor at the Policy Alternatives Research Institute, The University of Tokyo. His research interests include climate policy, energy technology innovation, and climate engineering.

Hajime Sasaki is a Project Researcher at the Policy Alternatives Research Institute, The University of Tokyo. His research interests include innovation policy, management of technology and data-driven decision-making.

Ichiro Sakata is a Professor at the Department of Technology Management for Innovation, the Director of Innovation Policy Research Centre and the Co-Head of Presidential Endowed Chair for Electricity Network Innovation by Digital Grid at the University of Tokyo. He received his Bachelor's degree and PhD from the same university, and Master's degree from Brandeis University. He has 20 years of working experience at the Japanese Ministry of Economy, Trade and Industry (METI). His research interests include technology management, technology roadmap and innovation network. He has published more than 100 papers in peer reviewed journals and conference proceedings.

This article is a revised and expanded version of a paper entitled 'Detection and introduction of emerging technologies for green buildings in Thailand' presented at PICMET'14 Conference, Kanazawa, 27–31 July 2014.

1 Introduction

1.1 Energy efficiency in South-East Asia

Energy intensity can be defined as the amount of energy used to produce a unit of gross domestic product. The higher the energy intensity means the lower the energy efficiency and vice versa. The improvement of energy intensity in Southeast Asia has been relatively slow as the region was unable to fully extract the available technical potential for energy efficiency while it transformed to more energy-intensive economies. In 2011, the region's energy intensity was more than one-third higher compared to the world's average and twice that of the Organization for Economic Cooperation and Development (OECD) countries (International Energy Agency, 2013).

As for Thailand, it is the second largest consumer of energy in Association of Southeast Asian Nations (ASEAN), but it is heavily dependent on energy imports due to the limited energy resources. Oil and gas are imported into Thailand annually and this rising trend is threatening the country's energy security. On the other hand, with electricity being the second largest fuel consumed in Thailand, there is also an urgent need for Thailand to diversify its electricity generation as almost 90% originates from fossil fuels alone (Department of Alternative Energy Development and Efficiency, 2013). In 2011, more than half of the energy consumption by economic sector went to buildings whereby 70% of that energy is consumed by ventilation and air conditioning system which accounts for roughly 50,000 GWh per year (Pongtornkulpanich et al., 2008). Thus, it is critical for Thailand to improve its energy security and energy efficiency circumstances for a more stable and sustaining energy future. Inefficient energy consumption in buildings especially for air conditioning and ventilation represents a sector with substantial prospective for improvement.

1.2 Bibliometrics

It is undeniable that we are now living in an era of big data. Without the right data management tools, a comprehensive data analysis could be an onerous task. A bibliometric approach represents one such possible solution and it is employed in this study. Bibliometrics refers to a set of approaches to quantitatively analyse bibliographic information of academic literature, patents and other publications.

It has been widely used and proved to be a powerful tool for exploring the impact of several factors in a field of research, to detect emerging trends and the direction of research as can be shown in diverse literatures. Kajikawa et al. (2007) were able to track emerging research domains in the field of sustainable science effectively and efficiently using citation network analysis despite the tremendous wealth of data. Similar approaches have been successfully applied to a broad area of energy research (Kajikawa et al., 2008), regenerative medicine (Shibata et al., 2011), and robotics (in the context of gerontology) (Ittipanuvat et al., 2014).

Citation network analysis therefore presents a helpful tool for assisting the planners of energy research and policy makers alike to grasp the wider coverage of scientific and technological research and make decisions on worthwhile investment in promising technologies particularly under resources limitations.

1.3 Emerging technologies

The term 'emerging technologies' has been loosely defined in various literatures, but mostly centred around four main concepts: fast recent growth; in the process of transition and/or change; market or economic potential that is not fully tapped yet; and increasingly science-based (Cozzens et al., 2010). Some experts have defined 'emerging technologies' qualitatively such as Day and Schoemaker (2000) who defines emerging technologies as 'those which:

1 the knowledge-base is expanding

2 the application to existing markets is undergoing innovation

3 new markets are being tapped or created'.

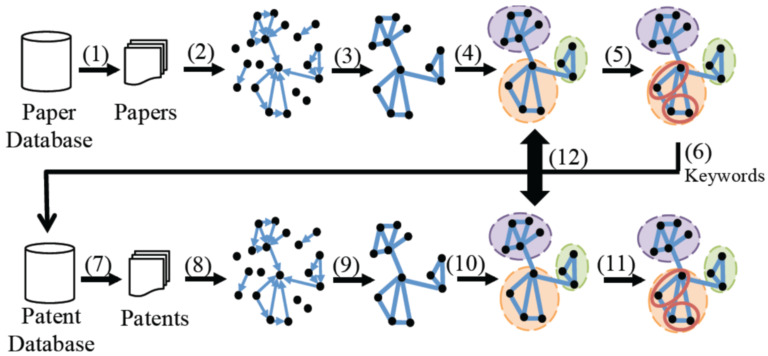
It is undeniable that expert foresights are valuable inputs for detecting emerging research fronts, planning of technology roadmaps, and drafting of policies; such was utilised by Shibata et al. (2011). However, several weaknesses of the expert-based approach have been identified in previous academic studies such as the fact that the amount of academic knowledge is increasing rapidly that it becomes difficult for experts to capture the entire knowledge structure of a specific knowledge domain; the expert-based approach is expensive and time consuming; and the commonly accepted definition of a targeted research field is sometimes missing (Shibata et al., 2011). Computer-based, bibliometric approaches can provide a complementary method to efficiently handle a flood of complex data.

Shibata et al. (2011) proposed a method to research fronts that are not commercialised yet, and analysed the case of solar-cell research. In this paper, we apply this technique to the case of green buildings. In so doing, we extend the previous method in the following way. First, we couple patent search to paper identification by utilising keywords from the paper analysis for patent search. Second, we propose a new framework to identify emerging areas, comparing different alternatives. It is expected that the results of the analysis could serve as an initial step for assisting policy makers in solving the energy security and energy efficiency complications in tropical countries like Thailand.

2 Methodology

As noted above, we extend the method developed by Shibata et al. (2011) and apply it to the case of green buildings. The overview of the methodology used in this paper is illustrated schematically in Figure 1.

Figure 1 Overview of methodology (see online version for colours)



In step (1), the bibliographic data of academic papers were extracted from the science citation index expanded (SCI-EXPANDED), the social sciences citation index (SSCI), and the arts and humanities citation index (A&HCI) compiled by Thomson Reuters. Web of science by Thomson Reuters is the world's leading citation database resource covering more than 12,000 high impact journals worldwide with coverage from year 1900. Keyword search was used to search for relevant papers by specifying the following query in the field of topic and title. The results were further restricted to avoid irrelevant papers by excluding the field of Chemistry, Materials Science and Physics. The following query was applied: *((eco* OR energy efficien* OR low energy OR smart OR sustainab* OR low carbon OR low emission OR green) AND building*).* The time boundary was not restricted; therefore the search results would include all publications available from 1900 until 2013.

In step (2), academic paper data collected from the Web of Science were used to construct a network using respective papers as nodes (represented by black dots) and non-directed, non-weighted citation relationships as links (represented by blue lines). Direct citations or intercitation was employed as it has been shown that it is the most effective method for detecting emerging research fronts as core papers will always be included in the largest component and thus less likely to miss emerging research domains (Shibata et al., 2009). Consequently, irrelevant papers not linked to any paper in the largest connected components of the citation network were discarded and therefore offering a cleaner and more relevant set of information in step (3). Next, the citation network is grouped into different clusters using topological clustering method (Newman, 2004) in step (4). Each cluster was then represented by a name considering their contents as well as the important terms extracted from the highly cited academic papers within each cluster. To aid the visualisation, large graph layout (LGL) (Adai et al., 2004), which is based on a spring layout algorithm is used to visualise the academic landscape. The average year, median year and growth rate in recent years of publications in each cluster are investigated and analysed in order to detect emergence. The growth rate in percentage is calculated using the following equation:

$$\left[\left(\frac{m}{n}\right)^{\frac{1}{t}-1}\right]\times 100 \qquad (1)$$

where n is the sum of publications in year 2008 and 2009; m is the sum of publications in year 2010 and 2011; and t is the time interval, which is three years. Publications from year 2012 and 2013 are excluded since there is a time lag before academic findings or technological results are available to the public. Step (1) to step (4) can be regarded as the knowledge-structuring phase where an academic landscape was created in order help us better comprehend the structure and direction of the knowledge domain. Since top clusters generally contain a large number of nodes, recursive clustering, step (5), can be performed on each cluster as to help us understand the topics of individual clusters more in details. When each cluster is divided into sub-clusters, clusters are trimmed away from the original citation network, that is, each cluster becomes a new citation network and the maximum modularity is re-calculated within each cluster. The acquired keywords from step (5) were used as inputs for the patents search in step (6) where the time boundary was not restricted; therefore the search results would include all patents available from 1900 until 2013.

The citation network analysis was repeated for the patent data forming a technology landscape. Patent data were collected from the enhanced patent data consisting of Derwent world patents index (DWPI) and Derwent patent citation index (DPCI) served by Thomson innovation. Thomson innovation offers the world's most comprehensive platform for patent data, covering over 14.3 million basic inventions from 40 worldwide patent-issuing authorities. In step (7), the patent corpus was formed from the database. Similar to the academic domain, from step (8) to step (11), the knowledge-structuring phase was repeated with the exception that for patent cluster analysis, direct citations, co-citations and bibliographic couplings were all selected to create the network landscape since patents tend to have fewer citations than academic papers (Shibata et al., 2010). A meaningful citation network of patents cannot be formed without selecting all three types of citations.

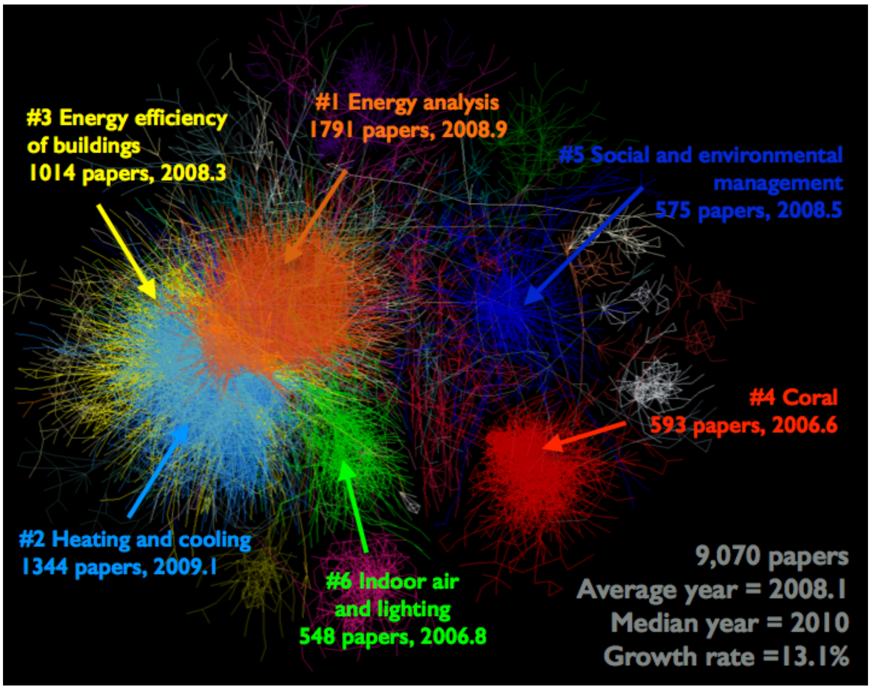
The last step, step (12) involved finding content-based similarities between the clusters of academic papers and patent data. Employing the extracted terms or keywords from each cluster as term vectors, relatedness among clusters can be calculated via semantic similarity. In this study, each keyword in the paper is scored and importance-based cosine similarity was employed to calculate the relatedness between the clusters. In principle, the higher the number of the same keywords clusters has, the more similar they are. Note that Shibata et al. (2011) compared three alternative scoring methods (Jaccard coefficient, cosine similarity of term frequency – inverse document frequency vectors, and cosine similarity of logarithm of the same set of vectors) and demonstrated the superiority of the cosine similarity metric (without logarithm).

3 Results

3.1 Results of analysis from the science layer

We extracted 27,191 academic papers from the web of science with the query previously mentioned in the methodology section and 9,070 papers were included in the largest connected component after the knowledge-structuring phase. More than 70% of the papers belong to the top six clusters. The visualisation of the academic landscape is shown in Figure 2.

Figure 2 Academic landscape in the domain of green buildings. the name of each cluster, average year and number of papers in each cluster are mentioned (see online version for colours)



The biggest cluster (cluster #1) is related to energy analysis and various building environmental assessment methods such as the life cycle assessment. The second largest cluster (cluster #2) discusses the various heating and cooling systems available for buildings including the utilisation of green roofs while cluster #3 is dedicated to energy efficiency of buildings. The positions of clusters #1, #2 and #3 are close together since their topics are closely related and some citations are shared between these clusters. Cluster #4 examines reef-building corals and their ecologies while cluster #5 deals with social and environmental management such as social-ecological system analysis. Clusters #4 and #5 are isolated from the main connected components, as their topics do not relate directly to the green buildings and this can also be confirmed by inspecting the lists of journals associated with those two clusters. Clusters #4 and #5 are thus excluded from further analysis in this paper. Cluster #6 relates to indoor air and lighting such as ventilation in buildings and natural daylighting.

To investigate the detailed structures of clusters #1, #2, #3 and #6, recursive clustering was performed where these clusters are further divided into sub-clusters. The sub-clusters are ranked according to their average year, median year and growth rate in Table 1. For some clusters the rankings are similar regardless of the indicator used. However, no obvious trends are found in most cases therefore recent growth rate of publications is used in this paper to define emerging technologies. The emerging research fields are life cycle analysis (#1-3), heat pump (#2-1), lighting/daylighting (#3-3), and daylighting (#6-4).

Table 1 Summary of academic paper clusters and sub-clusters

Rank	*Sorted by average year*		*Sorted by median year*		*Sorted by growth rate*	
	Cluster/ sub-cluster	*Year*	*Cluster/ sub-cluster*	*Year*	*Cluster/ sub-cluster*	*Rate*
1	#2 heating and cooling	2009.1	#1 energy analysis	2010	#3 energy efficiency of buildings	17.5%
2	#1 energy analysis	2008.9	#2 heating and cooling	2010	#2 heating and cooling	16.1%
3	#3 energy efficiency of buildings	2008.3	#3 energy efficiency of buildings	2010	#1 energy analysis	13.9%
4	#6 indoor air and lighting	2006.8	#6 indoor air and lighting	2009	#6 indoor air and lighting	7.4
			#1 energy analysis			
1	#1-4 design optimisation	2009.8	#1-1 heating	2011	#1-3 life cycle analysis	25.1%
2	#1-3 life cycle analysis	2009.4	#1-3 life cycle analysis	2011	#1-4 design optimisation	20.8%
3	#1-1 heating	2009.4	#1-4 design optimisation	2011	#1-1 heating	13.8%
4	#1-5 building stock	2008.2	#1-5 building stock	2009	#1-2 environmental assessment	6.5%
5	#1-2 environmental assessment	2007.6	#1-2 environmental assessment	2008	#1-5 building stock	5.3%
			#2 heating and cooling			
1	#2-1 heat pump	2009.7	#2-1 heat pump	2011	#2-1 heat pump	23.1%
2	#2-2 green roof	2009.5	#2-2 green roof	2011	#2-2 green roof	20.0%
3	#2-4 CHP/CCHP	2009.3	#2-5 phase change material and heat storage	2011	#2-3 solar cooling	16.4%
4	#2-3 solar cooling	2008.8	#2-3 Solar cooling	2010	#2-4 CHP/CCHP	15.2%
5	#2-5 phase change material and heat storage	2008.7	#2-4 CHP/CCHP	2010	#2-5 phase change material and heat storage	12.9%

Table 1 Summary of academic paper clusters and sub-clusters (continued)

Rank	*Sorted by average year*		*Sorted by median year*		*Sorted by growth rate*	
	Cluster/ sub-cluster	*Year*	*Cluster/ sub-cluster*	*Year*	*Cluster/ sub-cluster*	*Rate*
	#3 energy efficiency of buildings					
1	#3-5 energy benchmarking	2009.2	#3-1 HVAC system	2010	#3-3 Lighting/daylighti ng	26.0%
2	#3-3 lighting/ daylighting	2008.3	#3-3 lighting/ daylighting	2010	#3-2 photovoltaic/ thermal solar system	22.8%
3	#3-2 photovoltaic/ thermal solar system	2008.2	#3-5 energy benchmarking	2010	#3-1 HVAC system	17.8%
4	#3-1 HVAC system	2008.1	#3-2 photovoltaic/ thermal solar system	2009.5	#3-4 smart window	15.4%
5	#3-4 smart window	2007.7	#3-4 smart window	2009	#3-5 energy benchmarking	2.9%
	#6 indoor air and lighting					
1	#6-4 daylighting	2009.1	#6-4 daylighting	2011	#6-4 daylighting	26.0%
2	#6-5 indoor air quality	2008.7	#6-5 Indoor air quality	2010.5	#6-5 Indoor air quality	21.6%
3	#6-2 air pollutant	2006.5	#6-2 air pollutant	2007	#6-2 air pollutant	3.6%
4	#6-1 indoor air quality and health	2005.5	#6-3 volatile organic compound	2007	#6-3 volatile organic compound	0%
5	#6-3 volatile organic compound	2004.7	#6-1 indoor air quality and health	2006.5	#6-1 indoor air quality and health	–6.5%

From the academic landscape, it can be seen that various aspects of green buildings are being researched, covering energy analysis, energy systems, innovative technologies as well as quality of the environment in a building. Building assessment systems and environmental assessment tools are extensively studied such as the life cycle analysis, which is a technique to assess environmental impacts associated with all the stages of a product's life from cradle-to-grave, has been widely applied to buildings in terms of primary energy use and CO2 emission of buildings (Gustavsson and Joelsson, 2010).

Since cooling and heating constitutes the largest portion of energy consumption in buildings, many studies are dedicated to the thermal design aspects of buildings. In the recent years, exergy, which is related to the concept of quality of energy, has been rediscovered and consistently applied to new scenarios for energy supply both at building and community levels alongside with energy analysis in order to find the most rational use of energy (Torío et al., 2009). Similarly, geothermal or ground-source heat pumps (GSHPs) are also receiving increasing interest as a highly effectual, renewable energy technology for space heating and cooling. A geothermal heat pump can transfer heat stored underground into a building during the winter, and transfer heat out of the building during the summer. Initially, these systems were mostly installed in rural, residential applications where heating requirements were the prime consideration. However, recent improvements in heat pumps units and installation procedures have stretched the market to urban and commercial applications such as the vertical-borehole ground-coupled heat pump (GCHP) technology for applications in air-conditioning (Yang et al., 2010).

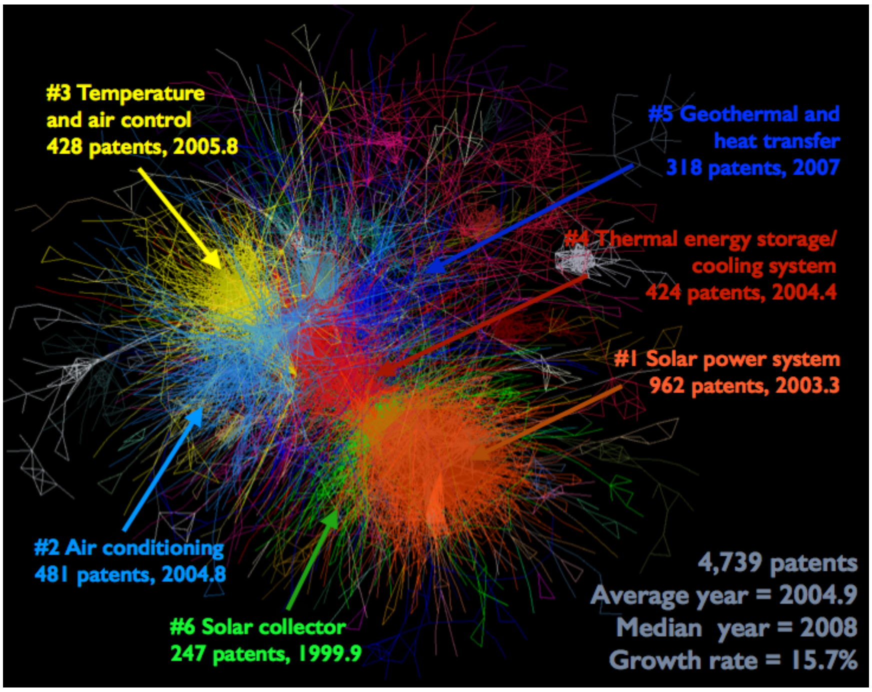
Another emerging research theme is the reduction of energy use for electric lighting through energy-efficient light fittings and lighting controls together with daylight harvesting. Some studies are related to the benefits of daylighting on humans and their preferred physical and luminous conditions in daylit building environments, while others discuss the techniques to maximise daylighting in building designs such as the utilisation of controllable glazing's transmittance to optimise daylighting and building's energy efficiency (Kim and Todorovic, 2013; Galasiu and Veitch, 2006).

Extracting specific keywords from the sub-cluster analysis presented a good overview of the range of topics that are being researched and are gaining attention in the domain of green buildings. Subsequently, these keywords were then used as inputs for patents search where two IPC's were chosen to cover the identified keywords. The two IPC's used were F24 and F25, which are related to HEATING; RANGES; VENTILATING and REFRIGERATION MACHINES, PLANTS, OR SYSTEMS; COMBINED HEATING and REFRIGERATION SYSTEMS; HEAT PUMP SYSTEMS, respectively. The search query was further refined by specifying 'energy AND efficien*' in the text fields.

3.2 Results of analysis from the technology layer

The search query for patents returned 24,643 patents and after the network structuring process 4,739 nodes were included in the technology landscape as displayed in Figure 3.

Figure 3 Technology landscape of patent data. the name of each cluster, average year and number of papers in each cluster are mentioned (see online version for colours)



The biggest cluster (cluster #1) of patents is related to solar power system such as the solar tracking technology and it is positioned closely to cluster #6 which deals with the solar collector technology. Clusters #2, #3, #4 and #5 are fairly bunched together and they are associated with air conditioning, temperature and air control, thermal energy storage/cooling system and geothermal and heat transfer technologies respectively.

Table 2 Summary of patent clusters and sub-clusters

Rank	*Sorted by average year*		*Sorted by median year*		*Sorted by growth rate*	
	Cluster/ sub-cluster	*Year*	*Cluster/ sub-cluster*	*Year*	*Cluster/ sub-cluster*	*Rate*
1	#5 geothermal and heat transfer	2007.0	#1 solar power system	2009	#4 thermal energy storage/cooling system	24.8%
2	#3 temperature and air control	2005.8	#5 geothermal and heat transfer	2009	#3 temperature and air control	23.1%
3	#2 air-conditioning	2004.8	#2 air-conditioning	2008	#6 solar collector	22.1%
4	#4 thermal energy storage/cooling system	2004.4	#3 temperature and air control	2008	#1 solar power system	19.2%
5	#1 solar power system	2003.3	#4 thermal energy storage/cooling system	2008	#2 air-conditioning	1.1%
			#1 solar power system			
1	#1-1 solar tracking	2007.1	#1-1 solar tracking	2010	#1-1 solar tracking	24.1%
2	#1-5 solar energy system	2004.6	#1-5 solar energy system	2009	#1-4 solar energy focusing lens	21.3%
3	#1-2 solar capturing	2004.5	#1-2 solar capturing	2008	#1-5 solar energy system	11.4%
4	#1-4 solar energy focusing lens	2000.0	#1-4 solar energy focusing lens	2005	#1-2 solar capturing	10.1%
5	#1-3 thermal transfer	1996.0	#1-3 thermal transfer	2001	#1-3 thermal transfer	4.3%
			#2 air-conditioning			
1	#2-3 heat pump	2006.2	#2-2 dehumidifier	2008	#2-1 desiccant dehumidifying system	39.5%
2	#2-2 dehumidifier	2004.8	#2-3 heat pump	2008	#2-5 evaporative air	31.0%
3	#2-5 evaporative air	2004.2	#2-5 evaporative air	2007	#2-2 dehumidifier	2.9%
4	#2-4 reheater	2004.1	#2-4 reheater	2006.5	#2-3 heat pump	–15.7%
5	#2-1 desiccant dehumidifying system	2001.4	#2-1 desiccant dehumidifying system	2003	#2-4 reheater	–28.6%

Table 2 Summary of patent clusters and sub-clusters (continued)

Rank	*Sorted by average year*		*Sorted by median year*		*Sorted by growth rate*	
	Cluster/ sub-cluster	*Year*	*Cluster/ sub-cluster*	*Year*	*Cluster/ sub-cluster*	*Rate*
#3 temperature and air control						
1	#3-4 data centre	2008.7	#3-1 Energy utilisation control	2010	#3-1 energy utilisation control	64.2%
2	#3-1 energy utilisation control	2008.6	#3-4 data centre	2010	#3-5 air supply control	38.7%
3	#3-2 chiller	2006.7	#3-2 chiller	2009	#3-2 chiller	33.2%
4	#3-5 air supply control	2003.3	#3-3 sensor and thermostat	2005.5	#3-4 data centre	19.4%
5	#3-3 sensor and thermostat	2002.8	#3-5 air supply control	2004.5	#3-3 sensor and thermostat	17.0%
#4 thermal energy storage/cooling system						
1	#4-4 refrigerant	2007.8	#4-1 solar air conditioning system	2008	#4-5 thermal energy storage/ cooling system	71.0%
2	#4-5 thermal energy storage/ cooling system	2006.3	#4-3 solar-powered refrigeration system	2008	#4-1 solar air conditioning system	28.3%
3	#4-3 solar-powered refrigeration system	2005.3	#4-4 refrigerant	2008	#4-4 refrigerant	22.4%
4	#4-2 hot water and heat pump	2005.1	#4-5 thermal energy storage/cooling system	2007.5	#4-2 hot water and heat pump	22.1%
5	#4-1 solar air conditioning system	2002.4	#4-2 hot water and heat pump	2007	#4-3 solar-powered refrigeration system	14.5%
#5 geothermal and heat transfer						
1	#5-3 energy storage system	2007.6	#5-1 hybrid thermal energy system	2009	#5-4 solar and geothermal heat pump	26.0%
2	#5-4 solar and geothermal heat pump	2006.5	#5-3 energy storage system	2009	#5-2 heat exchanger	16.3%
3	#5-1 hybrid thermal energy system	2006.0	#5-5 geothermal energy extraction	2009	#5-3 energy storage system	4.6%
4	#5-5 geothermal energy extraction	2004.8	#5-2 heat exchanger	2008	#5-1 hybrid thermal energy system	–2.9%
5	#5-2 heat exchanger	2004.3	#5-4 solar and geothermal heat pump	2008	#5-5 geothermal energy extraction	–14.5%

Table 2 Summary of patent clusters and sub-clusters (continued)

Rank	*Sorted by average year*		*Sorted by median year*		*Sorted by growth rate*	
	Cluster/ sub-cluster	*Year*	*Cluster/ sub-cluster*	*Year*	*Cluster/ sub-cluster*	*Rate*
			#6 solar collector			
1	#6-3 roof-type solar collector	2008.2	#6-3 roof-type solar collector	2010	#6-3 roof-type solar collector	58.7%
2	#6-1 solar air conditioning devices	2001.2	#6-2 solar energy collector	2008	#6-4 solar collector configuration	58.7%
3	#6-2 solar energy collector	1998.6	#6-1 solar air conditioning devices	2006	#6-5 solar air heater material	58.7%
4	#6-4 solar collector configuration	1991.7	#6-5 solar air heater material	1987	#6-1 solar air conditioning devices	21.6%
5	#6-5 solar air heater material	1990.2	#6-4 solar collector configuration	1984	#6-2 solar energy collector	–10.6%

Recursive sub-clustering is performed on the patent clusters and ranking of sub-clusters are shown in Table 2. Hot areas of technologies detected with growth rate are solar tracking (#1-1), desiccant dehumidifying system (#2-1), energy utilisation control (#3-1), thermal energy storage/cooling system (#4-5), solar and geothermal heat pump (#5-4), roof-type solar collector (#6-3), solar collector configuration (#6-4), and Solar air heater material (#6-5).

Development in solar tracking technology ranges from the advancement of the heliostat orientation controlling method for use in solar power plant to solar tracking sensors and sunlight collecting devices. Recent patents on a desiccant dehumidifier used in heating, ventilating, and air-conditioning systems are also observed. In the area of temperature and air control, progresses are made in the field of heating, ventilation and air conditioning (HVAC) data processing and communication network to facilitate system control and performance evaluation. Energy storage system is also receiving much attention, as it is usually required with renewable energy systems. Examples of development in this field include study of refrigerant-based thermal energy storage/cooling system for use in commercial building and thermoelectric energy storage system. Last but not least, innovative features of a roof-type solar collector include the ice/snow-defrosting device for removing accumulated snow in winter. Materials such as inorganic oxide-coated plastic films with various designs are also being incorporated into the development of solar collectors and solar air heater.

3.3 Results from heat maps

In this paper, cosine similarities were calculated and represented graphically by a matrix called a heat map. Rows and columns in the heat map correspond to clusters of academic papers and patents respectively. They are arranged so that the clusters with the highest growth rates are positioned towards the top left corner. The gradient of each cell in the heat map signifies the level of relatedness between each pair of cluster where red and green indicate high and low relatedness respectively. Since cosine similarities are based on shared content or the keywords in each cluster, the higher the number of common keywords clusters has, the more similar they are. A high similarity between a pair of paper and patent clusters implies that there has been or will be some transfer of knowledge from the academia to the market, transforming research into industrial applications. Simultaneous utilisation of similarity and growth rate analysis can provide useful information about the technologies as can be suggested in Figure 4. In this paper, relevant and emerging technology is the main focus for indentifying a potential solution to the pressing energy issue in Thailand.

Figure 4 Four quadrants of the heat map where red and green indicate high and low relatedness respectively (see online version for colours)

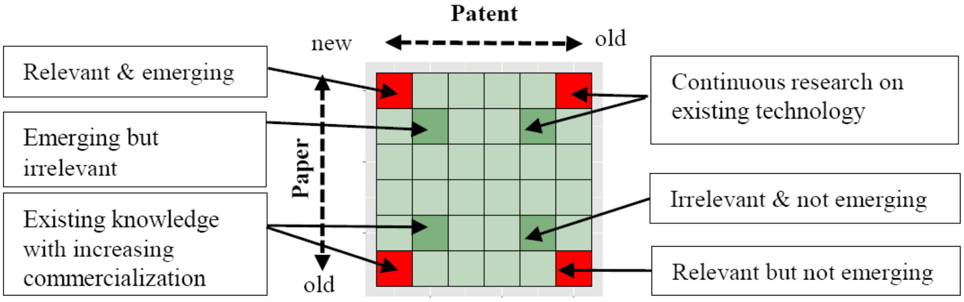
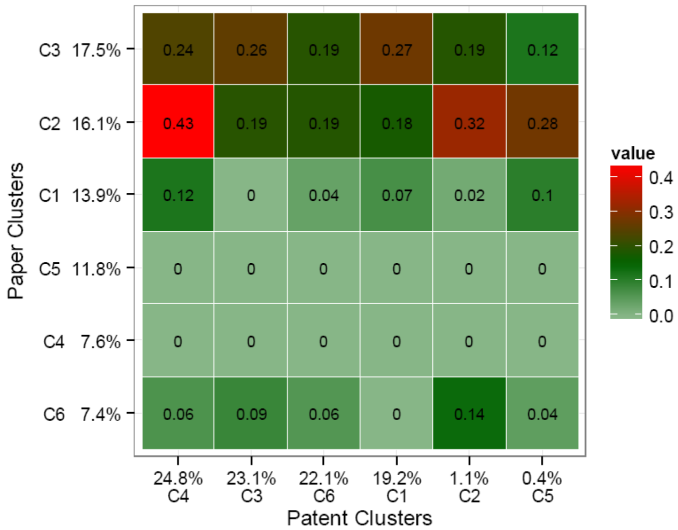


Figure 5 Similarity heat map of clusters of papers and patents where percent values indicate the growth rate of each cluster (see online version for colours)



The heat map of paper and patent clusters is shown in Figure 5 considering only the top six clusters and results are summarised in Table 3. Percent numbers indicate the growth rate of each cluster. The area with the highest similarity belongs to cluster #2 (heating and cooling) of academic papers and cluster #4 (thermal energy storage/cooling system) of patents. Both clusters also exhibit relatively high growth rate indicating their emergence. Subsequently, in order to understand why these two clusters exhibit such high similarity compared to rest of the clusters, a similarity analysis was repeated for papers in cluster #2 and patents in cluster #4 as shown in Figure 6 and Table 4.

Table 3 Summary of similarities between clusters of papers and patents

Similarities	*Paper cluster and keywords*	*Patent cluster and keywords*
0.4318	#2 heat, cooling, thermal	#4 water, refrigerant, hot water
0.3202	#2 heat, cooling, thermal	#2 air, desiccant, cooling
0.2753	#2 heat, cooling, thermal	#5 geothermal, probe, geothermal energy
0.2721	#3 chiller, solar, thermal	#1 solar, solar energy, collector

Table 4 Summary of similarities between sub-clusters of papers and patents

Similarities	*Paper sub-cluster and keywords*	*Patent sub-cluster and keywords*
0.3330	#2-3 cooling, solar, cooling system	#4-1 water, fluid, solar
0.3270	#2-1 exergy, heat pump, pump	#4-1 water, fluid, solar
0.1720	#2-1 exergy, heat pump, pump	#4-2 water, hot water, water supply
0.1679	#2-1 exergy, heat pump, pump	#4-4 valve, refrigeration, refrigerant

Among the pair of top five sub-clusters, paper sub-cluster #2-3 and patent sub-cluster #4-1 exhibit the highest similarity. Moreover, they also exhibit reasonably high activity and recent growth in the number of publications and patents.

Paper sub-cluster #2-3 contains 214 papers with the average year of publications of 2008.8. The keywords for this cluster are cooling, solar, cooling system, collector and desiccant. Hub papers that have the highest within-cluster citations are 'Solar air conditioning in Europe – an overview' (Balaras et al., 2007), "a review for research and new design options of solar absorption cooling systems" (Zhai et al., 2011) and "energy and economic analysis of an integrated solar absorption cooling and heating" (Mateus and Oliveira, 2009). After analysing the contents of papers in the clusters, it can be derived that the papers in this sub-cluster are related to solar cooling systems, solar sorption/absorption cooling systems, solar refrigeration systems and solar integrated energy systems. The countries with the largest number of publications are China, Italy, USA, Spain and France, respectively. This result agrees with the fact that most of solar cooling related research is being carried out all around the world and intensely in those countries. The Engineering Research Center of Solar Power and Refrigeration funded by China's Ministry of Education is devoted to developing new technologies on solar energy utilisation together with low-grade thermal energy harvesting such as solar air conditioning systems and comprehensive use of solar energy in energy conservation of buildings. On the other hand, the Solar Air Conditioning in Europe (SACE) project and Promoting Solar Air-Conditioning (CLIMASOL) project are examples of collaborative research efforts in Europe on solar air conditioning (Balaras et al., 2007). The research of solar heating and cooling has long gained attention on a global scale as can be reflected by the International Energy Agency's Solar Heating and Cooling (SHC) Programme which was established since 1977. The project's work is accomplished through the international collaborative effort of experts from member countries and the European Union. Clearly, public funded projects have a prominent impact on academic publications in this field.

Patent sub-cluster #4-1 contains 145 patents with the average year of publications of 2002.4. Keywords related to this sub-cluster are water, fluid, solar, hot water and pump. Analysis of the contents of the patents revealed that are applications for solar cooling components, heat pump systems, solar air conditioning systems, water heater apparatus, hybrid heating and cooling systems for building. USA, China, Germany and France represent the countries with highest number of patents respectively. The high industrial activities in the field of solar cooling in the USA can be partly demonstrated by the presence of the Solar Energy Industries Association (SEIA) established in 1974 as the national non-profit trade association of the US solar energy industry.

After examining the paper sub-cluster #2-3 and patent sub-cluster #4-1, it can be concluded that the two sub-clusters are both related to the technology of solar cooling which represent a promising area not only from the academic perspective but also from the industrial perspective as well. High transfer of knowledge from research to industrial applications suggests that there is a high possibility of realising this technology for real market applications.

4 Discussion

4.1 Policy implications

Solar cooling was identified from the similarities analysis of academic publications and patents as one of the promising technologies for real applications from both the scientific and technological point of views. Its characteristics and prospects need to be further investigate explicitly to confirm its suitability with the circumstances and features of targeted country in this study. Solar cooling or solar air conditioning can be accomplished using thermally activated cooling systems (TACS) driven by solar thermal energy. The system is particularly attractive for tropical countries with abundant sunlight and where air conditioning is required all year round. The two most widely used types are solar absorption systems and solar desiccant systems (Solar Energy Industries Association, 2013). Solar cooling offers various advantages over the conventional electric air conditioning since it utilises the solar energy, it saves electricity and hence primary fossil fuels cutting down drastically on greenhouse gas (GHG) emissions. It is also energy efficient since the cooling load coincides generally with solar energy availability and therefore cooling requirements of a building are approximately in phase with the solar incidence. Employing solar cooling can also helps to ease the load during peak electricity demand benefitting the electricity network and could lead to electricity cost savings. In addition, solar cooling technologies are environmentally safe, employing absolutely harmless working fluids such as water or solutions of certain salts. In terms of installation, solar cooling systems can be easily implemented, either as stand-alone systems or with conventional air conditioning, to improve the indoor air quality of all types of buildings.

Despite the fact that there is a large potential market for solar cooling technology especially in countries with abundant sun exposure, the existing solar cooling systems are not yet economically competitive with the conventional HVAC systems due to high initial investment cost of solar cooling systems and the cheap prices of conventional fuels. Continual efforts to bring down the cost of solar cooling components as well as improving their performance will alter the situation radically. Means and supporting measures are necessary in order to make solar cooling more feasible and accelerate market deployment.

4.2 Methodological issues

We have successfully utilised the extended method of Shibata et al. (2011) and applied it to an area which has not been previously explored: green buildings. The contribution of the present paper beyond exploring a new area is two-fold. First, unlike the previous analyses, we applied the keywords extracted from the paper corpus to search for patents, thereby explicitly coupling the two phases. Our results show that this method allows us to identify the relevant research fronts. Second, we assessed three metrics in identifying emerging technologies, and demonstrated that the growth rate is a reasonable choice.

Although our method yielded useful insights efficiently and swiftly, limitations' of the present method abound. Obviously there is no single, best technique to find emerging technologies, and understanding the deficiencies of our method enables for properly combining the proposed method with other (e.g., expert-based) approaches.

Firstly, there is a time lag before academic findings or technological outcomes can be published to the public. Moreover, it can take up to two years before a paper/patent receives citations from other papers/patents. There are also limited citations between patents reducing the effectiveness of the network structuring process in capturing the characteristics of the knowledge structure. Integrating the technique of text-mining could be a novel way of tracking emerging patents.

Secondly, our corpus was retrieved from the database via search queries. Some irrelevant data were present but we manually excluded them based on their contents and their segregated locations in the visualised knowledge landscape. At the same time, the search queries used may not have yielded all the related papers that should essentially be included in our analysis.

Thirdly, citation network analysis is based on the clustering technique to identify technologies. This approach possesses a probability of missing isolated papers, meaning that we disregard plausible promising technologies until they have accumulated enough citations and bundle together into a coherent network. Non-cited influential papers and publications such as non-English papers, conference proceedings, technical reports, textbooks and data sheets were also not taken into account in our analysis. Incorporating a text-based approach, experts' insights and a thorough selection of the corpus may assist to overcome such a limitation.

Fourthly, different indicators of technology emergence are available and the selection can be subjective. In this paper, the growth rate of publications and patents are used to identify emerging technologies but results may vary with other indicators.

Lastly, although the outputs of our method suggest certain promising technologies with potential for future industrialisation, there is no definite assurance of success. The results should be further studied extensively to assess the feasibility and suitable for each country's context.

5 Concluding remarks

Recently, the topics of energy efficiency, energy security and environmental problems related to the use of conventional fuel sources have become the primary concerns of policy makers worldwide. Thailand is no exception; its energy security is being threatened by its dependency on fossil fuels. Energy used in buildings, especially for hot climate countries, where air-conditioning is indispensable, made up the biggest share of electricity consumers, and therefore represents a sector with a significant potential for improvement.

In this work, citation-network analysis was employed in order to detect emerging research fronts and technologies in the domain of green buildings as well as to study the characteristics of the knowledge structures. Databases of academic papers and patents were utilised and an analysis of similarities between the two domains suggests areas with high transfer of knowledge from the academia to the industry and a substantial prospect of realising the technology. Our results indicated that solar cooling is one of the promising technologies for buildings efficiency improvement. The benefits and features of solar cooling systems also closely fit the energy situation in tropical countries like Thailand.

It is hoped that the method proposed in this paper would be a useful tool for policy makers to assist them in their initial stage of research and identification of prospective alternatives.

Acknowledgements

Part of this paper has been presented and published as conference proceedings of the Portland International Center for Management of Engineering and Technology (PICMET) 2014 Conference in Kanazawa, Japan.

References

Adai, A.T. et al. (2004) 'LGL: creating a map of protein function with an algorithm for visualizing very large biological networks', *Journal of Molecular Biology*, Vol. 340, No. 1, pp.179–90.

Balaras, C.A. et al. (2007) 'Solar air conditioning in Europe – an overview', *Renewable and Sustainable Energy Reviews*, Vol. 11, No. 2, pp.299–314.

Cozzens, S. et al. (2010) 'Technology analysis & strategic management emerging technologies: quantitative identification and measurement', *Technology Analysis & Strategic Management*, Vol. 22, No. 3, pp.361–376.

Day, G.S. and Schoemaker, P.J.H. (2000) 'A different game', in Day, G.S. and Schoemaker, P.J.H. (Eds.): *Wharton on Managing Emerging Technologies*, pp.1–23, John-Wiley, New York.

Department of Alternative Energy Development and Efficiency (2013) *Energy in Thailand: Facts & Figures Q1-Q2/2013*, DEDE, Bangkok [online] http://www.dede.go.th/dede/index.php?option=com_content&view=article&id=11667%3Aenergy-in-thailand-facts-a-figures-q1-q2 2013preliminary&catid=146%3Ahot-issue&lang=en (accessed 11 October 2013).

Galasiu, A.D. and Veitch, J.A. (2006) 'Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review', *Energy and Buildings*, Vol. 38, No. 7, pp.728–742.

Gustavsson, L. and Joelsson, A. (2010) 'Life cycle primary energy analysis of residential buildings', *Energy and Buildings*, Vol. 42, No. 2, pp.210–220.

International Energy Agency (2013) *Southeast Asia Energy Outlook*, Paris [online] http://www.iea.org/publications/freepublications/publication/SoutheastAsiaEnergyOutlook_WEO2013SpecialReport.pdf (accessed 10 December 2013).

Ittipanuvat, V. et al. (2014) 'Finding linkage between technology and social issue: a literature based discovery approach', *Journal of Engineering and Technology Management*, April–June, Vol. 32, pp.160–184, doi:10.1016/j.jengtecman.2013.05.006.

Kajikawa, Y. et al. (2007) 'Creating an academic landscape of sustainability science: an analysis of the citation network', *Sustainability Science*, Vol. 2, No. 2, pp.221–231.

Kajikawa, Y., Yoshikawa, J., Takeda, Y. and Matsushima, K. (2008) 'Tracking emerging technologies in energy research: toward a roadmap for sustainable energy', *Technological Forecasting and Social Change*, July, Vol. 75, No. 6, pp.771–782, doi:10.1016/j.techfore. 2007.05.005.

Kim, J.T. and Todorovic, M.S. (2013) 'Tuning control of buildings glazing's transmittance dependence on the solar radiation wavelength to optimize daylighting and building's energy efficiency', *Energy and Buildings*, August, Vol. 63, pp.108–118 [online] http://www. sciencedirect.com/science/article/pii/S0378778813002041.

Mateus, T. and Oliveira, A.C. (2009) 'Energy and economic analysis of an integrated solar absorption cooling and heating system in different building types and climates', *Applied Energy*, Vol. 86, No. 6, pp.949–957.

Newman, M.E.J. (2004) 'Fast algorithm for detecting community structure in networks', *Phys. Rev. E*, Vol. 69, No. 6, p.066133.

Pongtornkulpanich, A. et al. (2008) 'Experience with fully operational solar-driven 10-ton LiBr/H2O single-effect absorption cooling system in Thailand'. *Renewable Energy*, Vol. 33, No. 5, pp.943–949.

Shibata, N. et al. (2009) 'Comparative study on methods of detecting research fronts using different types of citation', *Journal of the American Society for Information Science and Technology*, Vol. 60, No. 1971, pp.571–580.

Shibata, N. et al. (2011) 'Detecting emerging research fronts in regenerative medicine by the citation network analysis of scientific publications', *Technological Forecasting and Social Change*, Vol. 78, No. 2, pp.274–282.

Shibata, N., Kajikawa, Y. and Sakata, I. (2010) 'Extracting the commercialization gap between science and technology – case study of a solar cell', *Technological Forecasting and Social Change*, Vol. 77, No. 7, pp.1147–1155.

Solar Energy Industries Association (2013) *Solar Heating & Cooling: Energy for a Secure Future*, Washington, DC [online] http://www.seia.org/research-resources/solar-heating-cooling-energysecure- future (accessed 1 January 2014).

Torío, H., Angelotti, A. and Schmidt, D. (2009) 'Exergy analysis of renewable energy-based climatisation systems for buildings: a critical view', *Energy and Buildings*, Vol. 41, No. 3, pp.248–271.

Yang, H., Cui, P. and Fang, Z. (2010) 'Vertical-borehole ground-coupled heat pumps: a review of models and systems', *Applied Energy*, Vol. 87, No. 1, pp.16–27.

Zhai, X.Q. et al. (2011) 'A review for research and new design options of solar absorption cooling systems', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 9, pp.4416–4423.

Patent-based technology forecasting: case of electric and hydrogen vehicle

Samira Ranaei* and Matti Karvonen

LUT School of Business and Management,
Lappeenranta University of Technology,
FI-53851 Lappeenranta, Finland
Email: samira.ranaei@lut.fi
Email: matti.karvonen@lut.fi
*Corresponding author

Arho Suominen

VTT Technical Research Center of Finland,
FI-02044 VTT Espoo, Finland
Email: arho.suominen@vtt.fi

Tuomo Kässi

LUT School of Business and Management,
Lappeenranta University of Technology,
FI-53851 Lappeenranta, Finland
Email: tuomo.kassi@lut.fi

Abstract: The purpose of this paper is to study the evolution of emerging technological paths in the automotive industry. Worldwide patent data from the years 1990–2010 was collected and utilised to define the technological life cycles of the electric and fuel cell vehicle technologies. The novelty of our study is practicing the patent analysis approach using text mining techniques to collect patents according to their concepts in the automotive industry. The patent analysis results are compared to existing literature and expert opinion studies in alternative fuel vehicles field. The findings suggest that the development of electric vehicles will be quicker with a higher R&D share, compared to hydrogen vehicles. By gathering data and insights, the paper also offers general views on future automotive technology trajectories.

Keywords: technology forecasting; patent analysis; text mining; technology life cycle; electric vehicle; hydrogen vehicle; zero emission vehicle.

Reference to this paper should be made as follows: Ranaei, S., Karvonen, M., Suominen, A. and Kässi, T. (2016) 'Patent-based technology forecasting: case of electric and hydrogen vehicle', *Int. J. Energy Technology and Policy*, Vol. 12, No. 1, pp.20–40.

Biographical notes: Samira Ranaei works as a doctoral student in the School of Business and Management at Lappeenranta University of Technology. She received her Master's in Innovation Management from Lappeenranta

University of Technology in 2013. Her research interests are in innovation and technology forecasting, technology management and patent analysis techniques.

Matti Karvonen is a Post-doctoral Researcher in the School of Business and Management at Lappeenranta University of Technology. He received his master's degree from Joensuu University in 1999 and Lappeenranta University of Technology in 2004, followed by the doctoral degree from Lappeenranta University of Technology in 2011. His research interests are in intellectual property management, industry evolution, convergence, and patent analysis methods.

Arho Suominen received his doctoral degree from University of Turku, Finland. Suominen had previously received his MSc and BSc from the University of Turku and also holds a degree from the National Defense University. His research interests include technology foresight, research policy and technology management. Currently, he holds the position of Senior Scientist at the Innovation and Knowledge Economy unit at the VTT Technical Research Centre of Finland, while also lecturing at the Department of Information Technology at the University of Turku.

Tuomo Kässi is a Professor Emeritus of the school of Business and Management at Lappeenranta University of Technology. He has an MSc in Technical Physics and in Economics. He wrote his doctoral thesis in Industrial Engineering and Management. He has worked in research and development, and sales and marketing; and as the director of machinery production and a consultant in industry some 25 years before entering his academic career. His research interests are in technology management, innovation and strategy.

This paper is a revised and expanded version of a paper entitled 'Forecasting emerging technologies of low emission vehicle' presented at PICMET Conference, Kanazawa, Japan,27 July 2014.

1 Introduction

The transition towards sustainable transportation options is a response to increasing environmental regulations (Nieuwenhuis and Wells, 1997), the depletion of fossil fuels and climate change. So far the technological limitations, high costs and risks have kept the automotive industry focused on incremental innovations rather than propel it into a radical shift to alternative engine technologies. Currently, the internal combustion engine (ICE) and its more environmentally friendly version, hybrid electric vehicles (HEVs) are the dominant components of unsustainability in today's car industry. Two competing solutions are primarily working towards a sustainable option, the electric vehicle (EV) and hydrogen vehicle (HV). These vehicles are called zero-emission vehicles (ZEVs), because they have no local exhaust pipe emissions. EV and HV contain a full or partial electric engine and subsystem technologies that are different from the ICE. Both technological variety and organisational competition in these alternative vehicle technologies have been increased over the last years (Oltra and Saint Jean, 2009b).

There are several challenges on the path towards ZEVs. There is a lack of infrastructure or alternative fuel production systems, known as the chicken or the egg problem (Browne et al., 2012). The technological transition is a radical shift for the automotive industry, and the transition requires great investments (Utterback, 1996; Christensen, 1997). In addition, the growing awareness of environmental issues together with concerns about competitiveness have created considerable interest in research of advanced technologies for highly efficient ICE (Berggren and Magnusson, 2012; Oltra and Saint Jean, 2009a). Also, the development trend of EVs and HVs have been characterised as a hype, which was attributed to the high optimism period of their commercialisation followed by the disappointment of customers and stakeholders, specifically in the case of fuel cells (Suominen et al., 2011). It remains unclear what the dominant design of sustainable automotive transportation will be.

Recent research shows optimistic projections for the ZEV. The technologies are currently more expensive than conventional passenger cars, but projections suggest that they will become less costly thanks to technological learning (Weiss et al., 2012). The number of companies producing EV models has substantially increased (Sierzchula et al., 2012). HV development shows a promising future as well. Despite the 'hydrogen hype' (Bakker, 2010b), which caused huge disappointment, recent research (Rizzi et al., 2014) shows that the interest in hydrogen technologies in the automotive industry has not decreased over time.

The aim of this paper is to analyse the development of the ZEV through patenting. Even though patents are a mere proxy for actual development, patenting behaviour in the automotive sector has been shown to reflect actual research and development efforts (van den Hoed, 2005). Our proxy analysis with patents draws from connecting patent classifications to ZEV technologies and using the identified patent classifications as a source for the patent sample, subsequently used to model the developments of ZEVs. The methodological novelty of the approach is circumventing the caveats of using international patent classification (IPC) as a sole basis for sample creation by classifying patents to relevant and non-relevant patents using text mining in automotive industry. The results of the modelling will be compared with existing literature and expert opinion studies to enrich the interpretation.

The remainder of this paper is structured as follows. In the next section we provide the theoretical background to the patent analysis approach and the peculiarity of alternative technology vehicles in the automotive industry. The methodology section presents our patent search strategy on collecting relevant patent data, and afterwards plotting patents with the life cycle approach. The result and discussion will be presented in the last sections.

2 Background

The basis of a patent analysis lies in understanding the managerial implications of the results. The managerial implications of patent analysis have been drawn from multiple bodies of literature, such as technological evolution (Abernathy and Utterback, 1978) and the resource-based view of the firm (Barney, 1991; Chen, 2011). Patent analysis implicitly creates a window to quantify the knowledge embedded in organisations. This study draws from the literature on technology cycles (Abernathy and Utterback, 1978), looking at the competence-destroying transformation in the automotive industry and subsequent changes in the knowledge transformations embedded in organisations.

Technological evolution is composed of three main phases (Anderson and Tushman, 1991; Tushman, 1997): firstly, technological discontinuities trigger the periods of technological and competitive ferment with many technology options and a lot of market uncertainty among producers and customers. Secondly, in the course of the evolution of a technology, an era of standardisation emerges, during which product design and market needs stabilise and a dominant design emerges. Thirdly, the emergence of a dominant design opens an evolutionary path based on incremental innovation activities, focusing on refining the existing design. Technological discontinuities have been normally viewed as a threat to industry incumbents (Tushman, 1997) where technologies are emergent and more radical in nature. In these circumstances entrants enjoy potential competitive advantage over incumbents. The described pattern repeats itself when a new technology with the potential to substitute the older one is introduced. Patent information can quantify the patterns of technological cycles, the introduction of a discontinuity and the subsequent emergence of a dominant design.

Considering patents as the source of information to learn about technological development has both benefits and pitfalls. The major benefit of patent data is its uniqueness, meaning that the information stored in patents may not be republished in non-patent literature like books or articles (Liebesny, 1974), and its rich technological information is accessible online with a long time series. On the other hand, patent counts analysis per se does not reflect variation in technological quality or the commercialisation of inventions (Verspagen, 2007).

Patent data remains a unique resource for the study of technical change (Griliches, 1990). It represents a valuable source of technical information that can be used to quantify the evolution of technologies over time (Daim et al., 2006). Patents can be used to measure the impact of R&D activities (Ernst, 1997), diffusion of technologies and technological trajectories (Liu and Shyu, 1997). Patent analysis can support the study of prioritisation of R&D programs (Jeon et al., 2011) and technological assessment of competitors (Narin et al., 1987).

In the automotive industry, patent analysis has been used to understand the technological transformation of alternative vehicle technologies (Pilkington, 2004; van den Hoed, 2007; Oltra and Saint Jean, 2009b; Frenken et al., 2004; Yang et al., 2013). A majority of the studies have applied conventional patent analysis strategies, using keywords and 'elementary measures' (Suominen, 2013). Recent studies have developed from the mere quantification of countries, authors or technologies and augmented the analysis with text mining (Yau et al., 2014).

The assumption in patent analysis with the text mining approach is that the high probability of occurrence of one specific term or phrase (combination of a few words) in a title or abstract of patent documents is a better indicator for its relevance to one technology area or industry. Traditional patent search queries were formed, for instance, 'electric' AND 'vehicle' in an attempt to search for EVs. These types of queries produce patents that can be related to any type of vehicle that uses electric current (Wesseling et al., 2014). Therefore, the high number of irrelevant patents reduces the reliability of the study results. On the other hand, considering the patents that represented a high rate of occurrence of the phrase 'electric' with 'brushless motor' and 'vehicle' somewhat convey the contextual meaning of the document which may be related to EVs. Another dominant patent search strategy is to use patent classification codes (e.g., IPC). However, they are considered too broad to be directly applied to a technology area of interest.

In the automotive industry, the development of emission-free vehicles is in the state of ferment (Pohl and Yarime, 2012; Sierzchula et al., 2012), associated with a high level of uncertainty about the evolution of alternative technology vehicles (Contestabile et al., 2011). The uncertainty related to the technology evolution and prospects can be reduced by understanding the technology cycles. Indicators such as patents, publications or citations have been introduced as a major asset in technology forecasting (Watts and Porter, 1997). Patent applications, particularly in the manufacturing sector such as the automotive industry, can be effectively utilised to forecast and scrutinise the trends of technological activities (Yoon, 2012).

While the technology evolution model of Abernathy and Utterback presents the three main technology cycles, Watts and Porter (1997) suggested a method known as the *technology life cycle* (TLC) that can identify the technology development stages. The TLC approach suggests a linear five-step development model identified by bibliometric methods. The five cycles, basic research, applied research, development, application and social impact can be plotted by the number of patents, scientific publications or daily news databases. Despite the criticism over the linearity of the model (Rosenberg, 1994), it remains a practical illustration of technological life cycles (Balconi et al., 2010).

The TLC model is based on the assumption of a sigmoid growth curve. It assumes that following basic research, applied research saturates through a sigmoid growth pattern for which a patent application serves as a proxy measure (the number of patent applications over time generally follows an S-shaped curve) (Ernst, 1997). The curve starts with a slow progress, followed by an exponential growth after which the technology reaches saturation. The stage of saturation, or maturity, implies that the technology maybe is in the process of being substituted by a new technology or a new generation of an existing technology. Extrapolating patent data with time series on a given technology at a given time using the S-shaped curve as a reference links patent data to the technology cycle. This straightforward analysis is not without caveats related to the nature of patent data (Watts and Porter 1997) and challenges related to the limits of the S-shaped growth model (Suominen and Seppänen 2014). By understanding the limitations, however, patent data can create a powerful managerial tool.

3 Research method

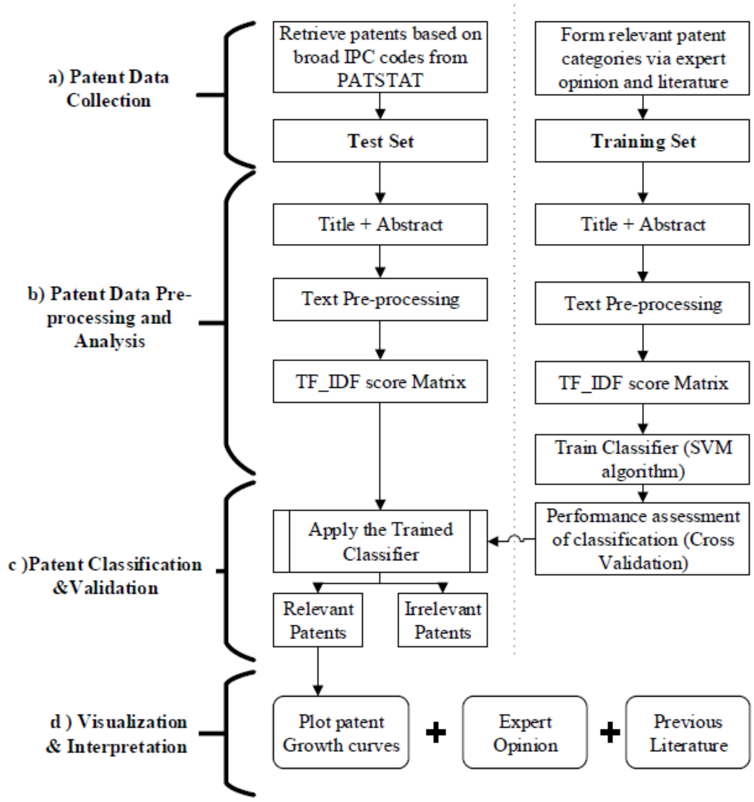
The research design is based on creating a patent data proxy for the technology cycle of ZEV technology and modelling the technological development to the future. The technological lifecycles of the EV and HV will be plotted based on the number of patents to illustrate the evolution of these alternative technologies in the automotive sector. As illustrated in Figure 1, our research process includes

a the collection of patent data from the European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT, 2013), supplemented with previous literature and expert opinions

b and c the application of text mining and machine learning algorithms to filter out patents irrelevant to the EV and HV from our sample

d the comparison of patent analysis results with expert opinion and existing literature on EV and HV development, to provide meaningful future projections.

Figure 1 Research process



The patent data is retrieved from the PATSTAT database and limited to a period from 1990 to 2010. The literature shows that the ZEV development intensified since 1990 (Kemp, 2005), which makes it a practical starting point. The years 2011 to 2013 are excluded due to the restrictions related to patent application becoming public. We did not use the patent family filter as emphasised by Wesseling et al. (2014) and Oltra and Saint Jean (2009a) as the same inventions registered in several countries shows their crucial value. Therefore, the high weight of one specific invention in our data set indicates its importance.

Pilkington et al. (2002) showed that analysis based on patent classification is of limited value in studying EVs. They investigated EV development by using the patent class search B60L11 resulting in a significant amount of irrelevant patents included in the sample. The IP classification includes a wide range of EVs, not just automobiles, and therefore the patents included within this classification relate to many other applications apart from EVs. Moreover, the ZEV consists of several components and emerging technologies that are not all categorised under one patent class and may be assigned in more than one class simultaneously.

The study by Pilkington et al. (2002) emphasises that a study should use clear boundaries between generic patents related to electric device technologies and automotive-oriented patents. This can be achieved by using an archive of reliable keywords (Rizzi et al., 2014; Frenken et al., 2004; Wesseling et al., 2014). However, the problem of keywords is the inconsistency of how terminologies are used by companies, researchers or attorneys. In addition, the database search is based on the match of exact wording; it is merely a means of finding phrases without contextual meanings. Also, being unfamiliar to the technology area, for which the patent data are being gathered, it would be quite difficult to build an exhaustive keyword list.

To improve the accuracy of the patent retrieval process, we adopted the patent analysis method using machine learning and text mining previously practiced on semi-conductor technology (Wu et al., 2010). The text-mining approach for patent analysis shown to be a practical technique in other technology areas (Tseng et al., 2007; Yoon and Park, 2004; Ranaei et al., 2014). The focus of these methods is on changing the unstructured part of patents (e.g., title, abstract), which contains valuable technical information, to structured data (numbers) to facilitate its analysis.

In this study RapidMiner software and its text-processing extension was used to classify documents and filter out irrelevant patent documents from the sample. The aim is to filter irrelevant patent documents, in respect to the EV and HV, from the large collection of patents listed under the vehicle section of IPC green inventory[1]. The green inventory is a list of patent classification developed by IPC committee experts to help users to retrieve information on environmentally sound technologies (ETS). The IPC green inventory, while significant, is not an exhaustive list of patents, and additional IPC classes relating to ultra-capacitor types, hydrogen storages or electric motors were added based on expert opinion. As a result, we formed the query (see Appendix A) based on a broad IPC collection on PATSTAT, which resulted in a sample of 174,188 patent documents (named as our test set in Figure 1).

To select the relevant patents to our target technology, the supervised learning process used requires a training set validated by experts. The training set contains the most relevant phrases and the relevancy of test set keywords will be assessed against them. To collect patent for the training set, another set of queries was structured based on IPCs and keywords (see Table 1). These phrases and patent classes were collected from a literature review (Rizzi et al., 2014; Chan, 2007; Ball and Wietschel, 2009; Bakker, 2010a; Chen et al., 2011; Sierzchula et al., 2012) and expert interviews.

Table 1 Technology options and key components of EV and HV

Vehicle technology alternatives			
EVs		*HVs*	
Propulsion motor	*Battery types*	*Conversion type*	*Storage options*
PM[a] synchronous or PM brushless motors	Lead acid	ICE	Gaseous hydrogen
Induction motor	Nickel base	PEM[b] fuel cell	Liquid hydrogen
Switched reluctance motors (SRM)	Lithium base		Metal hydrides
	Na-Nicim		On-board reforming
			Carbon material

Notes: [a]Permanent magnet
[b]Proton exchange membrane.

The sample retrieved for the training set was manually screened, reviewed and classified by experts. The process which took about five weeks, included several rounds of manual screening and interviews with experts. Then followed by the actual manual classification of relevant HV and EV patents by help of six experts. As a result, the EV training set includes 147 relevant and non-relevant patents where the relevant patents comprise a balanced selection of patents relevant to the key technologies of electric motors (brushless motor, induction motor, permanent magnet, etc.) and battery types (lithium and nickel based, lead acid, etc.), and the non-relevant class contains all other patents not related to the EV, like the ICE and fuel cell patents. A similar categorisation process was done to structure the HV training set of 193 relevant and non-relevant patents.

After creating the training and test sets, we conducted the patent classification process in four phases (Steps b and c in Figure 1). Firstly, text pre-processing was applied on the training set to reduce its complexity. The pre-processing methods used included stop-word filtering and n-gram identification. The data was thereafter tokenised and transformed using the TF-IDF[2] scheme. This process yields a matrix that reflects the keyword occurrence probability measure (Appendix B). Secondly, a support vector machine (SVM) classifier (Cortes and Vapnik, 1995) was selected to learn the TF-IDF scores of all true and false categories. For instance, considering the EV training set, the TF-IDF score of 'combustion engine' will be zero in the relevant category but higher in the non-relevant category. Therefore, the SVM classifier will label a patent document as irrelevant, if it indicates a high TF-IDF score for the phrase 'combustion engine'.

Thirdly, a cross-validation process was conducted using the training set to show the classification accuracy of the system. The classifier indicated 90.45% and 95% accuracy levels for the EV and HV, respectively. Fourthly, the text-processing step was replicated for the test set. The trained SVM was then applied to the TF-IDF matrix of our test set and the patents were classified into two categories. The final results labelled as relevant patent documents to the EV (16,595 docs) and HV (10,291 docs) were plotted on the growth curves. An overlap of about 0.04% was identified between the two categories, which is acceptable since we had small training sets and 5% classification errors.

Good forecasts usually draw upon a range of perspectives and methods (Porter et al., 2011). To achieve comprehensive interpretations we utilised patent analysis, growth curves, expert opinion and reviewing the literature on hydrogen and EV development (Step d in Figure 1). Regarding expert opinion, we kept in contact with the experts during the structuring of our patent classification system and used their comments for our result interpretation. Furthermore, the comparison between the patenting behaviour of the two green vehicle technologies was conducted based on previous literature on prototype and production analysis (Sierzchula et al., 2012), prototype and basic research (Sjoerd et al., 2012) and patents (Wesseling et al., 2014).

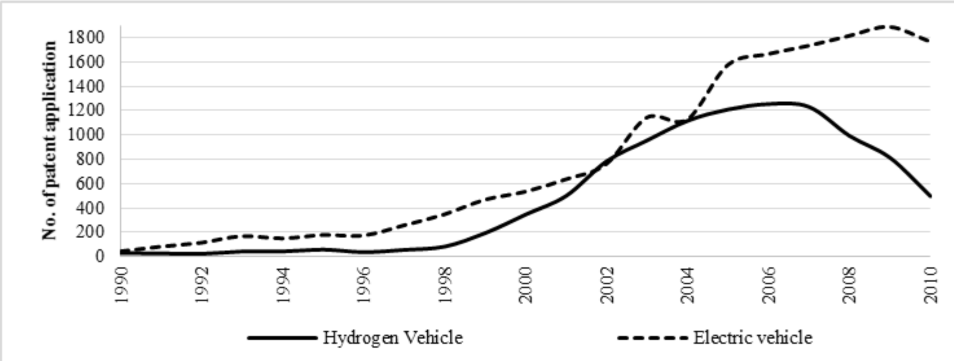
4 Results

In this section we present the main findings related to the patent trends, assignees contribution, analysis of new entrants per year and industry diversity of applicants.

4.1 Trend analysis: competition within and between trajectories

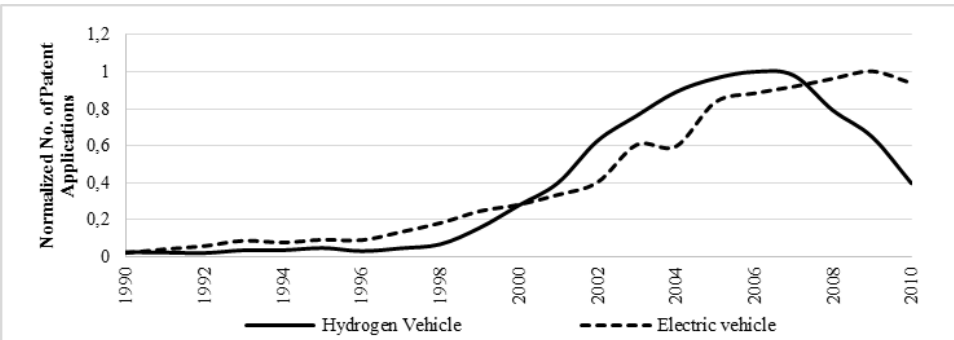
The relevant patent documents contained two main alternative technology categories, EVs and HVs using either the PEM[3] fuel cell or ICE as an energy conversion unit. The number of retrieved patents on the EV and HV, were 16,595 and 10,291, respectively, during a time period of 1990–2010.

Figure 2 The number of patent applications of EV and HV 1990–2010



Distribution by a patent publication year is an indicator that quantifies the intensity of R&D within a technology area. Based on Figure 2, it can be argued that both technology options have received increased attention after 1990, partly owing to the concerns over development of green technologies. The patent dynamic between the two alternative technology vehicles, confirms that EVs are attracting a larger share of green-oriented R&D in the automobile industry, also supported by the findings of Sierzchula et al. (2012).

Figure 3 Normalised number of patent applications of EV and HV 1990–2010



The periods of optimism and disappointment known as hype periods for hydrogen cars and EVs have affected the patenting behaviour. The changes in the patenting behaviour are more visible in the unit-normalised diagram, where both trends are illustrated on the same scale between zero to one (see Figure 3). What is evident from the unit-normalised number of patent activities is the three phases of attraction shift between the two vehicle alternatives. Previous studies of the EV and HV, based on other data sources like prototypes and magazine articles, illustrated a similar competition trend (Sjoerd et al., 2012).

Figure 4 Comparison of total assignees and new entrants of EV and HV

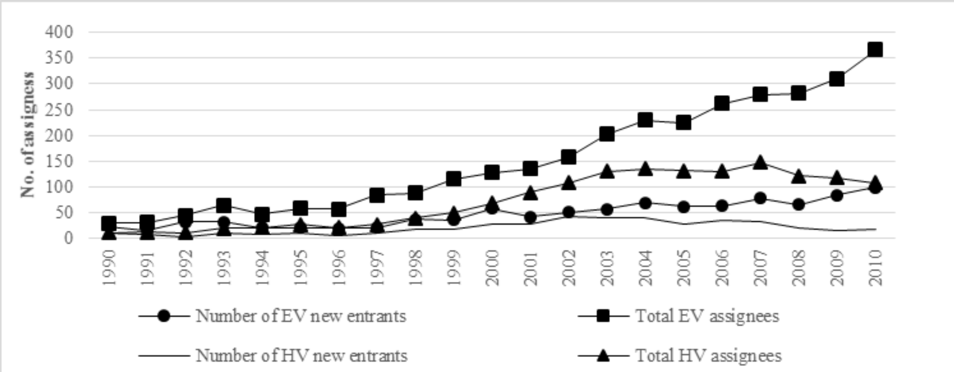
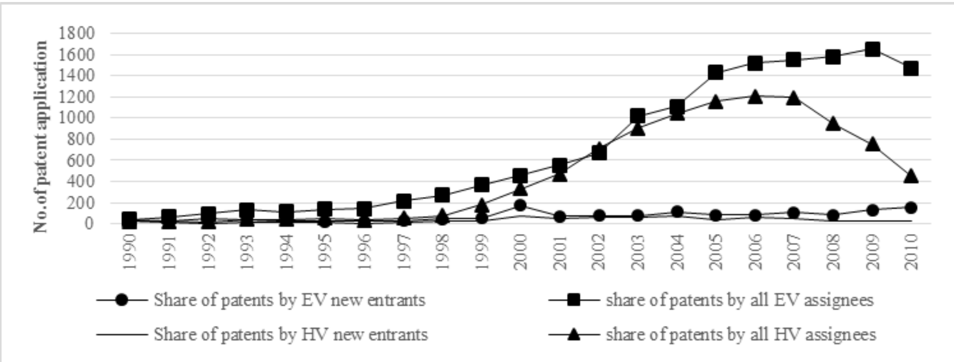


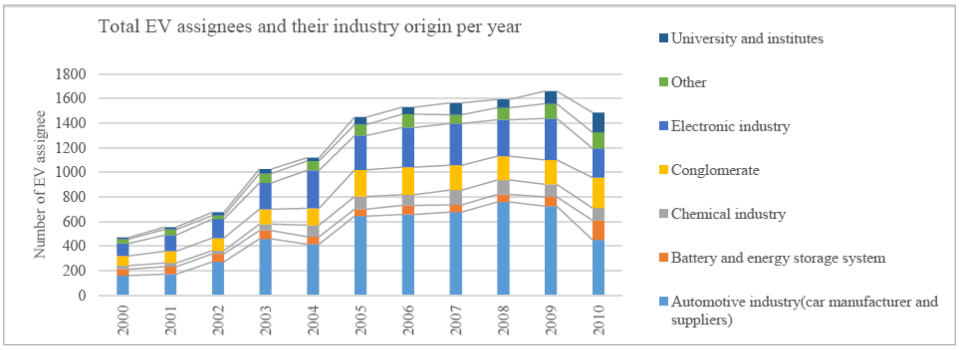
Figure 5 Comparison of patenting behaviour of assignees and new entrants of EV and HV



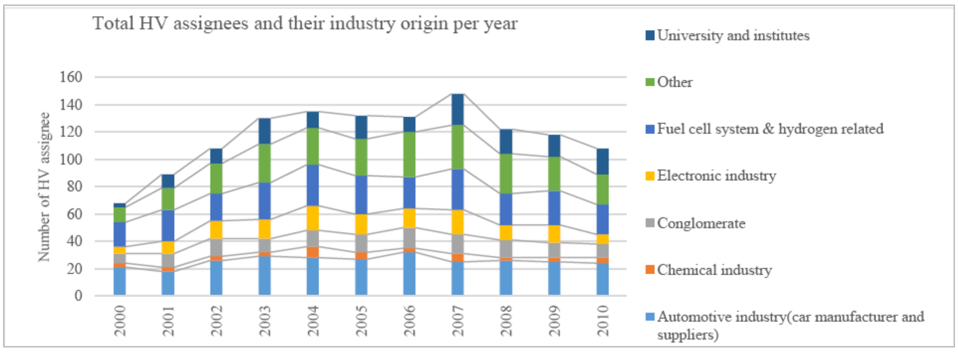
Following the innovation activities of two technology alternatives illustrated by previous diagrams, Figures 4 and 5 represent the proportion of existing patent applicants, rate of new entrants and their contributions to the development of HV and EV over the years. In this paper, the number new entrants are defined as new applicants in each year that have not been appeared in previous years (Suominen, 2013). To simplify the applicant analysis on our large data sets, individual assignees and those firms with less than five patents are excluded. Figure 4 exhibits higher number of industry players and new entrants for EV comparing to HV. Similarly in Figure 5, the proportion of EV patents from both existing applicants and new comers exceeds its competitor's share of contribution.

Figure 6 is demonstrating industry diversity of patent applicants. Both EV and HV assignees have been clustered in seven groups based on their industry origin. Since the patenting activity before 21st century was relatively low for green technology vehicles, only the years between 2000 and 2010 are considered. The highest proportions of EV applicants are from automotive companies, electronic industry and conglomerate firms. While in case of HV, besides automotive industry, applicants from fuel cell systems and other industries (biotechnology, mechatronics, oil and gas) have highest contributions. Also, it is worth to note that share of universities and research institutes applied for EV related patents have slightly increased by later years. Moreover, rate of new entrants signals the attraction of specific technology area and the level of market dynamic. It can be observed from Figure 7, that the number of HV new entrant has been considerably declined after 2007, while EV is gradually attracting rising number of new industry players.

Figure 6 Industry diversity of (a) EV and (b) HV assignees 2000–2010 (see online version for colours)



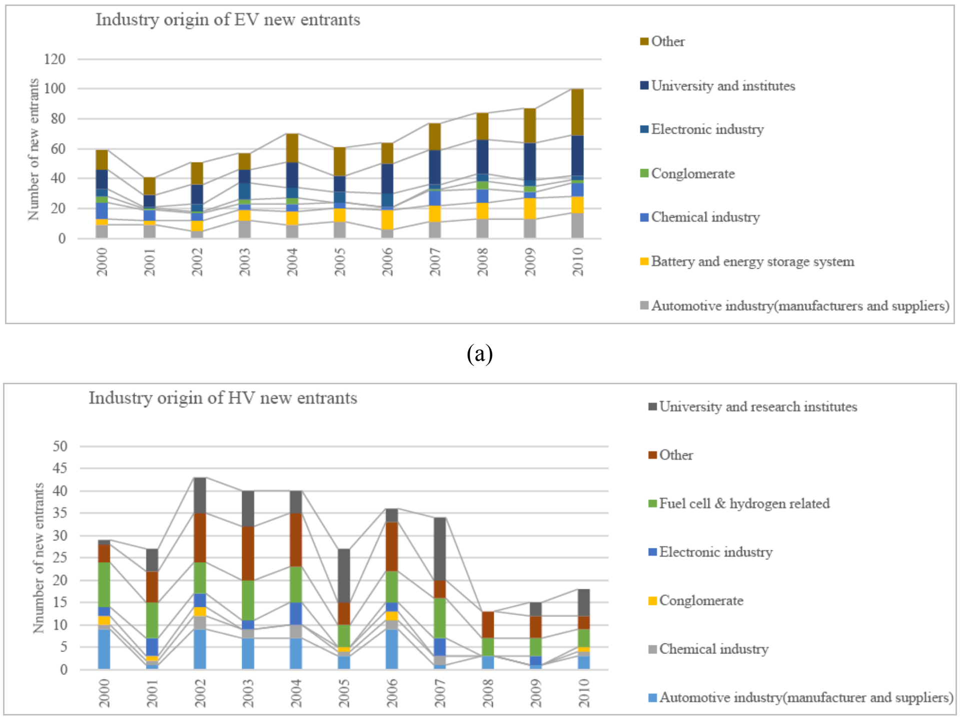
(a)



(b)

To provide a clearer picture of the competition between HV and EV development in this paper, detail comparison of patenting behaviour is explained in three periods of time. During the first decade starting from 1990 to 2000, EVs were dominating the automotive industry (Figure 3). The number of EV prototypes between 1990 and 1997 is reported much higher than its technology competitor: 47 EV vs. nine HV prototypes (Sjoerd et al., 2012). During this time car producers were concerned with the low range between recharging and finding a suitable battery type. The high number of EV patenting or prototypes indicate an era of experimentation and exploration. Additionally, the time lag between prototypes (applied research) and patent (development) perhaps suggests the applicability of a technology life cycle model in the automotive industry. The EV trend shows even higher patenting activity by 2000, which is three years after the announced EV prototypes.

Figure 7 Industry diversity of new entrants for (a) EV and (b) HV 2000–2010 (see online version for colours)



(a)

(b)

The second phase of competition from 2001 to 2007, illustrates a higher share of HV related patents. Figure 6 also presents a dramatic increase in HV patent applicants in this period. Furthermore, Figure 7 depicts the rate of new entrants in HV market which is at its highest for three years in a row (2002–2004) before a dramatic decline occurred by 2007. In addition, prior studies on car prototypes have reported 33 number of HV prototypes between the years 1998–2005, and only nine EV prototypes (Sjoerd et al., 2012).

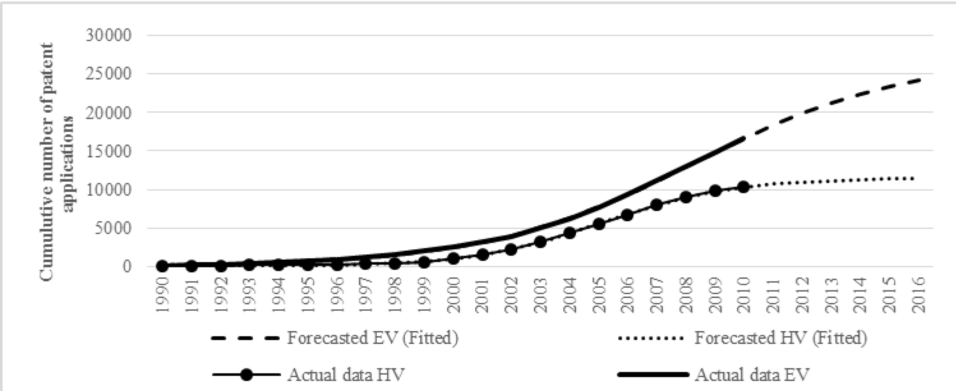
Third phase started from mid-2007, an upward surge in the patenting activity of EVs can be observed (Figure 3). Unlike HV, number of EV assignees and even new entrants show a steady growth toward 2010, which may signal the return of EV with high potential of commercialisation (Figures 6 and 7). Previous literature argued that the most important driving force behind EV returning to the picture are; increasing number of car manufacturers, appearance of start ups and convergence of car companies toward a single mutual battery type (Sierzchula et al., 2012).

4.2 Future development paths for electric and hydrogen cars

The extrapolation of EV and HV patent trends provide perspectives on the technology life cycle of these technologies and estimate future R&D developments (see Figure 8).

The patent data was modelled using the Fisher-Pry function[4] and fitted data with a high R^2 coefficient of 0.99. The estimated value of a, b and L of Fisher-Pry function are reported on Appendix C. Although Figure 3 suggests that EVs are moving forward with a higher proportion of patents than HV, it seems that EV will have a considerably higher share of light-duty vehicle fleet in the future than today.

Figure 8 Trend extrapolation of the EV and HV



The HV growth curve currently shows development on the technology life cycle and will enter the maturity phase and later the plateau level approximately by 2016. Although the graph shows the saturation point for hydrogen cars, we cannot directly interpret that there will be no further advancement. The development of hydrogen cars hinges on the key technology components and various types of subsystems. Considering the PEM fuel cell as one of the key technology subsystems, the R&D activity may shift from a low-temperature PEM fuel cell to a high-temperature PEM fuel cell which would lead to a new S-curve (Mock and Schmid, 2009). On the other hand, technological development seems insufficient to explain fuel cell success in the automotive industry, and other vital issues like environmental regulations should be considered (van den Hoed, 2007).

In the case of EVs, it can be observed from the short forecast that the saturation phase will eventually appear, but within a longer time lag. Currently, the wave of EV development is being reinforced by intense competition, the high rate of new entrants and industry diversity of the involved market players. Also, as the experts commented, the possibility of sharing the present infrastructure and technologies established for hybrid cars may encourage more investments in the EV, rather than the HV. The experts also added that the adoption of the EV may differ in terms of geographical difference. For example, in Finland the present electric heating platforms established for winter time in parking lots can serve electric cars for the recharging purpose. Therefore, in the case of the transition to EVs, countries such as Finland may have the advantage of less initial investment in infrastructure and a more promising future with EV adoption. The predicted EV growth until 2016, or even after this, will continue if the influential factors and situation remain unchanged. All in all, EV appeared to have a considerably higher share patenting and technology development activities than HV and so the market expectations of EV light-duty vehicles seem to be higher than HV.

5 Discussion

The use of patent data is gaining increased interest in the field of technology management and technological forecasting. Patents represent technological evolution and include speculation about how that particular technology might be developed and used in the future. To gain insight into the development trend of the green vehicle alternative, historical and patent analyses were performed. By contrast to previous patent studies in the automotive industry, we applied text mining and machine learning approaches to retrieve and classify the patent documents, which resulted in a more comprehensive technology development study. Furthermore, extrapolation methods were applied to provide information on the future trajectory of emission free cars. In order to provide a meaningful interpretation and reliable forecast, expert opinion, previous literature and prototype analysis of electric and hydrogen cars were integrated into our results.

The reasons behind utilising text mining and machine learning in patent search and data retrieval in this paper are the following:

1. patent classes are too wide to analyse a specific technology field, and their hierarchal structure is based on technology fields rather than an application area
2. new emerging technologies are not assigned to a specific patent class
3. the inconsistency between the keywords entered by researchers, innovators and applicants may return irrelevant patents
4. the keyword search strategy may not capture the contextual meaning.

In response to these shortcomings of conventional patent search strategies, the application of a patent classification system yields more accurate patent data more efficiently. Once the training and test sets are defined, performing patent classification on free open source software only takes a few clicks on the mouse. The classification accuracy is measurable; in case of undesired results the training sets can be revised and updated under expert supervision. The possibility of modifying the presented classification process reflects its flexibility.

Significant growth for both the EV and HV, mainly triggered by the California Air Resources Board (CARB) regulation from 1990, was illustrated by patent trend analysis. A clear shift of industry interest between the two options during three distinct time periods was confirmed by integrating previous literature results, prototype analysis and vehicle production information (Sierzchula et al., 2012; Sjoerd et al., 2012; Wesseling et al. 2014). In the first phase, EV development took a larger share of R&D activities as from 1990 for a decade. Due to the technical and market limitations for EV development, a window of opportunity opened for the HV and attention gradually turned toward fuel cell vehicles by 2000. Finally, after seven years, by early 2008 electric cars returned, reinforced by a higher number of industry actors and new entrants.

Trend extrapolation was conducted to give insight into the future development of the two major green vehicle options. The S-shaped growth models have projected continuing growth for the EV and an early saturation level for hydrogen cars by 2016. Although extrapolations are powerful forecasting tools, the interpretations need to be structured with caution. We have learnt that several forces influence the development of electric cars (Wesseling et al., 2014), but extrapolation does not consider those factors. In fact, extrapolation methods lack casualty (Suominen and Seppänen, 2014), which underlines the need for complementary methods, revision and updating the forecast result by comparing it to actual development. This is specifically true in the case of modelling a technology such as fuel cells, which has been under significant policy interventions (Suominen, 2014). The saturation of HV patenting growth may even suggest a need for a discontinuity, a new generation of fuel cells, developed through a radical innovation that could push the technology to a new growth trajectory. As it stands now, the rapid saturation of HV technology suggests a commercialisation path that may be unfeasible. For EVs the technology life cycle suggests a path more in line with actual developments. According to the recent report of US Department of Energy (DOE) , the sale of EV (BMW Active, Ford Focus, Honda Fit, Tesla Model S, RAV4, Chevrolet Spark, Smart ED and Mitsubishi I) has been dramatically increased from 10,111 cars in 2011 to 23,112 by 2013 (USDOE, 2015).

Overall, the comparison made over patenting trends with other sources, shows that electric cars development may move forward with higher speed compared to HVs. Using an improved approach of patent data collection and supplementing the results with other sources of information assumed to provide more accurate support to the decision-making process. The extrapolation of patents to the future has its limitations, and too straightforward managerial implications can be misguided. As seen with the HV, the trend path seems unfeasible and without the understanding of how the hype around the technology impacts the model, we are bound to incorrect inferences.

The exploration of our patent analysis method is so far limited to the automotive industry field. This area appears suitable for text mining and classification since the keyword trends appeared simple. The method may yet not be ready to be generalised for sophisticated patent fields, like chemistry with complex symbols and chemical compounds. The language barrier is another limitation of this study, since only English patents have been considered. Future work can be directed to extract more information from patent text, such as application of unsupervised learners to identify the topical shift among pile of patent documents.

6 Conclusions

Owing to the rising demand for green technology in the automotive sector and uncertainty over the adoption of a future car technology, we have explored the technological development of hydrogen and electric vehicles. This study, firstly, utilised the automated patent analysis approach to retrieve relevant patents with application in the car industry. As a result, the patent search and analysis was accomplished more quickly with a higher accuracy in the data retrieval process.

Secondly, the competition between hydrogen and electric cars has been illustrated based on patent data and supplemented with various information sources including expert opinion and previous literature. Results indicated

a significant growth for both technology alternatives since 2000

b continuing development in future but with different speed.

However, in terms of R&D proportion, the EV has a greater share compared to hydrogen cars. Overall findings moreover suggest a faster and higher rate of development for the EV, if all external forces remain unchanged.

Although the forecasting results with extrapolation tools provide only rudimentary information, they can still shed some light on the direction of the technological trajectory. Decisions should be made, even though enough information is not available. Researchers and patent analysts can benefit from the cost-effective and quicker patent retrieval process since we used free open source software.

References

Abernathy, W. and Utterback, J. (1978) 'Patterns of industrial innovation', *Technology Review*, Vol. 80, No. 7, pp.40–47.

Anderson, P. and Tushman, M.L. (1991) 'Managing through cycles of technological change', *Research Technology Management*, Vol. 34, No. 3, pp.26–31.

Bakker, S. (2010a) 'Hydrogen patent portfolios in the automotive industry – the search for promising storage methods', *International Journal of Hydrogen Energy*, Vol. 35, No. 13, pp.6784–6793.

Bakker, S. (2010b) 'The car industry and the blow-out of the hydrogen hype', *Energy Policy*, Vol. 38, No. 11, pp.6540–6544.

Balconi, M., Brusoni, S. and Orsenigo, L. (2010) 'In defence of the linear model: an essay', *Research Policy*, Vol. 39, No. 1, pp.1–13.

Ball, M. and Wietschel, M. (2009) *The Hydrogen Economy: Opportunities and Challenges*', Cambridge University Press.

Barney, J. (1991) 'Firm resources and sustained competitive advantage', *Journal of Management*, Vol. 17, No. 1, pp.99–120.

Berggren, C. and Magnusson, T. (2012) 'Reducing automotive emissions – the potentials of combustion engine technologies and the power of policy', *Energy Policy*, February, Vol. 41, pp.636–643.

Browne, D., O'Mahony, M. and Caulfield, B. (2012) 'How should barriers to alternative fuels and vehicles be classified and potential policies to promote innovative technologies be evaluated', *Journal of Cleaner Production*, Vol. 35, No. 1, pp.140–151.

Chan, C. (2007) 'The state of the art of electric, hybrid, and fuel cell vehicles', *Proceedings of the IEEE*, Vol. 95, No. 4, pp.704–718.

Chen, Y. (2011) 'Using patent analysis to explore corporate growth', *Scientometrics*, Vol. 88, No. 2, pp.433–448.

Chen, Y., Chen, C. and Lee, S. (2011) 'Technology forecasting and patent strategy of hydrogen energy and fuel cell technologies', *International Journal of Hydrogen Energy*, Vol. 36, No. 12, pp.6957–6969.

Christensen, C. (1997) *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*, Harvard Business School Press, Boston.

Contestabile, M., Offer, G., Slade, R., Jaeger, F. and Thoennes, M. (2011) 'Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner?', *Energy & Environmental Science*, Vol. 4, No. 10, pp.3754–3772.

Cortes, C. and Vapnik, V. (1995) 'Support-vector networks', *Machine Learning*, Vol. 20, No. 3, pp.273–297.

Daim, T, Rueda, G., Martin, H. and Gerdsri, P. (2006) 'Forecasting emerging technologies: use of bibliometrics and patent analysis', *Technological Forecasting and Social Change*, Vol. 73, No. 8, pp.981–1012.

PATSTAT (2013) *Worldwide Patent Statistical Database*, April, EPO.

Ernst, H. (1997) 'The use of patent data for technological forecasting: the diffusion of CNC technology in the machine tool industry', *Small Business Economics*, Vol. 9, No. 4, pp.361–381.

Frenken, K., Hekkert, M. and Godfroij, P. (2004) 'R&D portfolios in environmentally friendly automotive propulsion: variety, competition and policy implications', *Technological Forecasting and SocialChange*, Vol. 71, No. 5, pp.485–507.

Griliches, Z. (1990) 'Patent statistics as economic indicators: a survey', *Journal of Economic Literature*, Vol. 28, No. 4, pp.1661–1707.

van den Hoed, R. (2005) 'Commitment to fuel cell technology?', *Journal of Power Sources*, Vol. 141,
No. 2, pp.265–271.

van den Hoed, R. (2007) 'Sources of radical technological innovation: the emergence of fuel cell technology in the automotive industry', *Journal of Cleaner Production*, Vol. 15, Nos. 11–12, pp.1014–1021.

Jeon, J., Lee, C. and Park, Y. (2011) 'How to use patent information to search potential technology partners in open innovation', *Journal of Intellectual Property Rights*, September, Vol. 16, pp.385–393.

Kemp, R. (2005) 'Zero emission vehicle mandate in California: misguided policy or example of enlightened leadership?', in Sartorius, C. and Zundel, S. (Eds.): *Time Strategies, Innovation and Environmental Policy*, pp.169–191, Edward Elgar, Cheltenham.

Liebesny, F. (1974) 'The scientific and technical information contained in patent specifications, the extent and time factors of its publication in other forms of literature', *Journal of Amercian society for Information Sciense*, Vol. 8, No. 4, pp.165–177.

Liu, S. and Shyu, J. (1997) 'Strategic planning for technology development with patent analysis', *International Journal of Technology Management*, Vol. 13, Nos. 5–6, pp.661–680.

Mock, P. and Schmid, S. (2009) 'Fuel cells for automotive powertrains – a techno-economic assessment', *Journal of Power Sources*, Vol. 190, No. 1, pp.133–140.

Narin, F., Noma, E. and Perry, R. (1987) 'Patents as indicators of corporate technological strength', *Research Policy*, Vol. 16, Nos. 2–4, pp.143–155.

Nieuwenhuis, P. and Wells, P. (1997) *The Death of Motoring? Car Making and Automobility in the 21st Century*, Wiley, New York.

Oltra, V. and Saint Jean, M. (2009a) 'Sectoral systems of environmental innovation: an application to the French automotive industry', *Technological Forecasting and Social Change*, Vol. 76, No. 4, pp.567–583.

Oltra, V. and Saint Jean, M. (2009b) 'Variety of technological trajectories in low emission vehicles (LEVs): a patent data analysis', *Journal of Cleaner Production*, Vol. 17, No. 2, pp.201–213.

Pilkington, A. (2004) 'Technology portfolio alignment as an indicator of commercialisation: an investigation of fuel cell patenting', *Technovation*, Vol. 24, No. 10, pp.761–771.

Pilkington, A., Dyerson, R. and Tissier, O. (2002) 'The electric vehicle: patent data as indicators of technological development', *World Patent Information*, Vol. 24, No. 1,pp.5–12.

Pohl, H. and Yarime, M. (2012) 'Integrating innovation system and management concepts: the development of electric and hybrid electric vehicles in Japan', *Technological Forecasting and Social Change*, Vol. 79, No. 8, pp.1431–1446.

Porter, A., Cunningham, S., Banks, J., Roper, T., Mason, T. and Rossini, F.(2011) *Forecasting and Management of Technology*, 2nd ed., John Wiley and Sons, Chichester.

Ranaei, S., Karvonen, M., Suominen, A. and Kässi, T. (2014) 'Forecasting emerging technologies of low emission vehicle', *Portland International Conference on Management of Engineering and Technology (PICMET)*, Kanazawa, Japan, pp.2924–2937.

Rizzi, F., Annunziata, E., Liberati, G. and Frey, M. (2014) 'Technological trajectories in the automotive industry: are hydrogen technologies still a possibility?', *Journal of Cleaner Production*, March, Vol. 66, pp.328–336.

Rosenberg, N. (1994) *Exploring the Black Box: Technology, Economics, and History*, Cambridge University Press, Cambridge.

Sierzchula, W., Bakker, S., Maat, K. and Wee, B. (2012) 'The competitive environment of electric vehicles: an analysis of prototype and production models', *Environmental Innovation and Societal Transitions*, March, Vol. 2, pp.49–65.

Sjoerd, B., Harro, V. and Remko, E. (2012) 'Competition in a technological niche: the cars of the future', *Technology Analysis & Strategic Management*, Vol. 24, No. 3, pp.421–434.

Suominen, A. (2013) 'Analysis of technological progression by quantitative measures: a comparison of two technologies', *Technology Analysis & Strategic Management*, Vol. 25, No. 6, pp.687–706.

Suominen, A. (2014) 'Phases of growth in a green tech research network: a bibliometric evaluation of fuel cell technology from 1991 to 2010', *Scientometrics*, Vol. 100, No. 1, pp.51–72.

Suominen, A. and Seppänen, M. (2014) 'Bibliometric data and actual development in technology life cycles: flaws in assumptions', *Foresight*, Vol. 16, No. 1, pp.37–53.

Suominen, A., Tuominen, A. and Kantola, J. (2011) 'Analyzing prospects of portable fuel cells with an expert opinion study', *Futures*, Vol. 43, No. 5, pp.513–524.

Tseng, Y., Lin, C. and Lin, Y. (2007) 'Text mining techniques for patent analysis', *Information Processing and Management*, Vol. 43, No. 5, pp.1216–1247.

Tushman, M. (1997) 'Winning through innovation', *Strategy & Leadership*, Vol. 25, No. 4, pp.14–19.

USDOE (2015) *Electric and Hybrid Electric Vehicle Sales: December 2010–June 2013* [online] http://energy.gov/downloads/electric-and-hybrid-electric-vehicle-sales-december-2010-june-2013 (accessed 2 April 2015).

Utterback, J. (1996) *Mastering the Dynamics of Innovation*, Harvard Business School Press, Boston.

Verspagen, B. (2007) 'Mapping technological trajectories as patent citation networks – a study on the history of fuel cell research', *Advances in Complex Systems*, Vol. 10, No. 1, pp.93–115.

Watts, R. and Porter, A. (1997) 'Innovation forecasting', *Technological Forecasting and Social Change*, Vol. 56, No. 1, pp. 25–47.

Weiss, M., Patel, M., Junginger, M., Perujo, A., Bonnel, P. and Grootveld, G. (2012) 'On the electrification of road transport – learning rates and price forecasts for hybrid-electric and battery-electric vehicles', *Energy Policy*, September, Vol. 48, pp.374–393.

Wesseling, J., Faber, J. and Hekkert, M. (2014) 'How competitive forces sustain electric vehicle development' *Technological Forecasting and Social Change*, Vol. 81, No. 1, pp.154–164.

Wu, C-H., Ken, Y. and Huang, T. (2010) 'Patent classification system using a new hybrid genetic algorithm support vector machine', *Applied Soft Computing*, Vol. 10, No. 4, pp.1164–1177.

Yang, L., Xu, J. and Neuhäusler, P. (2013) 'Electric vehicle technology in China: an exploratory patent analysis', *World Patent Information*, Vol. 35, No. 4, pp.305–312.

Yau, C., Porter, A., Newman, N. and Suominen, A. (2014) 'Clustering scientific documents with topic modeling', *Scientometrics*, Vol. 100, No. 3, pp.767–786.

Yoon, B. (2012) 'Applicability of patent information in technological forecasting: a sector-specific approach', January, Vol. 17, No. 1, pp.37–45.

Yoon, B. and Park, Y. (2004) 'A text-mining-based patent network: analytical tool for high-technology trend', *The Journal of High Technology Management Research*, Vol. 15, No. 1, pp.37–50.

Notes

1 Listed by WIPO: http://www.wipo.int/classifications/ipc/en/est/
2 Term frequency –Inverse document Frequency
3 Proton Exchange Membrane
4 $y(t) = L/(1 + ae^{(-bt)})$

Appendix A

IPC classes used in the test set query

IPC green inventory	Brushless motors	H02K 29/08
	Electric propulsion with power supply from force of nature, e.g., sun, wind	B60L 8/00
	Electric propulsion with power supply external to vehicle	B60L 9/00
	• With power supply from fuel cells, e.g., for hydrogen vehicles	B60L 11/18 F02B 43/00
	• Combustion engines operating on gaseous fuels, e.g., hydrogen	F02M 21/02, 27/02 B60K 16/00
	• Power supply from force of nature, e.g., sun, wind	
Additional IPCs	Motor technology	H02K 17
	Battery technology, battery management, storage options	H01M4/13, H01M10/0525, H01M8/04, H01M8/0, H01M8/24, H01M2/02, H01M 16/00, H01M 4/00
	Electric vehicle controlling system	H02K 29/08, H02k 17/00
	• Arrangement or mounting of electrical propulsion units	B60K 1/04, B60K 8/00
	• Cooling of propulsion units	B60K 11/02
	• Arrangement in connection with fuel supply of combustion engines; Mounting or construction of fuel tanks	B60K 15/00, B60K 15/03
	• Hybrid propulsion systems comprising electrical and internal combustion motors, and storage of electric energy	B60k 6/28 , B60K 6/32
	• Arrangements in electrical propulsion in connection with power supply from force of nature, e.g., sun, wind	B60K 16/00
	• Electric equipment or propulsion of electrically-propelled vehicles	B60L 8/00, B60L 9/00, B60L 9/18, B60L 7/14
	• Control systems of fuel cell	B60w 10/26, B60w 10/28, F02M 21/06
	• Methods of moulding or forming tanks or container for hydrogen storage	B29C 63/08, B29C 53/08

IPC classes used in the test set query (continued)

Additional IPCs	• Vehicle body , substructures and sub-units	B62D 21/18, B62D 25/20
	• Electric or fluid circuits or arrangements of elements thereof specially adapted for vehicles, batteries and carrying-off electric charges, radiators.	B60R19/00, B60R 16/02
	• Rider propulsion of wheeled vehicles	B62M 6/90
	• Testing of vehicles, engines	G01M 16, 17/00
	• Cooling systems for vehicle, controlling of coolant flow	F01P 7/12
	• Hydrogen; Gaseous mixtures containing hydrogen; Separation of hydrogen from mixtures containing it	C01B 3/00

Appendix B

TF-IDF matrix for the electric vehicle training set (partial view)

Keywords	*Total occurrence*	*Doc occurrence*	*EV*	*Not_EV*
battery	1078.0	122.0	903.0	175.0
electric	732.0	138.0	557.0	175.0
lithium	657.0	49.0	657.0	0.0
lithium_ion_battery	511.0	36.0	511.0	0.0
vehicle	501.0	136.0	118.0	383.0
motor	415.0	87.0	251.0	164.0
automobile	385.0	60.0	366.0	19.0
charging	354.0	68.0	276.0	78.0
electric automobile	311.0	55.0	305.0	6.0
combustion	297.0	35.0	2.0	295.0
control	296.0	94.0	114.0	182.0
device	296.0	81.0	167.0	129.0
ignition	243.0	25.0	0.0	243.0
fuel_cell	232.0	51.0	21.0	211.0
permanent magnet	208.0	30.0	208.0	0.0
magnet_synchronous	201.0	30.0	201.0	0.0
permanent_magnet_synchronous	201.0	30.0	201.0	0.0
internal_combustion	194.0	33.0	0.0	194.0

Note: Explanation: it can be easily observed that, for example, the TF-IDF score of 'internal combustion' in the last row is 0 in the electric vehicle category and 194 in the irrelevant to electric cars category. A similar pattern is visible for permanent_magnet_synchronous, lithium_ion_battery, etc. Some neutral or generic keywords like device, control or battery that are being used in a variety of applications have more or less occurred in both categories.

Appendix C

Estimated parameters for the Fisher-Pry function

Technology cluster	*L*	*a*	*b*	R^2
Electric vehicle	27.0156	160.6386	0.2775	0.9998
Hydrogen vehicle	11.5341	927.7430	0.4499	0.9997

Modelling the causal linkages among residential electricity consumption, gross domestic product, price of electricity, price of electric appliances, population and foreign direct investment in Malaysia

Lee Lian Ivy-Yap and Hussain Ali Bekhet*

Graduate Business School,
Universiti Tenaga Nasional,
43000 Kajang-Selangor, Malaysia
Email: iv_yap@yahoo.com
Email: profhussain@uniten.edu.my
Email: drbekhet1953@hotmail.com
*Corresponding author

Abstract: Residential electricity consumption in Malaysia is increasing rapidly and effective measures are urgently needed to contain its rapid growth to achieve better energy security. The current paper attempts to investigate the multivariate Granger causalities and dynamic responses of residential electricity consumption in Malaysia for the 1978–2013 period. In the long run, all the determinants of residential electricity consumption (real disposable income, price of electricity, price of electric appliances, population and foreign direct investment) Granger cause it but in the short run, only the price of electric appliances and population do so. The response of residential electricity consumption to shocks alternates between positive and negative but diminishes with time. In addition to own shocks, shocks to the price of electricity contribute most of the variance in residential electricity consumption. The study shows that pricing policies are effective in reducing residential electricity consumption. As fossil fuels are finite, careful planning of energy consumption is necessary to safeguard energy security.

Keywords: residential electricity consumption; REC; co-integration; multivariate Granger causalities; dynamic responses; Malaysia.

Reference to this paper should be made as follows: Ivy-Yap, L.L. and Bekhet, H.A. (2016) 'Modelling the causal linkages among residential electricity consumption, gross domestic product, price of electricity, price of electric appliances, population and foreign direct investment in Malaysia', *Int. J. Energy Technology and Policy*, Vol. 12, No. 1, pp.41–59.

Biographical notes: Lee Lian Ivy-Yap is an Administrative and Diplomatic Officer at the Energy Sector, Ministry of Energy, Green Technology and Water, Malaysia. She is currently pursuing a PhD in Business Management specialising in energy and environment studies at Universiti Tenaga Nasional (UNITEN) under the Kursi Biasiswa Ekonomi Tenaga post graduate scholarship program. She has published four papers in international conferences and journals.

Hussain Ali Bekhet is a Professor in Quantitative Analysis in Applied Economics and he is currently teaching at the Graduate Business School, College of Graduate Studies of Universiti Tenaga Nasional (UNITEN), Malaysia. He received his PhD in Input-Output Methods from the University of Keele, England, UK, in 1991. He received his MSc from the Baghdad University and a BSc from the University of the Basra, Iraq. He taught at Baghdad University from April 1991 to May 2003, Al-Zyatoonh University, Jordan, from September 2003 to December 2007 and joined UNITEN in July 2008 up to date. He has already published more than 80 papers in peer-reviewed articles and five textbooks.

1 Introduction

Energy, especially in the form of fossil fuels, is a vital input for economic development. This is evident in the ever increasing demand for energy in developed and developing countries. As the world energy consumption continues to increase significantly, there is growing concern regarding energy security. Such concern is reasonable because finite energy sources are being depleted with consumption. The rate of energy source depletion is made more apparent by the huge increase in energy consumption over the past few decades. As a result, several countries are currently proposing strong energy substitution policies and radical energy conservation measures (Bloch et al., 2015). These policies are aimed at reducing energy consumption and consequently decreasing the depletion rate of fossil fuels. In the meantime, renewable and alternative energy sources are also being explored as substitutes for fossil fuels to achieve better energy security.

As a result of the depleting energy sources and the growing concern regarding energy security, researchers and academicians began to execute various studies in this area. Earlier studies focussed on bivariate models to examine the relationship between energy consumption and economic growth. However, bivariate models are heavily criticised as they are prone to suffer from the omitted variable bias problem (Alshehry and Belloumi, 2015; Glasure, 2002; Lean and Smyth, 2010). This leads to the widespread use of multivariate models. Among the elements frequently considered are real disposable income, price of electricity and price of alternative fuels (e.g. gas, diesel). In recent years, foreign direct investment (FDI) has been included in studies on energy consumption.

Malaysia is one of the fortunate countries in the world endowed with oil reserves. Nevertheless, since fossil fuels are finite and not renewable, efficient management and utilisation of these energy sources are crucial. The Malaysian government is cognizant of the importance of using energy efficiently. Hence, the first National Energy Policy (1979) was introduced. Subsequently, many energy policies and strategies were implemented (Bekhet and Ivy-Yap, 2014). However, electricity consumption in Malaysia has continued to increase rapidly (see Figure 1). One possible reason for the rapid growth is these energy policies and strategies have not addressed all the factors affecting electricity consumption. Since inappropriate policies would affect economic growth adversely, one of the most urgent tasks for the authorities is to develop effective, long-term energy policies (Chandran et al., 2010; Fei et al., 2011).

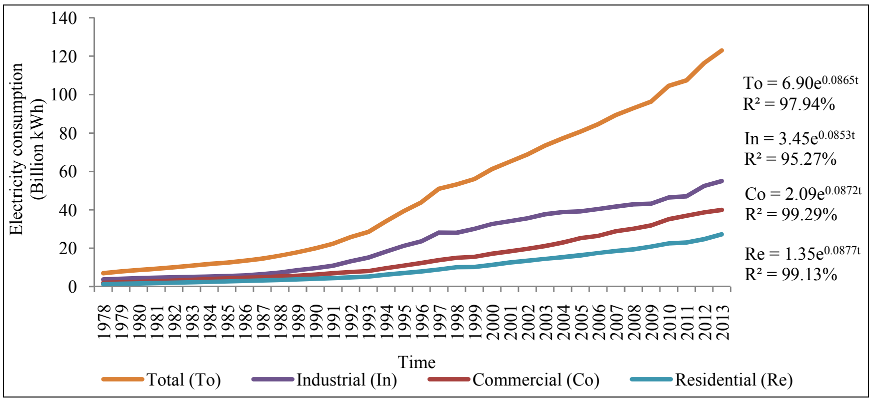
Clear evidence of the main factors that influence electricity consumption and the quantification of their impact are crucial in the contemplation of energy policy (Gam and Rejeb, 2012). Although existing literature has discussed at length the relationship between electricity consumption and economic development, the studies have not provided consistent results. In addition, the role of complements (e.g. price of electric appliances) is still missing in the literature. Since electricity consumption is basically due to the operation of electric appliances, complements play an important role and should be included in the consumption function of electricity (Ivy-Yap and Bekhet, 2014). The absence of this important variable is likely to explain the omitted variable bias problem, which causes the diverse results in the literature, despite having numerous studies on energy economics on Malaysia as well as other countries. Motivated by this argument, the goal of the current paper is to re-examine the residential electricity consumption (REC) function in Malaysia by including the price of electric appliances as a new variable to provide a more comprehensive analysis.

The rest of this paper is organised as follows. Section 2 presents a concise overview of the energy sector and policies in Malaysia. Section 3 provides the literature review. Section 4 explains the theoretical framework and model specification. Section 5 describes the data sources and methodologies. Section 6 reveals the empirical results and Section 7 discusses the conclusions and policy implications.

2 Overview of the energy sector and policies

Energy serves as a catalyst in promoting growth. Although energy consumption can be reduced via technology advancement, its consumption is still inevitable (Stern, 2011). In Malaysia, electricity consumption has increased tremendously over the years to meet social and economic needs. Three major electricity-consuming sectors in Malaysia are industrial, commercial and residential. Among these sectors, the residential sector has recorded the highest annual growth rate of 8.77% (see Figure 1).

Figure 1 Electricity consumption in Malaysia (see online version for colours)



Source: Malaysia Energy Commission (2014) *Statistical Database* [online] http://meih.st.gov.my; Data point for 2013 is estimated by the authors

To contain the rapid growth of electricity consumption, the government has implemented various policies (Ivy-Yap and Bekhet, 2014; Oh et al., 2010). For the residential sector, the government announced an electricity bill exemption up to RM20 (Tenaga Nasional Berhad, 2013a). However, if the electricity bill exceeds RM20, no exemption is given and the bill has to be paid in full. This program is envisioned to encourage consumers to use electricity more cautiously. Averagely, more than one million households are exempted from paying electricity bill. Besides offering electricity bill exemption, the government also gave rebate to escalate the penetration of energy efficient appliances (Tenaga Nasional Berhad, 2013b). Refrigerators and air conditioners were chosen as the targeted appliances because they are the electricity intensive appliances in most households (Saidur et al., 2007).

In addition to providing incentives, the government imposed a penalty on over-consumption to encourage prudent use of electricity. Beginning 1 April 2015, the 301st unit of electricity and above consumed by the residential consumers within a month are subjected to goods and services tax (GST) of 6.0%. The implementation of GST is aimed to impose higher costs of electricity to households as their electricity consumption increases to prevent over-consumption of electricity.

3 Literature review

The relationship between energy consumption and economic growth has been studied by many researchers using various methodologies for different time periods and geographic locations, especially since the pioneering work of Kraft and Kraft (1978). As energy consumption is experiencing a transition towards electricity, the literature is also more interested in electricity compared to other forms of energy (Al-Faris, 2002; Amusa et al., 2009). Most of the studies have considered total electricity consumption. Realising the different properties of each sector, sector-wise study on electricity consumption is gaining attention, especially the residential sector (Adom et al., 2012; Atanasiu and Bertoldi, 2010; Cebula, 2012; Dergiades and Tsoulfidis, 2008, 2011; Fell et al., 2014; Filippini and Pachauri, 2004; Halicioglu, 2007; Holtedahl and Joutz, 2004; Krishnamurthy and Kriström, 2015; Nakajima, 2010; Narayan et al., 2007; Ziramba, 2008). This is due to a few reasons (Cebula, 2012; Dergiades and Tsoulfidis, 2008, 2011). First, the residential sector is one of the major sectors in terms of electricity consumption. Second, electricity consumption in the residential sector records a steady growth rate and the consumption is expected to continue to increase. Third, the residential sector is more amenable to theorisation and quantification, and finally, the residential sector is an important sector in energy policy formulation.

Prior to advancements in the bounds testing approach, initially introduced by Pesaran et al. (2001), the vector autoregressive (VAR) and vector error correction model (VECM) frameworks were widely used to investigate the relationship between energy consumption and macroeconomic variables. In the event of no co-integration relationship, the VAR was used (Chen et al., 2007; Masih and Masih, 1996). In contrast, if there were a co-integration relationship, the VECM was employed (Athukorala and Wilson, 2010; Bekhet and Othman, 2011a, 2011b; Bekhet and Yusop, 2009; Ho and Siu, 2007; Jamil and Ahmad, 2010, 2011; Narayan et al., 2007; Odhiambo, 2009). Realising the restrictions of VAR and VECM, coupled with the advantages of the autoregressive distributed lags (ARDLs) framework, the ARDL is gaining popularity and is employed in many studies (Adom et al., 2012; Amusa et al., 2009; Bloch et al., 2015; Chandran et al., 2010; Dergiades and Tsoulfidis, 2011; Halicioglu, 2007; Hamdi et al., 2014; Tang and Tan, 2013).

Each study begins with the development of a consumption function. Real disposable income, price of electricity, price of substitute energy, population, weather and urbanisation are among the favourite variables considered in the literature. Recent studies have suggested the inclusion of FDI (Bekhet and Othman, 2011b; Hamdi et al., 2014; Lau et al., 2014; Solarin and Shahbaz, 2015). Among the aspects investigated in these studies were the multivariate Granger causalities and dynamic responses of electricity consumption. Understanding the direction of multivariate Granger causalities and the relative strength of causal relationships is important for policy makers in formulating appropriate policies for sustainable development. Unfortunately, the results in the literature were not consistent. For example, Hamdi et al. (2014), Tang (2008) and Yoo (2005) found electricity consumption and real disposable income Granger cause each other but Alshehry and Belloumi (2015) and Morimoto and Hope (2004) found unidirectional Granger causality from electricity consumption to real disposable income. On the other hand, Boutabba (2014) and Jumbe (2004) found the reverse.

These diverse results in the literature arise due to various reasons. Among them are the different datasets considered, alternative econometric methodologies employed and different countries' characteristics (Asafu-Adjaye, 2000; Ozturk, 2010). For example, the estimates of causal relationship using bivariate models are vulnerable to omitted variable bias problem. Hence, the current paper utilises a multivariate model to reduce the omitted variable bias problem so as to provide more reliable results.

4 Theoretical framework and model specification

The current paper is built on two main economic theories: production theory and demand theory. These theories serve as the basis for model building and support the model specification. The Cobb-Douglas production [equation (1)] gives quantity of output (Q) as a function of capital (K) and labour (L) at a particular technology (T).

$$Q_t = T_t K_t^{\pi_1} L_t^{\pi_2} \tag{1}$$

where π_1 and π_2 are coefficients. Applying the Cobb-Douglas production function in the area of the current paper, the quantity of REC is specified as a function of the stock of the electric appliances (K) and population (Po) at a particular state of electric appliances technology (T). Hence, equation (1) can be re-written as in equation (2).

$$REC_t = T_t K_t^{\pi_1} Po_t^{\pi_2} \tag{2}$$

However, the state of electric appliance technology does not remain constant. Instead, it advances with the level of FDI (Hamdi et al., 2014). This is because FDI utilises advanced technologies and facilitates technological advancement and its diffusion. FDI also enables more active and rigorous research and development (R&D) activities to be executed for technological progress, whereby obsolete and dirty technologies are replaced with new and cleaner technologies (Lau et al., 2014). Through these technology innovations, more energy-saving products can be produced (Tang and Tan, 2013). Hence, technology is defined as in equation (3).

$$T_t = a_1 FDI_t^{\phi_1} \tag{3}$$

where a_1 is a constant. In the meantime, the stock of electric appliances (K) is the total electric appliances operating within the residential sector, consisting of new purchases and the replacement of old electric appliances (Ivy-Yap and Bekhet, 2015). Since consumers cannot purchase an infinite quantity of electric appliances due to income constraints and prices, the stock of electric appliances (K) is determined by the price of electric appliances (Pa), real disposable income (Y) and price of electricity (Pe), as shown in equation (4).

$$K_t = a_2 Pa_t^{\gamma_1} Y_t^{\gamma_2} Pe_t^{\gamma_3} \tag{4}$$

where a_2 is a constant to capture the replacement rate of old electric appliances. Substituting equation (3) and equation (4) into equation (2) and rearranging it results in equation (5). The relationship described in equation (5) gives REC as a function of Y, Pe, Pa, Po and FDI.

$$REC_t = AY_t^{\theta_1} Pe_t^{\theta_2} Pa_t^{\theta_3} Po_t^{\theta_4} FDI_t^{\theta_5} \tag{5}$$

where $A = (a_1).(a_2)\pi_1$, $\theta_1 = (\gamma_2).(\pi_1)$, $\theta_2 = (\gamma_3).(\pi_1)$, $\theta_3 = (\gamma_1).(\pi_1)$, $\theta_4 = \pi_2$ and $\theta_5 = \phi_1$. Equation (5) is a nonlinear equation. To linearise it, logarithm (l) transformation is applied on both sides of the equation. Logarithm transformation also effectively linearises the exponential trend in time series data, which obscures the real relationship among the variables. Another advantage of logarithm transformation is that it allows the regression coefficients to be interpreted as elasticities. For these reasons, logarithm transformation is popular in econometrics (Asteriou and Hall, 2007). The logarithm transformation of equation (5) is given in equation (6).

$$lrec_t = \alpha + \theta_1 ly_t + \theta_2 lpe_t + \theta_3 lpa_t + \theta_4 lpo_t + \theta_5 lfdi_t + \mu_t \tag{6}$$

where $\alpha = lA$ and μ_t is the error term with zero mean and constant variance, $\mu_t \sim N(0, \sigma^2)$. Equation (6) also represents the long-run relationship between REC and its determinants.

5 Data sources and methodologies

Annual data are collected for the 1978–2013 period at a constant price (2005 = 100). Real gross domestic product (GDP) serves as a proxy for real disposable income (Amusa et al., 2009; Asafu-Adjaye, 2000; Athukorala and Wilson, 2010). Price indexes are used as proxy for price of electricity (gross rent, fuel and power) and price of electric appliances (furniture, furnishings and household equipment and operation) (Bekhet and Othman, 2011a; Chandran et al., 2010). The data on FDI, given as a percentage of GDP, are converted into real FDI by multiplying by real GDP. The data are collected from the Malaysia Energy Commission (REC), the World Development Indicators (real GDP and FDI), the Department of Statistics Malaysia (price indexes and population).

Related computational works in the current paper are executed using Eviews version 7.1 and Microfit version 4.1. First, all the data are checked in terms of the distribution characteristics and pair-wise inter-correlations. Second, the variables are tested for stationarity via the unit root test. The current paper employs three unit root tests, augmented Dickey-Fuller (Dickey and Fuller, 1979), Phillips-Perron (Phillips and Perron, 1988) and Kwiatkowski, Phillips, Schmidt and Shin (Kwiatkowski et al., 1992), to obtain more robust results. The unit root test can be executed in three situations (i.e.

without both constant term and linear trend, with constant term but not linear trend or with both constant term and linear trend). Unless the data-generating process is known, there is no definite answer regarding which of the three situations to use (Asteriou and Hall, 2007). However, Vogelvang (2005) argued that for most economic variables, a constant is necessary but an additional trend term is generally superfluous. Hence, the current paper includes only a constant term.

Although all the tests are aimed at testing the stationarity of each variable, the hypothesis statements and results interpretations for ADF and P-P differ from KPSS. The null hypothesis, H_0 for ADF and P-P, in the series contains the unit root while the alternative hypothesis, H_1, in the series is stationary. Therefore, the series has to be differenced until H_0 is rejected. On the other hand, H0 for KPSS in the series is stationary and H_1 in the series is not stationary, which is the reverse of ADF and P-P (Boutabba, 2014). Hence, in the case of KPSS, the series must be differenced until H_0 cannot be rejected. Since each unit root test may yield different results, the conclusion on the order of integration of each variable is drawn based on the majority of the three unit root test results.

Subsequently, the ARDL bounds testing approach is performed to ascertain the existence of co-integration relationship among the variables. This approach has many advantages (Bekhet and Matar, 2013; Farhani et al., 2014). First, this method is applicable regardless of the integration order of the variables, i.e. $I(0)$ and $I(1)$. Second, the method is more efficient for study involving small samples ($30 \leq t \leq 80$). Third, the method allows the variables to have different optimal lags and, finally, the method is currently in trend. This approach involves the estimation of equation (7) through equation (12).

$$\begin{aligned}\Delta lrec_t = {} & \alpha_1 + \beta_{11} lrec_{t-1} + \beta_{12} ly_{t-1} + \beta_{13} lpe_{t-1} + \beta_{14} lpa_{t-1} + \beta_{15} lpo_{t-1} + \beta_{16} lfdi_{t-1} \\ & + \sum_{i=1}^{j_1} \delta_{(11)i} \Delta lrec_{t-i} + \sum_{i=0}^{k_1} \delta_{(12)i} \Delta ly_{t-i} + \sum_{i=0}^{l_1} \delta_{(13)i} \Delta lpe_{t-i} + \sum_{i=0}^{m_1} \delta_{(14)i} \Delta lpa_{t-i} \\ & + \sum_{i=0}^{n_1} \delta_{(15)i} \Delta lpo_{t-i} + \sum_{i=0}^{o_1} \delta_{(16)i} \Delta lfdi_{t-i} + \mu_{1t}\end{aligned} \tag{7}$$

$$\begin{aligned}\Delta ly_t = {} & \alpha_2 + \beta_{21} lrec_{t-1} + \beta_{22} ly_{t-1} + \beta_{23} lpe_{t-1} + \beta_{24} lpa_{t-1} + \beta_{25} lpo_{t-1} + \beta_{26} lfdi_{t-1} \\ & + \sum_{i=0}^{j_2} \delta_{(21)i} \Delta lrec_{t-i} + \sum_{i=1}^{k_2} \delta_{(22)i} \Delta ly_{t-i} + \sum_{i=0}^{l_2} \delta_{(23)i} \Delta lpe_{t-i} + \sum_{i=0}^{m_2} \delta_{(24)i} \Delta lpa_{t-i} \\ & + \sum_{i=0}^{n_2} \delta_{(25)i} \Delta lpo_{t-i} + \sum_{i=0}^{o_2} \delta_{(26)i} \Delta lfdi_{t-i} + \mu_{2t}\end{aligned} \tag{8}$$

$$\begin{aligned}\Delta lpe_t = {} & \alpha_3 + \beta_{31} lrec_{t-1} + \beta_{32} ly_{t-1} + \beta_{33} lpe_{t-1} + \beta_{34} lpa_{t-1} + \beta_{35} lpo_{t-1} + \beta_{36} lfdi_{t-1} \\ & + \sum_{i=0}^{j_3} \delta_{(31)i} \Delta lrec_{t-i} + \sum_{i=0}^{k_3} \delta_{(32)i} \Delta ly_{t-i} + \sum_{i=1}^{l_3} \delta_{(33)i} \Delta lpe_{t-i} + \sum_{i=0}^{m_3} \delta_{(34)i} \Delta lpa_{t-i} \\ & + \sum_{i=0}^{n_3} \delta_{(35)i} \Delta lpo_{t-i} + \sum_{i=0}^{o_3} \delta_{(36)i} \Delta lfdi_{t-i} + \mu_{3t}\end{aligned} \tag{9}$$

$$\begin{aligned}\Delta lpa_t = {} & \alpha_4 + \beta_{41} lrec_{t-1} + \beta_{42} ly_{t-1} + \beta_{43} lpe_{t-1} + \beta_{44} lpa_{t-1} + \beta_{45} lpo_{t-1} + \beta_{46} lfdi_{t-1} \\ & + \sum_{i=0}^{j_4} \delta_{(41)i} \Delta lrec_{t-i} + \sum_{i=0}^{k_4} \delta_{(42)i} \Delta ly_{t-i} + \sum_{i=0}^{l_4} \delta_{(43)i} \Delta lpe_{t-i} + \sum_{i=1}^{m_4} \delta_{(44)i} \Delta lpa_{t-i} \\ & + \sum_{i=0}^{n_4} \delta_{(45)i} \Delta lpo_{t-i} + \sum_{i=0}^{o_4} \delta_{(46)i} \Delta lfdi_{t-i} + \mu_{4t}\end{aligned} \tag{10}$$

$$\begin{aligned}\Delta lpo_t = {} & \alpha_5 + \beta_{51} lrec_{t-1} + \beta_{52} ly_{t-1} + \beta_{53} lpe_{t-1} + \beta_{54} lpa_{t-1} + \beta_{55} lpo_{t-1} + \beta_{56} lfdi_{t-1} \\ & + \sum_{i=0}^{j_5} \delta_{(51)i} \Delta lrec_{t-i} + \sum_{i=0}^{k_5} \delta_{(52)i} \Delta ly_{t-i} + \sum_{i=0}^{l_5} \delta_{(53)i} \Delta lpe_{t-i} + \sum_{i=0}^{m_5} \delta_{(54)i} \Delta lpa_{t-i} \\ & + \sum_{i=1}^{n_5} \delta_{(55)i} \Delta lpo_{t-i} + \sum_{i=0}^{o_5} \delta_{(56)i} \Delta lfdi_{t-i} + \mu_{5t}\end{aligned} \tag{11}$$

$$\begin{aligned}\Delta lfdi_t = {} & \alpha_6 + \beta_{61} lrec_{t-1} + \beta_{62} ly_{t-1} + \beta_{63} lpe_{t-1} + \beta_{64} lpa_{t-1} + \beta_{65} lpo_{t-1} + \beta_{66} lfdi_{t-1} \\ & + \sum_{i=0}^{j_6} \delta_{(61)i} \Delta lrec_{t-i} + \sum_{i=0}^{k_6} \delta_{(62)i} \Delta ly_{t-i} + \sum_{i=0}^{l_6} \delta_{(63)i} \Delta lpe_{t-i} + \sum_{i=0}^{m_6} \delta_{(64)i} \Delta lpa_{t-i} \\ & + \sum_{i=0}^{n_6} \delta_{(65)i} \Delta lpo_{t-i} + \sum_{i=1}^{o_6} \delta_{(66)i} \Delta lfdi_{t-i} + \mu_{6t}\end{aligned} \tag{12}$$

where Δ is the first difference operator, αs are constants, βs are long-run parameters, δs are short-run parameters and μ_ts are the error terms with zero mean and constant variance, $\mu_t \sim N(0, \sigma^2)$. j, k, l, m, n and o are the optimal lag orders. The inclusion of one or two lags is usually sufficient for annual series data (Dergiades and Tsoulfidis, 2011). However, to obtain more robust results, the current paper tests up to three lags and the optimal lag orders are selected based on the Akaike information criterion (AIC). This is because AIC is superior in small samples (Hamdi et al., 2014; Lütkepohl, 2005). The bounds F-test on lec_{t-1}, ly_{t-1}, lpe_{t-1}, lpa_{t-1}, lpo_{t-1}, $lfdi_{t-1}$ is performed to determine if the variables are co-integrated. The null hypothesis of no long-run relationship among the variables, H_0: $\beta_{i1} = \beta_{i2} = \beta_{i3} = \beta_{i4} = \beta_{i5} = \beta_{i6} = 0$, is tested against the alternative hypothesis of co-integration, H_a: $\beta_{i1} \neq \beta_{i2} \neq \beta_{i3} \neq \beta_{i4} \neq \beta_{i5} \neq \beta_{i6} \neq 0$. The hypothesis statements for equation (7) through equation (12) are summarised in Table 1.

Table 1 Hypothesis statements for bounds F-test

Equation	*H_0 (no co-integration)*	*H_a (co-integrated)*
(7)	$\beta_{11} = \beta_{12} = \beta_{13} = \beta_{14} = \beta_{15} = \beta_{16} = 0$	$\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_{14} \neq \beta_{15} \neq \beta_{16} \neq 0$
(8)	$\beta_{21} = \beta_{22} = \beta_{23} = \beta_{24} = \beta_{25} = \beta_{26} = 0$	$\beta_{21} \neq \beta_{22} \neq \beta_{23} \neq \beta_{24} \neq \beta_{25} \neq \beta_{26} \neq 0$
(9)	$\beta_{31} = \beta_{32} = \beta_{33} = \beta_{34} = \beta_{35} = \beta_{36} = 0$	$\beta_{31} \neq \beta_{32} \neq \beta_{33} \neq \beta_{34} \neq \beta_{35} \neq \beta_{36} \neq 0$
(10)	$\beta_{41} = \beta_{42} = \beta_{43} = \beta_{44} = \beta_{45} = \beta_{46} = 0$	$\beta_{41} \neq \beta_{42} \neq \beta_{43} \neq \beta_{44} \neq \beta_{45} \neq \beta_{46} \neq 0$
(11)	$\beta_{51} = \beta_{52} = \beta_{53} = \beta_{54} = \beta_{55} = \beta_{56} = 0$	$\beta_{51} \neq \beta_{52} \neq \beta_{53} \neq \beta_{54} \neq \beta_{55} \neq \beta_{56} \neq 0$
(12)	$\beta_{61} = \beta_{62} = \beta_{63} = \beta_{64} = \beta_{65} = \beta_{66} = 0$	$\beta_{61} \neq \beta_{62} \neq \beta_{63} \neq \beta_{64} \neq \beta_{65} \neq \beta_{66} \neq 0$

The computed F-statistic is compared with the critical values. Since the computed F-statistic has non-standard distribution, Pesaran et al. (2001) computed the upper and lower bound critical values for sample size exceeding 500. Nevertheless, Narayan (2005) argued that sample size does matter and computed a new set of critical values for small sample (30 to 80 observations). If the computed F-statistic is greater than the upper bound critical value, the null hypothesis of no co-integration relationship is rejected in favour of the alternative hypothesis that the variables are co-integrated. Contrary, the variables are not co-integrated if the computed F-statistic is less than the lower bound critical value. However, if the computed F-statistic is between both upper and lower bounds, no conclusion can be drawn. The presence of co-integration relationship among the variables implies that they can be modelled in an error correction model as in equation (13).

$$\begin{bmatrix}\Delta lrec\\ \Delta ly\\ \Delta lpe\\ \Delta lpa\\ \Delta lpo\\ \Delta lfdi\end{bmatrix}_t = \begin{bmatrix}\theta_1\\ \theta_2\\ \theta_3\\ \theta_4\\ \theta_5\\ \theta_6\end{bmatrix} + \begin{bmatrix}\phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} & \phi_{15} & \phi_{16}\\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} & \phi_{25} & \phi_{26}\\ \phi_{31} & \phi_{32} & \phi_{33} & \phi_{34} & \phi_{35} & \phi_{36}\\ \phi_{41} & \phi_{42} & \phi_{43} & \phi_{44} & \phi_{45} & \phi_{46}\\ \phi_{51} & \phi_{52} & \phi_{53} & \phi_{54} & \phi_{55} & \phi_{56}\\ \phi_{61} & \phi_{62} & \phi_{63} & \phi_{64} & \phi_{65} & \phi_{66}\end{bmatrix}_1 \begin{bmatrix}\Delta lrec\\ \Delta ly\\ \Delta lpe\\ \Delta lpa\\ \Delta lpo\\ \Delta lfdi\end{bmatrix}_{t-1}$$

$$+ \begin{bmatrix}\phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} & \phi_{15} & \phi_{16}\\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} & \phi_{25} & \phi_{26}\\ \phi_{31} & \phi_{32} & \phi_{33} & \phi_{34} & \phi_{35} & \phi_{36}\\ \phi_{41} & \phi_{42} & \phi_{43} & \phi_{44} & \phi_{45} & \phi_{46}\\ \phi_{51} & \phi_{52} & \phi_{53} & \phi_{54} & \phi_{55} & \phi_{56}\\ \phi_{61} & \phi_{62} & \phi_{63} & \phi_{64} & \phi_{65} & \phi_{66}\end{bmatrix}_2 \begin{bmatrix}\Delta lrec\\ \Delta ly\\ \Delta lpe\\ \Delta lpa\\ \Delta lpo\\ \Delta lfdi\end{bmatrix}_{t-2}$$

$$+ \cdots + \begin{bmatrix}\phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} & \phi_{15} & \phi_{16}\\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} & \phi_{25} & \phi_{26}\\ \phi_{31} & \phi_{32} & \phi_{33} & \phi_{34} & \phi_{35} & \phi_{36}\\ \phi_{41} & \phi_{42} & \phi_{43} & \phi_{44} & \phi_{45} & \phi_{46}\\ \phi_{51} & \phi_{52} & \phi_{53} & \phi_{54} & \phi_{55} & \phi_{56}\\ \phi_{61} & \phi_{62} & \phi_{63} & \phi_{64} & \phi_{65} & \phi_{66}\end{bmatrix}_p \begin{bmatrix}\Delta lrec\\ \Delta ly\\ \Delta lpe\\ \Delta lpa\\ \Delta lpo\\ \Delta lfdi\end{bmatrix}_{t-p}$$

$$+ \begin{bmatrix}\gamma_1\\ \gamma_2\\ \gamma_3\\ \gamma_4\\ \gamma_5\\ \gamma_6\end{bmatrix} \left[ECT_{t-1}\right] + \begin{bmatrix}\mu_1\\ \mu_2\\ \mu_3\\ \mu_4\\ \mu_5\\ \mu_6\end{bmatrix}_t \qquad (13)$$

where γs are the speeds of adjustment, p is the optimal lag orders determined by AIC, θs are the constant terms, ϕs are the short-run coefficients and μs are the error terms with zero mean and constant variance, $\mu_t \sim N(0, \sigma^2)$. ECTt-1 is the lagged error correction term derived from the normalised co-integrating equation as in equation (14) (Shahbaz and Hooi, 2012; Tang and Tan, 2013).

$$ECT_{t-1} = lrec_{t-1} + \frac{\alpha_1}{\beta_{11}} + \frac{\beta_{12}}{\beta_{11}} ly_{t-1} + \frac{\beta_{13}}{\beta_{11}} lpe_{t-1} + \frac{\beta_{14}}{\beta_{11}} lpa_{t-1} + \frac{\beta_{15}}{\beta_{11}} lpo_{t-1} + \frac{\beta_{16}}{\beta_{11}} lfdi_{t-1} \quad (14)$$

The rate of convergence to the long-run disequilibrium is given by the speed of adjustment while the long-run multivariate Granger causality is exposed by the significance of the lagged error correction term via t-testing. If the lagged error correction term is significant, there is long-run multivariate Granger causality from the explanatory variable to the dependent variable. The short-run multivariate Granger causality is exposed in the significance of the first differenced lagged explanatory variables via Wald F-testing. If the F-statistic is significant, there is short-run Granger causality from the explanatory variable to the dependent variable.

Nevertheless, the Granger causality approach has some limitations (Hamdi et al., 2014). This is because the VECM Granger causality test can only indicate the relative strength of causal relationships within the selected time period. This weakens the reliability of the results. To circumvent this limitation, the generalised impulse response function (GIRF) and generalised forecast error variance decomposition (GFEVD) methods are employed. These approaches use a VAR system and do not require a pre-specified causal ordering of the variables to orthogonalise the innovations (Pesaran and Shin, 1998). Hence, they are more robust and insensitive to the ordering of variables. The GIRF shows the time profile of the effect of shocks while the GFEVD shows the proportional effect of the shocks.

6 Results analysis

The descriptive statistics of all the variables under investigation are summarised in Table 2. Generally, there are no missing data or outliers. The standard deviations for all variables range from 0.179 to 1.018. All the variables are normally distributed except for *lfdi*. The correlation matrix shows that the variables are highly inter-correlated, which is not too surprising because most macroeconomic variables contains a unit root.

The results of unit root tests are presented in Table 3. ADF and P-P confirmed that REC and real disposable income are integrated on the order of one but price of electricity is integrated on the order of zero. All three unit root tests show that the price of electric appliances is integrated on the order of one. As for population and FDI, neither ADF nor KPSS give a clear indication on the integration order because the ADF's null hypothesis of unit root could not be rejected at level and first difference while the KPSS's null hypothesis of stationary is rejected at level and first difference. However, the P-P's null hypothesis of unit root is rejected at level at a high significance level of 1%. This suggests that population and FDI are integrated on the order of zero. Hence, electricity consumption, real disposable income and price of electric appliances are taken as $I(1)$ variables while price of electricity, population and FDI are taken as $I(0)$ variables. These results are consistent with the findings of past studies whereby most of the macroeconomic variables were found to be not stationary at level but stationary after first differencing (Bekhet and Yasmin, 2013; Caraiani et al., 2015; Lau et al., 2014; Zamani and Branch, 2012).

Table 2 Descriptive statistics and correlation matrix

Statistics	*lrec*	*ly*	*lpe*	*lpa*	*lpo*	*lfdi*
Mean	1.924	5.728	4.402	4.479	3.023	2.291
Median	2.016	5.877	4.434	4.533	3.042	2.687
Max	3.304	6.668	4.724	4.746	3.399	3.616
Min	0.246	4.638	3.802	4.074	2.580	–1.030
Std. dev.	0.928	0.627	0.243	0.179	0.255	1.018
Skewness	–0.180	–0.181	–0.723	–0.526	–0.172	–1.102
Kurtosis	1.721	1.683	2.807	2.343	1.753	4.144
J-B	2.648	2.800	3.196	2.307	2.510	9.246
Prob.	0.266	0.247	0.202	0.315	0.285	0.010
lrec	1.000					
ly	0.996	1.000				
lpe	0.972	0.961	1.000			
lpa	0.981	0.983	0.981	1.000		
lpo	0.999	0.996	0.969	0.981	1.000	
lfdi	0.494	0.533	0.467	0.532	0.499	1.000

Source: Output of Eviews package version 7.1

Table 3 Unit root tests on each variable

Variable	*ADF*		*P-P*		*KPSS*	
	I(0)	*I(1)*	*I(0)*	*I(1)*	*I(0)*	*I(1)*
lrec	–2.806[c]	–5.142[a]	–2.786[c]	–5.160[a]	0.712[b]	0.40[c]
ly	–1.383	–4.782[a]	–1.314	–4.787[a]	0.709[b]	0.203[c]
lpe	–4.026[a]	NA	–3.331[b]	NA	0.709[b]	0.347
lpa	–1.609	–3.556[b]	–2.747[c]	–2.997[b]	0.713[b]	0.355
lpo	–1.990	0.982	–4.780[a]	NA	0.711[b]	0.589[b]
lfdi	–1.617	–2.453	–4.033[a]	NA	0.544[b]	0.443[c]

Notes: a, b, c denotes statistical significance at 1%, 5% and 10% level respectively.

Source: Output of Eviews package version 7.1

Since there are $I(0)$ and $I(1)$ variables, ARDL bounds testing is performed to deduce the existence of the co-integration relationships among the variables and the results are tabulated in Table 4. The calculated F-statistics for all models are larger than the 5% upper bound critical value, which indicates the existence of strong co-integrating relationships among the variables. Therefore, all the variables are concluded as co-integrated.

Table 4 Long-run relationship results

Model	F-statistic	Critical values						Decision
		1%		5%		10%		
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
lrec | ly, lpe, lpa, lpo, lfdi	4.875[b]	4.257	6.040	3.037	4.443	2.508	3.763	Co-integrated
ly | lrec, lpe, lpa, lpo, lfdi	74.844[a]	4.257	6.040	3.037	4.443	2.508	3.763	Co-integrated
lpe | lrec, ly, lpa, lpo, lfdi	9.917[a]	4.257	6.040	3.037	4.443	2.508	3.763	Co-integrated
lpa | lrec, ly, lpe, lpo, lfdi	5.147[b]	4.257	6.040	3.037	4.443	2.508	3.763	Co-integrated
lpo | lrec, ly, lpe, lpa, lfdi	8.794[a]	4.257	6.040	3.037	4.443	2.508	3.763	Co-integrated
lfdi | lrec, ly, lpe, lpa, lpo	18.492[a]	4.257	6.040	3.037	4.443	2.508	3.763	Co-integrated

Notes: a, b, c as defined in Table 3. d denotes inconclusiveness (falls between upper bound and lower bound values). Critical values obtained from Narayan (2005) for unrestricted intercept and no trend (k = 5, T = 35).

Source: Output of Eviews package version 7.1

The diagnostic tests (Jarque-Bera, autoregressive conditional heteroskedasticity, Breusch-Godfrey Lagrange multiplier (LM) test, Ramsey regression specification error test) are executed to ensure the models do not violate any regression assumptions, while the cumulative sum control chart (CUSUM) and CUSUM of squares tests are performed to check for model's parameters instability (not reported here to conserve space). The results of all the diagnostic tests show that none of the models are plagued with regression assumption violations and both of the CUSUM and CUSUM of squares curves do not exceed the 5% critical boundaries. Hence, one can conclude that all the models are correct and stable over the sample period (1978–2013).

The variables are then modelled in an error correction model, whereby the short-run behaviours are tied to the long-run relationship via an error correction term (*ECT*) (Holtedahl and Joutz, 2004). The coefficients of the lagged error correction term (ECT_{t-1}) signify the rate of convergence to the long-run disequilibrium. Meanwhile, their significance exposes the direction of long-run multivariate Granger causalities. To determine the directions of short-run multivariate Granger causalities, Wald F-tests on the first differenced lagged explanatory variables are performed (Sbia et al., 2014). Table 5 shows the results of the long-run and short-run multivariate Granger causalities.

The speed of adjustment in the model for REC is –0.446. This shows that about half (44.6%) of the long-run disequilibrium is corrected in the short run of REC. Note also the high speed of adjustment (–0.218) in the model for price of electric appliances. The results show that the price of electric appliances responded substantially to the long-run disequilibrium in REC. This further supports the importance of the price of electric appliances in examining REC. Furthermore, the lagged error correction term is significant in the model for REC, price of electricity and price of electric appliances. This shows that bidirectional multivariate Granger causality exists between REC and both prices in the long run. Meanwhile, the error correction term in the model for real disposable income, population and FDI is insignificant. Hence, unidirectional multivariate Granger causality flows from these variables to REC in the long run.

Table 5 Long-run and short-run multivariate Granger causalities results

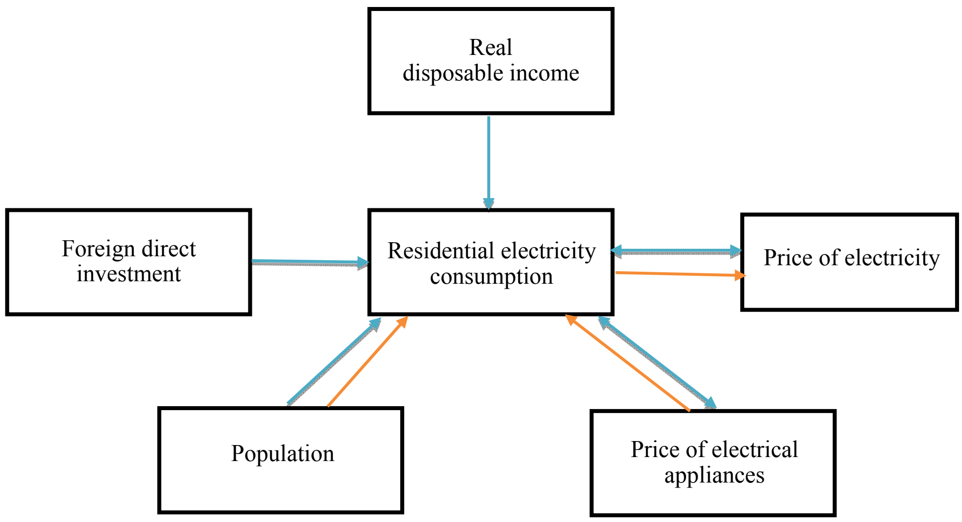
Model	*Short-run causality (Wald F-test)*						*Long-run causality*	
	$\Delta lrec_{t-i}$	Δly_{t-i}	Δlpe_{t-i}	Δlpa_{t-i}	Δlpo_{t-i}	$\Delta lfdi_{t-i}$	γ	*t-statistic*
$\Delta lrec_t$	-	0.596	0.192	3.646[b]	4.903[b]	2.400	–0.446	–4.047[a]
Δly_t	0.692	-	2.364	1.242	0.057	0.510	–0.024	–0.105
Δlpe_t	5.097[b]	2.069	-	0.869	5.345[b]	0.948	–0.129	–2.772[b]
Δlpa_t	0.824	2.734[c]	1.754	-	1.616	1.845	–0.218	–3.879[a]
Δlpo_t	0.385	0.072	0.460	0.286	-	0.062	–0.001	–0.103
$\Delta lfdi_t$	1.054	0.681	2.334	1.539	0.422	-	–3.208	–0.469

Note: a, b, c as defined in Table 3.

Source: Output of Eviews package version 7.1

In the model for REC, only the first differenced lagged price of electric appliances and population are significant, which show that price of electric appliances and population Granger cause REC in the short-run. Similarly, the first differenced lagged REC is significant in the model for price of electricity, which shows that REC Granger causes the price of electricity in the short-run. Hence, in the short run, unidirectional multivariate Granger causality flows from price of electric appliances and population to REC. Unidirectional multivariate Granger causality also flows from REC to price of electricity. There is no multivariate Granger causality between REC and real disposable income or FDI in the short run. The results on the long- and short-run multivariate Granger causalities are illustrated in Figure 2.

Figure 2 Long- and short-run multivariate Granger causalities (see online version for colours)

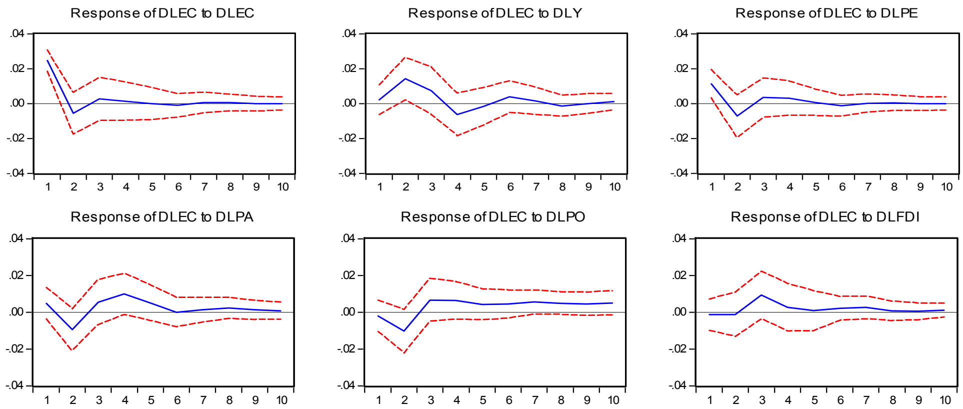


Notes: [long-run line] represents long-run and [short-run line] represents short-run

The multivariate Granger causality results show that the price of electric appliances and population Granger cause REC in the long and short run. Hence, policies that control the price of electric appliances will affect REC. The absence of multivariate Granger causality from REC to real disposable income in the long and short run indicates that policies that reduce REC do not affect real disposable income adversely. Therefore, policies that reduce REC should be implemented.

The VECM Granger causality only shows the causality directions among the variables. To capture the causal relationships beyond the selected time period, the GIRF and GFEVD are performed. The impulse response function shows the reaction in one variable to shocks stemming from other variables. Figure 3 shows the response of REC to innovation for each variable in the model.

Figure 3 Generalised impulse response function plots for REC (see online version for colours)



Source: Output of Eviews package version 7.1

Table 6 Generalised forecast error variance decomposition results

Time horizon	*Variable shocked*					
	lrec	*ly*	*lpe*	*lpa*	*lpo*	*lfdi*
1	61.37	4.12	41.61	2.56	0.33	1.63
2	52.46	4.64	42.01	2.75	1.54	1.55
3	46.60	9.23	35.36	2.73	2.04	4.67
4	45.16	9.26	30.05	3.21	2.33	4.79
5	43.94	9.07	27.87	3.84	2.20	4.72
6	42.83	8.97	27.47	3.96	1.99	4.85
7	42.06	8.89	27.66	3.95	1.79	4.83
8	41.47	8.87	27.79	3.93	1.63	4.86
9	40.72	8.89	27.74	3.93	1.50	4.86
10	39.94	8.87	27.62	3.95	1.40	4.85

Source: Output of Microfit package version 4.1

Figure 3 shows that the response of REC to shocks to all variables alternate between positive and negative. However, the effects of the shocks diminish with time. This shows that REC stabilises after some time regardless of which variable is shocked. In contrast to the impulse response function, the variance decomposition approach indicates the magnitude of the predicted error variance accounted for by innovations from each variable. Table 6 shows the results on GFEVD for REC over different time horizons.

The results indicate that in the first horizon, 61.37% of variance in REC is due to its own innovative shocks. Akpan and Akpan (2012), Alshehry and Belloumi (2015) and Bloch et al. (2015) also found that most of the variance in energy consumption is due to own shocks. A one standard deviation shock in real disposable income explains 4.12% of the REC variance. Price of electricity, price of electric appliances, population and FDI explain 41.61%, 2.56%, 0.33% and 1.63% of the variance in REC, respectively. Among all the determinants of REC, shocks on price of electricity explain most of the variance in REC. At the tenth time horizon, the results are still comparable to the results in the first time horizon. Own shocks still explain most of the variance in REC and price of electricity remains the determinant that explains most of the variance in REC.

7 Conclusions and policy implications

Contrary to existing studies, the current paper includes the price of electric appliances in the consumption function of residential electricity. Focussing on the residential sector enables the special characteristics of this sector to prevail. The results show that all the variables are co-integrated, proving the existence of a genuine relationship among them in the long run. Nearly half of the disequilibrium of REC in the long run is corrected in the short run. The price of electric appliances Granger causes REC in the long and short run but the price of electricity only Granger causes REC in the long run. Throughout all time horizons, the response of REC to shocks to all variables alternates between positive and negative and diminishes with time. The variance in REC is mostly due to its own shocks. In addition to own shocks, shocks to the price of electricity contribute most of the variance in REC.

Since the price of electricity Granger causes REC and a one standard deviation shock in the former causes almost one third of the variance in the latter, pricing policies is effective in controlling and reducing REC. Under the electricity bill exemption programme introduced by the government, the consumer will not enjoy any bill exemption if the consumption exceeds RM20 a month. The impact of this policy is a substantial increase in the relative price of electricity (i.e. from zero to full electricity bill) if the consumer does not use electricity efficiently and exceeds RM20. This is similar to a huge price increase whenever the electricity consumption surpasses the threshold limit. Since a small increase in the price of electricity is sufficient to cause REC to decrease, this policy serves as a strong deterrent to over-consumption. However, this policy only affects 15% of the total households due to the rather low limit of RM20. In order to increase the effect of this policy, it is suggested that the mechanism of this policy is replaced with a diminishing exemption mechanism. This means that full exemption can be given if the electricity bill is RM20 or below but partial exemption should also be given to higher consumption levels i.e. the percentage of exemption reduces as the consumption level increases so that households in all consumption levels are motivated to reduce their electricity consumption to enjoy a higher exemption percentage.

Acknowledgements

This research is funded by Kursi Biasiswa Ekonomi Tenaga, a post graduate scholarship program administered by Institute of Energy Policy and Research and supported by Malaysia Energy Supply Industry Trust Account, a trust account under the administration of Ministry of Energy, Green Technology and Water, Government of Malaysia.

References

Adom, P.K., Bekoe, W. and Akoena, S.K.K. (2012) 'Modelling aggregate domestic electricity demand in Ghana: an autoregressive distributed lag bounds cointegration approach', *Energy Policy*, Vol. 42, pp.530–537.

Akpan, G.E. and Akpan, U.F. (2012) 'Electricity consumption, carbon emissions and economic growth in Nigeria', *International Journal of Energy Economics and Policy*, Vol. 2, No. 4, pp.292–306.

Al-Faris, A.R.F. (2002) 'The demand for electricity in the GCC countries', *Energy Policy*, Vol. 30, pp.117–124.

Alshehry, A.S. and Belloumi, M. (2015) 'Energy consumption, carbon dioxide emissions and economic growth: the case of Saudi Arabia', *Renewable and Sustainable Energy Reviews*, Vol. 41, pp.237–247.

Amusa, H., Amusa, K. and Mabugu, R. (2009) 'Aggregate demand for electricity in South Africa: an analysis using the bounds testing approach to cointegration', *Energy Policy*, Vol. 37, pp.4167–4175.

Asafu-Adjaye, J. (2000) 'The relationship between energy consumption, energy prices and economic growth: time series evidence from Asian developing countries', *Energy Economics*, Vol. 22, pp.615–625.

Asteriou, D. and Hall, S.G. (2007) *Applied Econometrics: A Modern Approach*, revised ed., Palgrave Macmillan, New York.

Atanasiu, B. and Bertoldi, P. (2010) 'Latest assessment of residential electricity consumption and efficiency trends in the European Union', *International Journal of Green Energy*, Vol. 7, No. 5, pp.552–575.

Athukorala, P.P.W. and Wilson, C. (2010) 'Estimating short and long-term residential demand for electricity: new evidence from Sri Lanka', *Energy Economics*, Vol. 32, pp.S34–S40.

Bekhet, H.A. and Ivy-Yap, L.L. (2014) 'Highlighting energy policies and strategies for the residential sector in Malaysia', *International Journal of Energy Economics and Policy*, Vol. 4, No. 3, pp.448–456.

Bekhet, H.A. and Matar, A. (2013) 'Co-integration and causality analysis between stock market prices and their determinates in Jordan', *Economic Modelling*, Vol. 35, pp.508–514.

Bekhet, H.A. and Othman, N.S. (2011a) 'Assessing the elasticities of electricity consumption for rural and urban areas in Malaysia: a non-linear approach', *International Journal of Economics and Finance*, Vol. 3, No. 1, pp.208–217.

Bekhet, H.A. and Othman, N.S. (2011b) 'Causality analysis among electricity consumption, consumer expenditure, gross domestic product (GDP) and foreign direct investment (FDI): case study of Malaysia', *Journal of Economics and International Finance*, Vol. 3, No. 4, pp.228–235.

Bekhet, H.A. and Yasmin, T. (2013) 'Disclosing the relationship among CO2 emissions, energy consumption, economic growth and bilateral trade between Singapore and Malaysia: an econometric analysis', *International Journal of Social, Human Science and Engineering*, Vol. 7, No. 9, pp.321–326.

Bekhet, H.A. and Yusop, N.Y.M. (2009) 'Assessing the relationship between oil prices, energy consumption and macroeconomic performance in Malaysia: co-integration and vector error correction model (VECM) approach', *International Business Research*, Vol. 2, No. 3, pp.152–175.

Bloch, H., Rafiq, S. and Salim, R. (2015) 'Economic growth with coal, oil and renewable energy consumption in China: prospects for fuel substitution', *Economic Modelling*, Vol. 44, pp.104–115.

Boutabba, M.A. (2014) 'The impact of financial development, income, energy and trade on carbon emissions: evidence from the Indian economy', *Economic Modelling*, Vol. 40, pp.33–41.

Caraiani, C., Lungu, C.I. and Dascălu, C. (2015) 'Energy consumption and GDP causality: a three-step analysis for emerging European countries', *Renewable and Sustainable Energy Reviews*, Vol. 44, pp.198–210.

Cebula, R.J. (2012) 'US residential electricity consumption: the effect of states' pursuit of energy efficiency policies', *Applied Economics Letters*, Vol. 19, No. 15, pp.1499–1503.

Chandran, V.G.R., Sharma, S. and Madhavan, K. (2010) 'Electricity consumption-growth nexus: the case of Malaysia', *Energy Policy*, Vol. 38, pp.606–612.

Chen, S-T., Kuo, H-I. and Chen, C-C. (2007) 'The relationship between GDP and electricity consumption in 10 Asian countries', *Energy Policy*, Vol. 35, pp.2611–2621.

Dergiades, T. and Tsoulfidis, L. (2008) 'Estimating residential demand for electricity in the United States, 1965–2006', *Energy Economics*, Vol. 30, pp.2722–2730.

Dergiades, T. and Tsoulfidis, L. (2011) 'Revisiting residential demand for electricity in Greece: new evidence from the ARDL approach to cointegration analysis', *Empirical Economics*, Vol. 41, pp.511–531.

Dickey, D.A. and Fuller, W.A. (1979) 'Distribution of the estimators for autoregressive time series with a unit root', *Journal of the American Statistical Association*, Vol. 74, No. 366, pp.427–431.

Farhani, S., Shahbaz, M., Arouri, M. and Teulon, F. (2014) 'The role of natural gas consumption and trade in Tunisia's output', *Energy Policy*, Vol. 66, pp.677–684.

Fei, L., Dong, S., Xue, L., Liang, Q. and Yang, W. (2011) 'Energy consumption-economic growth relationship and carbon dioxide emissions in China', *Energy Policy*, Vol. 39, pp.568–574.

Fell, H., Li, S. and Paul, A. (2014) 'A new look at residential electricity demand using household expenditure data', *International Journal of Industrial Organization*, Vol. 33, pp.37–47.

Filippini, M. and Pachauri, S. (2004) 'Elasticities of electricity demand in urban Indian households', *Energy Policy*, Vol. 32, pp.429–436.

Gam, I. and Rejeb, J.B. (2012) 'How can we assess the relation between equipment, price and electricity demand in Tunisia?', *International Journal of Energy Economics and Policy*, Vol. 2, No. 3, pp.159–166.

Glasure, Y.U. (2002) 'Energy and national income in Korea: further evidence on the role of omitted variables', *Energy Economics*, Vol. 24, pp.355–365.

Halicioglu, F. (2007) 'Residential electricity demand dynamics in Turkey', *Energy Economics*, Vol. 29, pp.199–210.

Hamdi, H., Sbia, R. and Shahbaz, M. (2014) 'The nexus between electricity consumption and economic growth in Bahrain', *Economic Modelling*, Vol. 38, pp.227–237.

Ho, C-Y. and Siu, K.W. (2007) 'A dynamic equilibrium of electricity consumption and GDP in Hong Kong: an empirical investigation', *Energy Policy*, Vol. 35, pp.2507–2513.

Holtedahl, P. and Joutz, F.L. (2004) 'Residential electricity demand in Taiwan', *Energy Economics*, Vol. 26, pp.201–224.

Ivy-Yap, L.L. and Bekhet, H.A. (2014) 'Modeling residential electricity consumption function in Malaysia: time series approach', *International Journal of Electrical, Electronic Science and Engineering*, Vol. 8, No. 3, pp.39–45.

Ivy-Yap, L.L. and Bekhet, H.A. (2015) 'Examining the feedback response of residential electricity consumption towards changes in its determinants: evidence from Malaysia', *International Journal of Energy Economics and Policy*, Vol. 5, No. 3, pp.772–781.

Jamil, F. and Ahmad, E. (2010) 'The relationship between electricity consumption, electricity prices and GDP in Pakistan', *Energy Policy*, Vol. 38, pp.6016–6025.

Jamil, F. and Ahmad, E. (2011) 'Income and price elasticities of electricity demand: aggregate and sector-wise analyses', *Energy Policy*, Vol. 39, pp.5519–5527.

Jumbe, C.B. (2004) 'Cointegration and causality between electricity consumption and GDP: empirical evidence from Malawi', *Energy Economics*, Vol. 26, pp.61–68.

Kraft, J. and Kraft, A. (1978) 'On the relationship between energy and GNP', *The Journal of Energy and Development*, Vol. 3, No. 2, pp.401–403.

Krishnamurthy, C.K.B. and Kriström, B. (2015) 'A cross-country analysis of residential electricity demand in 11 OECD-countries', *Resource and Energy Economics*, Vol. 39, pp.68–88.

Kwiatkowski, D., Phillips, P.C.B., Schmidt, P. and Shin, Y. (1992) 'Testing the null hypothesis of stationarity against the alternative of a unit root: how sure are we that economic time series have a unit root?', *Journal of Econometrics*, Vol. 54, pp.159–178.

Lau, L., Choong, C. and Eng, Y. (2014) 'Investigation of the environmental Kuznets curve for carbon emissions in Malaysia: do foreign direct investment and trade matter?', *Energy Policy*, Vol. 68, pp.490–497.

Lean, H.H. and Smyth, R. (2010) 'On the dynamics of aggregate output, electricity consumption and exports in Malaysia: evidence from multivariate Granger causality tests', *Applied Energy*, Vol. 87, pp.1963–1971.

Lütkepohl, H. (2005) *New Introduction to Multiple Time Series Analysis*, Springer-Verlag, Berlin.

Masih, A.M.M. and Masih, R. (1996) 'Energy consumption, real income and temporal causality: results from a multi-country study based on cointegration and error-correction modelling techniques', *Energy Economics*, Vol. 18, pp.165–183.

Morimoto, R. and Hope, C. (2004) 'The impact of electricity supply on economic growth in Sri Lanka', *Energy Economics*, Vol. 26, pp.77–85.

Nakajima, T. (2010) 'The residential demand for electricity in Japan: an examination using empirical panel analysis techniques', *Journal of Asian Economics*, Vol. 21, No. 4, pp.412–420.

Narayan, P.K. (2005) 'The saving and investment nexus for China: evidence from cointegration tests', *Applied Economics*, Vol. 37, No. 17, pp.1979–1990.

Narayan, P.K., Smyth, R. and Prasad, A. (2007) 'Electricity consumption in G7 countries: a panel cointegration analysis of residential demand elasticities', *Energy Policy*, Vol. 35, pp.4485–4494.

Odhiambo, N.M. (2009) 'Electricity consumption and economic growth in South Africa: a trivariate causality test', *Energy Economics*, Vol. 31, pp.635–640.

Oh, T.H., Pang, S.Y. and Chua, S.C. (2010) 'Energy policy and alternative energy in Malaysia: issues and challenges for sustainable growth', *Renewable and Sustainable Energy Reviews*, Vol. 14, pp.1241–1252.

Ozturk, I. (2010) 'A literature survey on energy-growth nexus', *Energy Policy*, Vol. 38, pp.340–349.

Pesaran, H.H. and Shin, Y. (1998) 'Generalized impulse response analysis in linear multivariate models', *Economics Letters*, Vol. 58, pp.17–29.

Pesaran, M.H., Shin, Y. and Smith, R.J. (2001) 'Bounds testing approaches to the analysis of level relationships', *Journal of Applied Econometrics*, Vol. 16, pp.289–326.

Phillips, P.C.B. and Perron, P. (1988) 'Testing for a unit root in time series regression', *Biometrika*, Vol. 75, No. 2, pp.335–346.

Saidur, R., Masjuki, H.H. and Jamaluddin, M.Y. (2007) 'An application of energy and exergy analysis in residential sector of Malaysia', *Energy Policy*, Vol. 35, No. 2, pp.1050–1063.

Sbia, R., Shahbaz, M. and Hamdi, H. (2014) 'A contribution of foreign direct investment, clean energy, trade openness, carbon emissions and economic growth to energy demand in UAE', *Economic Modelling*, Vol. 36, pp.191–197.

Shahbaz, M. and Hooi, H. (2012) 'The dynamics of electricity consumption and economic growth: a revisit study of their causality in Pakistan', *Energy*, Vol. 39, No. 1, pp.146–153.

Solarin, A.S. and Shahbaz, M. (2015) 'Natural gas consumption and economic growth: the role of foreign direct investment, capital formation and trade openness in Malaysia', *Renewable and Sustainable Energy Reviews*, Vol. 42, pp.835–845.

Stern, D.I. (2011) 'The role of energy in economic growth', *Annals of the New York Academy of Sciences*, Vol. 1219, pp.26–51.

Tang, C.F. (2008) 'A re-examination of the relationship between electricity consumption and economic growth in Malaysia', *Energy Policy*, Vol. 36, pp.3077–3085.

Tang, C.F. and Tan, E.C. (2013) 'Exploring the nexus of electricity consumption, economic growth, energy prices and technology innovation in Malaysia', *Applied Energy*, Vol. 104, pp.297–305.

Tenaga Nasional Berhad (2013a) *RM20 Government Subsidy* [online] http://www.tnb.com.my.

Tenaga Nasional Berhad (2013b) *SAVE Rebate Program* [online] http://www.tnb.com.my.

Vogelvang, B. (2005) *Econometrics: Theory and Applications with EViews*, 1st ed., Pearson, Harlow.

Yoo, S-H. (2005) 'Electricity consumption and economic growth: evidence from Korea', *Energy Policy*, Vol. 33, pp.1627–1632.

Zamani, M. and Branch, A. (2012) 'Evaluating the relationship between the energy consumption and the macroeconomic indicators', *Research Journal of Environmental and Earth Sciences*, Vol. 4, No. 12, pp.1025–1032.

Ziramba, E. (2008) 'The demand for residential electricity in South Africa', *Energy Policy*, Vol. 36, pp.3460–3466.

Management and technical economic analysis of a hybrid system (wind/diesel) in southern Algeria

Abdelhamid Ksentini* and Ahmed Bensalem

Department of Electrical Engineering,
El-hadj Lakhdar University,
Batna, 05000, Algeria
Email: ninaks23@yahoo.fr
Email: Bensalem_ahmed_dz@yahoo.fr
*Corresponding author

El-Bahi Azzag

Department of Electrical Engineering,
Badji Mokhtar University,
Annaba, 23000, Algeria
Email: azzag15@yahoo.fr

Abstract: The increase in energy sources using fossil fuels is the main source of pollution. Diesel power stations are adapted to remote sites of energy sources. From an economic and technical point of view the integration of a hybrid system is beneficial. In this situation, the combination of hybrid power system (wind-diesel-battery)-based renewable energy is a strategy for the use of three complementary sources that will be suitable for continuity of service, reducing energy costs, longevity of the generator and the elimination of part of the greenhouse gas, this is the reason that motivated us to develop this product that addresses the optimal management of the production of electronic system energy to weather conditions (wind speed, temperature, relief) and the technical and economic analysis to meet our energy requirements to reduce emissions of greenhouse gases.

Keywords: wind; hybrid system; modelling; rural electrification; energy management; fuel; cost; Algeria.

Reference to this paper should be made as follows: Ksentini, A., Bensalem, A. and Azzag, E-B. (2016) 'Management and technical economic analysis of a hybrid system (wind/diesel) in southern Algeria', *Int. J. Energy Technology and Policy*, Vol. 12, No. 1, pp.60–83.

Biographical notes: Abdelhamid Ksentini is Doctorant in Electrical Engineering and member of the Laboratory of Electrical Engineering of University El-hadj Lakhdar, Batna, Algeria. His research activities include: renewable energy and high voltage (HV).

Ahmed Bensalem received his MSc in Electrical Engineering from the University of McGill, Montreal, Canada and PhD from the University of Batna. His research activity is focused on power system operation, mainly on optimal generation management. Currently, he is Professor and Lecturer at the Electrical Engineering Department of the University of Batna. He is a member of the Algerian Association of HV Electrical Networks.

El-Bahi Azzag received his Doctor of Electrical Networks from Department of Electrical Badji Mokhtar University of Annaba, Algeria. He is a Lecturer in the Department of Electrical Engineering at the University Badji Mokhtar. His research activities also include devices renewable energy, facts, and high voltage. His is a team leader in Laboratory Electrical Engineering from the University of Badji Mokhtar, Annaba, Algeria.

1 Introduction

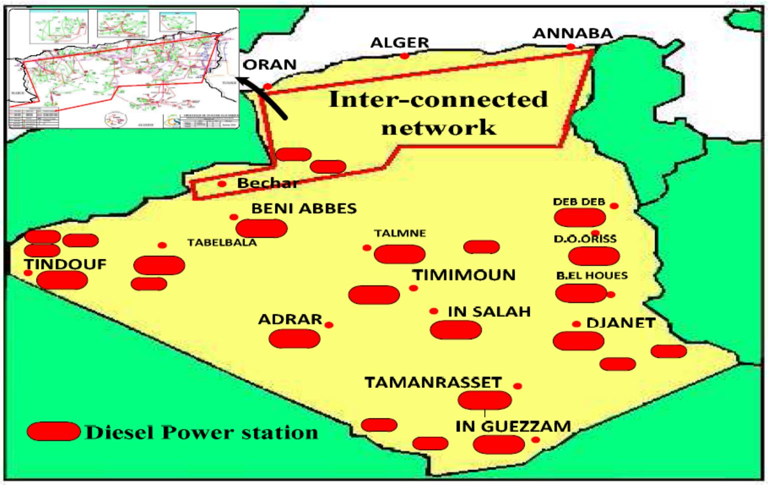
The electric power is an essential factor for the development and the evolution of the human societies that is also the field of the improvement of the living conditions and the development of the industrial activities. Although, the need of electricity is always increasing nowadays, and far from the use of polluting fossil energies like oil and the gas, several countries turned to the new form of energy known as 'renewable energies'. Indeed, a true world challenge is being taken with serious today, as well as on the policy of reducing of the gas emissions for purpose of greenhouse, while bringing back them to a tolerable level according to the convention of Kyoto. The evolution of technologies of the components returns the conversion of these energies increasingly profitable and thus their uses economically become competitive compared to the traditional sources (Galdi et al., 2009). These energies are exploited in mono source or hybrid and mode autonomous or connected to the network (Merzouk and Merzouk, 2006; Stoyanov et al., 2007). The power plant by several sources must meet connection architecture. Similarly, proper management of production sources for the consumer to cover the energy needs of the facility and ensure optimal use of the energy produced. In this context, we propose a study for a judicious choice of the network architecture composed by an autonomous wind diesel generator and a storage battery.

After this introductory, Section 1, this article is organised as follows: Section 2 presents the problem of the production of electricity in Algeria by the group diesel. Section 3 presents policy implications. In Section 4, we show the wind resource in Algeria. Section 5 presents the component wind diesel generation system. Section 6 shows the modelling of the wind diesel hybrid system (WDHS) components. Section 7 presents the control strategy of the isolated hybrid system. Section 8 presents the simulation and results. Conclusions have been made in Section 9.

2 Problems of the production of electricity by a diesel group

The Algerian network consists of an interconnected network in the north and more isolated networks are built around generating systems based on diesel generators to the South. The diesel generating fleet is distributed through the south of the country on more than 22 sites (see Figure 1). Diesel power stations are located in inaccessible areas, making it difficult fuel supply (see Table 1), moving the staff for operation and maintenance. This is why the use of diesel generators combined with a source of renewable energy and a storage system are recommended. It is with this objective that fits my article with the use of multiple sources for energy supply of the appropriate system.

Figure 1 Distribution of diesel generators in remote Algeria in the regions (see online version for colours)



Source: Catalogue SONELGAZ

Table 1 Supply fuel

Central	*Supply distance (Km)*	*Number of rotation of trucks per month*
TINDOUF	2,000	35
TAMANRASSET	1,600	54
DJANET	1,620	14
B.EL HAOUES	1,500	2
IN GUEZZAM	2,000	4

Source: Catalogue SONELGAZ

3 Policy implications

Algeria is a vast country with gas and petroleum the rising price of oil in the world will not necessarily encourage the use of renewable energies. However, the signing of the Kyoto agreements by Algeria and the emergence of environmental problems have a government program which was set up to boost investment in the field of power generation from wind energy for 3% of the national balance sheet for 2027. Knowing that the energy resources of Algeria have been estimated by the Renewable Energy Development Centre (REDC) since the '90s.

In this context, Algeria can be among the countries using major sources of renewable energy in the world with all its essential elements in this context, especially as the global perspective today on the search for alternative sources energy from traditional sources tends towards the exploitation of wind as an energy source and a number of other energy sources like the sun and the water, thus Algeria is naturally is concerned by such sources, especially wind.

4 Wind speed in Algeria

The wind resource in Algeria varies greatly from one place to another. This is mainly due to a highly diversified topography and climate. Table 2 shows the wind speed in different region of Algeria. Average annual rates obtained vary from 1.9 to 6.3 m/s. Note that regions in southern Algeria (Adrar, H'Rmel, ..) are characterised by higher wind speeds than the north, particularly in the region of Adrar that they exceed the value of 6 m/s; on the contrary the regions in the North (Algiers, Jijel), we notice that overall the average speed is low.

Table 2 Monthly and annual averages of wind speed in different site in Algeria (m/s)

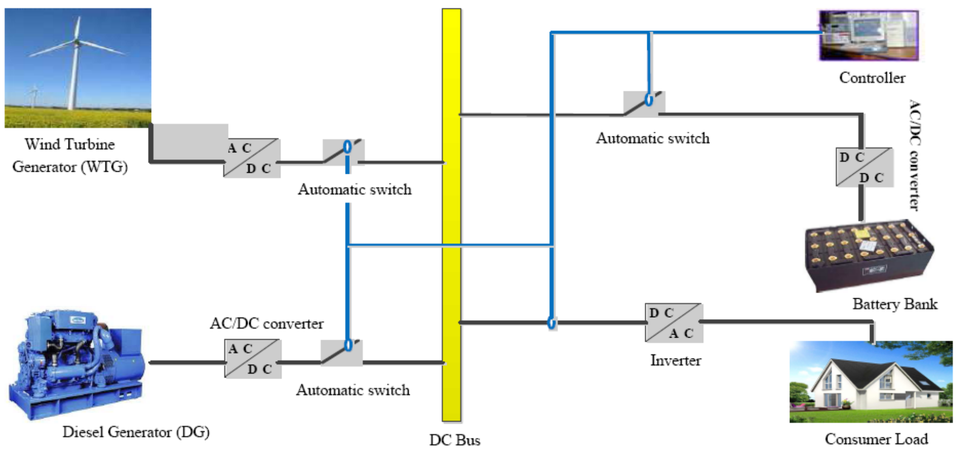
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Yearly* (V_m)
Adrar	6.2	6.4	6.5	6.5	6.9	6.1	6.7	6.2	6	5.8	5.9	5.8	6.3
Algiers	2.2	2.2	2.2	2.1	1.9	1.8	1.6	1.5	1.6	1.4	1.9	2.4	1.9
HR'mel	5.7	6.3	7.6	8.1	7.8	6.6	5.3	5.4	5.4	4.8	4.5	5.7	6.1
Jijel	2.6	2.9	3.3	2.8	2.1	2.1	2.1	2	2.1	2.2	2.5	3.1	2.5

Source: Chellali et al. (2011)

5 Schematic of the isolated power system

Figure 2 shows a remote area power system and its components. The WDHS presented in this article consists of a diesel engine (DE), a synchronous machine (SM), a wind turbine generator (WTG), the consumer load (PL), a (Ni-Cd) battery based on energy storage system (BESS) (Sebastian, 2011).

Figure 2 Renewable generation hybrid system (see online version for colours)

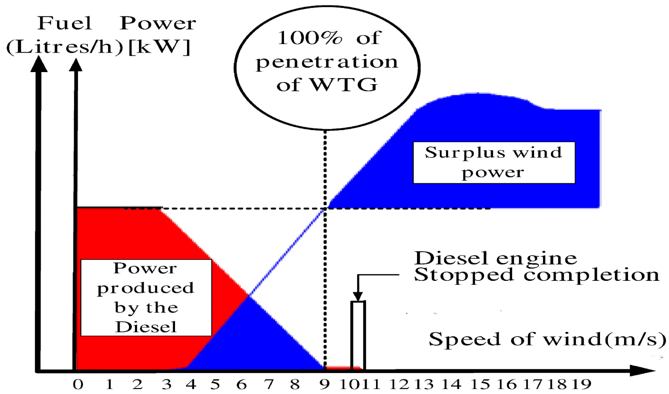


The connection of these elements is produced at a DC bus. This bus has the advantage of more easily interconnect the various components of the hybrid system from the DC bus the network connection is achieved through a DC/AC power converter which adjusts the voltage and frequency before it is transformed into the AC power to be transmitted to the loads (PL).

Power management of the different sources is ensured by controlling the opening and closing manager of different power electronic switches according to the strategy indicated in Section 7.

This system is classified as being high penetration (HP) as shown in Figure 3. Hybrid wind-diesel systems with high penetration of wind power (HWDS-HP) have three plant modes: diesel only (DO), wind-diesel (WD) and wind only (WO).

Figure 3 Variation of energy covered by a system wind-diesel and diesel consumption as a function of wind speed (see online version for colours)



Source: Ibrahim (2010)

We studied in this article, the energetic modelling study of a comprehensive model of a hybrid system (wind-diesel), this system is based on the new strategy in energy management providing timekeeping hybrid system the objectives of this article are:

- insurance of continuity of electric service
- the availability of wind source (free and inexhaustible)
- the protection of the environment, particularly in terms of reducing CO_2 emissions
- the reduction in fuel consumption.

6 Modelling of sources

6.1 Modelling of the turbine of the wind

Generator wind farm, consisting of a turbine at variable speed coupled with a synchronous generator with permanent magnets through a multiplier.

6.1.1 Model wind

The wind speed is usually represented by a scalar function that evolves over time.

$$V_v = f(t) \tag{1}$$

The wind speed will be modelled in this part, as deterministic as a sum of several harmonics (Slotine and Li, 1991):

$$V_v = A + \sum_{n=1}^{i} a_n.\sin\left(b_n.W_v.t\right) \tag{2}$$

6.1.2 *Model of the turbine*

Applying the theory of momentum and Bernoulli, we can determine the incident power (theoretical) due to wind (Alesina and Venturini, 1988; Seyoum et al., 2003):

$$P_{incidente} = \frac{1}{2}.\rho.S.V^3 \tag{3}$$

S the area swept by the blades of the turbine surface [m^2]

ρ the density of the air [ρ = 1.225 (m^3/kg) at atmospheric pressure]

V wind speed [m/s].

In wind energy system due to various losses, provided on the power extracted from the turbine rotor is less than the forward power. The power extracted is expressed by the following formula:

$$P_{extraite} = \frac{1}{2}.\rho.S.Cp(\lambda, \beta).V^3 \tag{4}$$

$Cp(\lambda/\beta)$: power coefficient, which expresses the aerodynamic efficiency of the turbine. It depends on the ratio λ, which represents the ratio between the speed at the tips of the blades and the wind speed, and the angle of orientation of the blades β. The ratio λ expressed by the following formula:

$$\lambda = \frac{\Omega_t.R}{v} \tag{5}$$

The maximum power coefficient *Cp* was determined by Albert Betz as follows (Budinger et al., 2000):

$$Cp^{\max}(\lambda, \beta) = \frac{16}{17} \approx 0.593 \tag{6}$$

The power factor is the aerodynamic efficiency of the wind turbine. It depends on the shape of the turbine rotor and the angle of orientation of the blades β and the ratio of the speed λ. This coefficient can be written as follows:

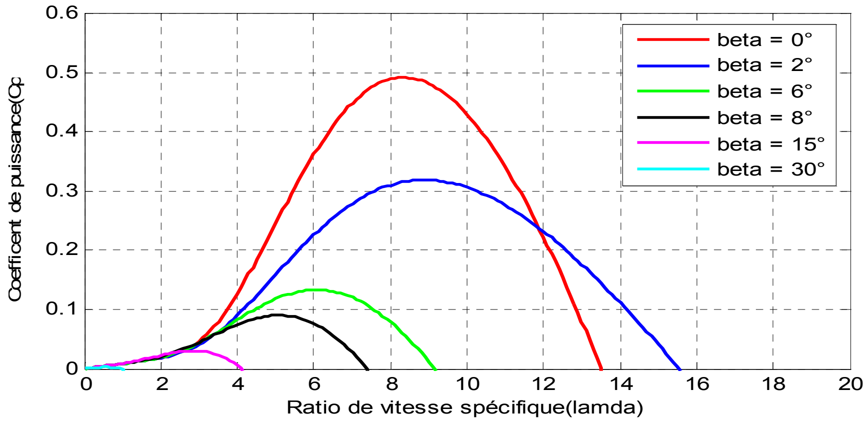
$$Cp(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda i} - 0.4\beta - 5\right)\ell^{\frac{21}{\lambda i}} + 0.0068\lambda i \tag{7}$$

with

$$\frac{1}{\lambda i} = \frac{1}{\lambda + .08\beta} - \frac{0.035}{\beta^3 + 1} \tag{8}$$

Figure 4 illustrates the curves of the power coefficient as a function of λ for different values of β.

Figure 4 Power coefficient $Cp(\lambda / \beta)$ versus λ (see online version for colours)



The aerodynamic torque on the output shaft can be expressed by the following formula:

$$C_{al} = \frac{P_{eol}}{\Omega_t} = \frac{1}{2}.\rho.S.Cp(\lambda, \beta).V^3.\frac{1}{\Theta_t} \tag{9}$$

Ω_t rotational speed of the turbine

C_{al} torque on the slow axis (turbine side).

6.1.3 *Model multiplier*

The multiplier is characterised by its gain '*G*'. It adjusts the speed of rotation (Ω_t) of the turbine to the generator speed Ω_g:

$$C_{aer} = G * C_g \tag{10}$$

6.1.4 *Tree model*

The basic equation of dynamics applied to the shaft of the generator determines the evolution of the mechanical speed Ω_m from the total mechanical torque C_m:

$$C_m = J\frac{d\Omega_m}{dt} \tag{11}$$

J total inertia that appears on the rotor of the generator:

$$J = \left(\frac{J_t}{G^2}\right) + J_g \tag{12}$$

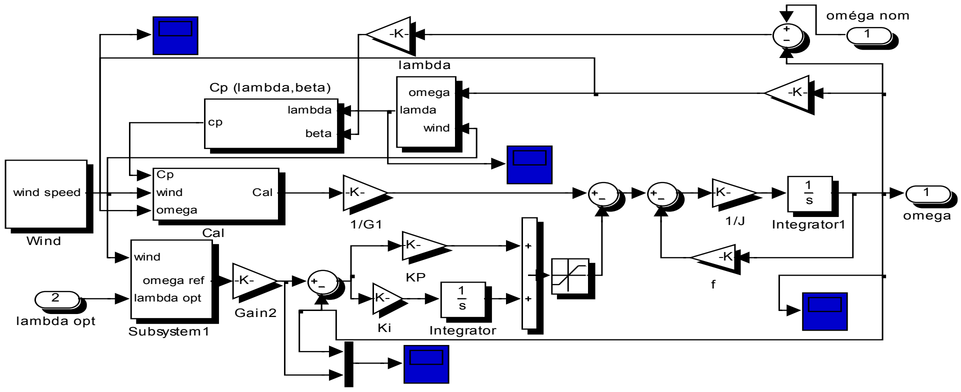
with

J_g the inertia of the generator

J_t the inertia of the turbine.

The above equations are used to establish the servo block diagram of the turbine speed (see Figure 5).

Figure 5 PMSG speed control loop (see online version for colours)



To capture the maximum power of the incident wind, it is recommended to adjust the rotational speed of the wind turbine. Optimal mechanical turbine speed is λopt and $\beta = 0°$. The speed of the permanent magnet synchronous generator (PMSG) is used as a reference for a controller proportional-integral type (PI phase lead). It may be determined that the control target is the electromagnetic torque that should be applied to the machine for rotating the generator at its optimum speed. The couple that is determined by the controller is used as a reference torque of the turbine model (see Figure 5). Variation of the system of the orientation angle of the blades (variation of the angle of incidence) to change the ratio between the lift and drag. To extract the maximum power (and keep constant), we adjust the angle of the blades to the wind speed.

6.1.5 Modelling of permanent magnet synchronous machine

Current machines alternating are generally modelled by equations nonlinear (differential equations). The nonlinearity is due to the inductance and coefficients of the dynamical equations which depend on the rotor position and time. In this article it is based on simplifying assumptions the model of the MAS becomes relatively simple.

After simplifications there (Hunter and Elliot, 1994):

$$\begin{aligned} V_d &= R_s i_d + L_d \frac{di_d}{dt} - \psi_q . w_r \\ V_q &= R_s i_q + L_q \frac{di_q}{dt} + \psi_d . w_r \end{aligned} \tag{13}$$

With

$$\begin{aligned} \psi_d &= L_d.i_d + \psi_f \\ \psi_q &= L_q.i_q \end{aligned} \tag{14}$$

ψ flow of permanent magnets.

The relationship (13) becomes

$$\begin{aligned} V_d &= R_s i_d + L_d \frac{di_d}{dt} - L_q.i_q.w_r \\ V_q &= R_s i_q + L_q \frac{di_q}{dt} + \left(L_d.i_d + \Phi_f\right).w_r \end{aligned} \tag{15}$$

The general expression of the electromagnetic torque and after simplification can be found:

$$Cem = P.\left(\phi_d i_q - \phi_q i_d\right) \tag{16}$$

By replacing ϕ_d and ϕ_q with their values is:

$$Cem = P.\left(\left(L_d - L_q\right).i_d + \phi_f\right).i_q \tag{17}$$

The mechanical equation is written:

$$J\frac{d\Omega}{dt} + f\,\Omega = C_{em} - C_r \tag{18}$$

$$\Omega = \frac{w_r}{P} \tag{19}$$

With angular velocity ω_r (electric pulse).

The permanent magnet synchronous machine (PMSM) is used in most conventional methods of electricity production. A PMSG is used to convert the mechanical energy of the wind into electrical energy.

6.2 Diesel generator

The generator consists of a diesel engine and a synchronous machine. The diesel engine produces mechanical energy by combustion of fuel. Synchronous generator converts mechanical energy into electrical energy (Tudorache and Roman, 2010). The frequency is regulated through regulation of the speed of the diesel engine, as the amplitude is controlled into the excitation of the synchronous machine (Chedid et al., 2000).

Instant fuel consumption $Consu_{fuel}$ of the generator depending on the instantaneous power supplied PDG is given by the following equation:

$$Consu_{fuel} = Consu_{0,fuel} + Consu_{speci,fuel}.P_{DG} \tag{20}$$

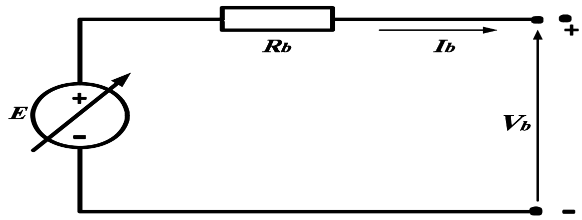
where

$Consu_{0,fuel}$	vacum fuel consumption of DG [l/h]
$Consu_{speci,fuel}$	specific fuel consumption of the generator [l/kWh].

6.3 Storage system modelling

There are three types of battery models reported in the literature, specifically: Experimental, electrochemical and electric circuit-based. Experimental and electrochemical models are not well suited to represent cell dynamics for the purpose of state-of-charge (SOC) estimations of battery packs. However, electric circuit-based models can be useful to represent electrical characteristics of batteries. The simplest electric model consists of an ideal voltage source in series with an internal resistance. In this work, a generic battery model suitable for dynamic simulation presented in Chan and Sutanto (2000) is considered. This model assumes that the battery is composed of a controlled-voltage source and a series resistance, as shown in Figure 6. This generic battery model considers the SOC as the only state variable (Ding et al., 2010).

Figure 6 Generic battery model



Source: Chan and Sutanto (2000)

The controlled voltage source is described by the following expression (Merzouk and Merzouk, 2006):

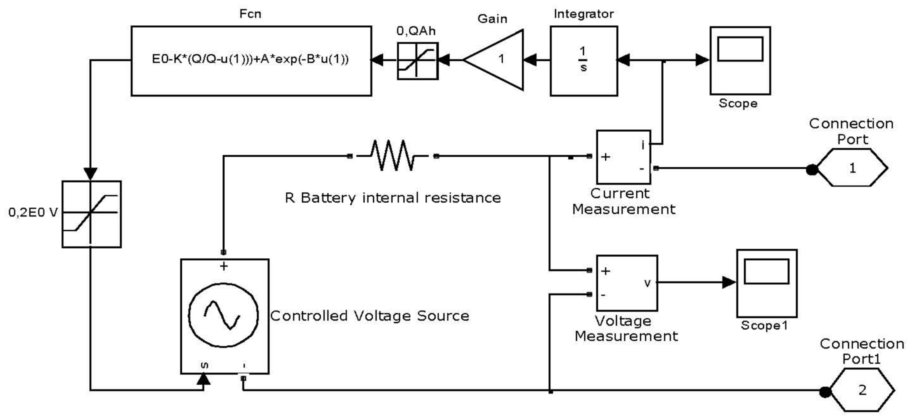
$$E = E_0 - \frac{V_p Q_b}{Q_b - \int i_b dt} + \tilde{A} \exp\left(-B_t . \int i_b dt\right) \tag{21}$$

when E is the battery constant voltage (V), E_0 is battery constant voltage (V); V_p is the polarisation voltage (V), Q_b is the battery capacity (AH), i_b is the battery current (A); $\tilde{A}$ is exponential zone amplitude (V), B_t is exponential zone time F constant inverse (AH^{-1}). The SOC of the battery is zero when the battery is empty and 100% when is fully charged and is calculated as (Sebastián, 2013):

$$SOC = 100\left(1 - \frac{1}{Q}\int i_b dt\right) \tag{22}$$

Under Matlab/*Simulink* environment, the battery block, used in this study, is of nickel-cadmium (Ni-Cd) type (see Figure 7).

Figure 7 (Ni-Cd) battery simulink schematic

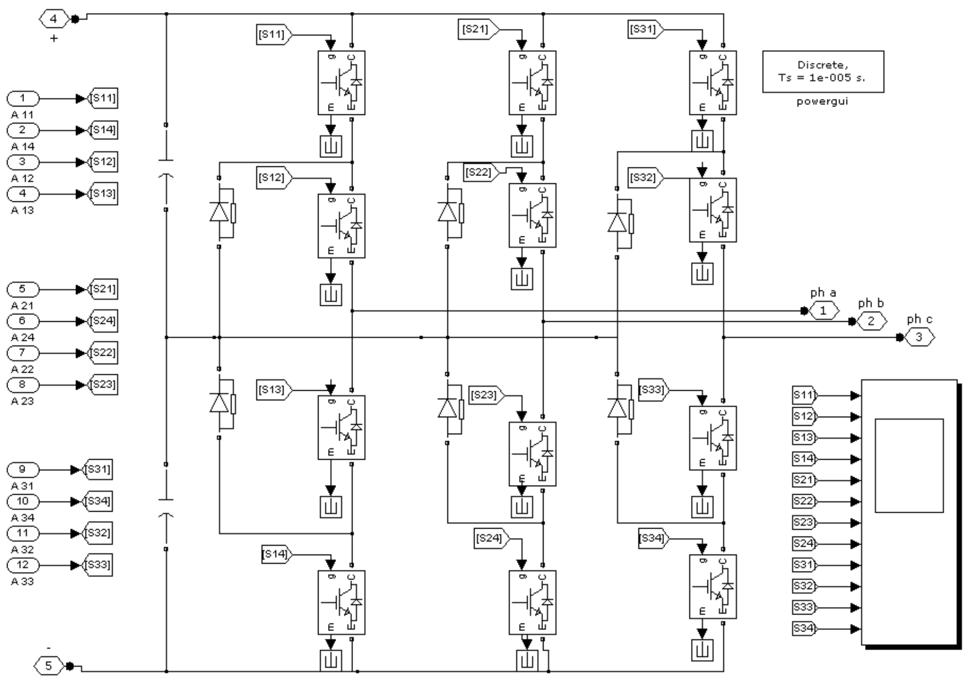


6.4 Model of the inverter PWM

6.4.1 Structure three levels inverter

The inverter on three levels is composed of three arms and two sources of Continue tension each arm of the inverter consists of four pairs bidirectional diode-switch and two median diodes make it possible to have level zero of the output voltage of the inverter. The middle point of each arm is connected to a DC supply following Figure 8 giving following schematic representation.

Figure 8 The inverter structure three levels



6.4.2 Control of static converters

A converter is said to order mode if the transitions between its different configurations only depend on the external command and no longer the internal commands.

6.4.2.1 Additional order

To prevent short circuits of the conduction voltage sources and to deliver the three desired voltage levels we must operate in its control mode.

Table 3 Excitation of switches

G_{k1}	G_{k2}	G_{k3}	G_{k4}	V_{ko}
0	0	1	1	V_{c2}
0	1	0	1	Unknown
1	0	1	0	0
1	1	0	0	V_{c1}

Three additional commands can be applied on an arm of ups at three levels.

$$\begin{cases} G_{k3} = \overline{G}_{k1} \\ G_{k4} = \overline{G}_{k2} \end{cases}; \begin{cases} G_{k2} = \overline{G}_{k1} \\ G_{k4} = \overline{G}_{k3} \end{cases}; \begin{cases} G_{k4} = \overline{G}_{k1} \\ G_{k3} = \overline{G}_{k2} \end{cases} \tag{23}$$

with G_{ks} is control switch arm k and T_{ks} is trigger.

In order to have full control of the three levels inverter, we must eliminate the case which gives an unknown response. By translating this additional order with the connection of the arm '*k*' switches functions, can be found:

$$\begin{cases} F_{k1} = 1 - F_{k4} \\ F_{k2} = 1 - F_{k3} \end{cases} \tag{24}$$

We define the function of connection of the semi-arm noted F_{km}^{b} with:

$$m = \begin{cases} 1 \text{ for the half arm top made up of } TD_{k1} \text{ and } TD_{k2} \\ 0 \text{ for the half arm top made up of } TD_{k3} \text{ and } TD_{k4} \end{cases}$$

Connection of the semi-arm functions are expressed using functions of the switches as follows:

$$\begin{cases} F_{k1}^{b} = F_{k1}F_{k2} \\ F_{k0}^{b} = F_{k3}F_{k4} \end{cases} \tag{25}$$

7 System operation strategies

Good management system (WDHS) should ensure both safety and good performance of the operation of the facility; this is why the constraints of individual system components must be taken into account in the management system strategy. For a multi-source energy system, a power flow management strategy is needed. According to wind speed values

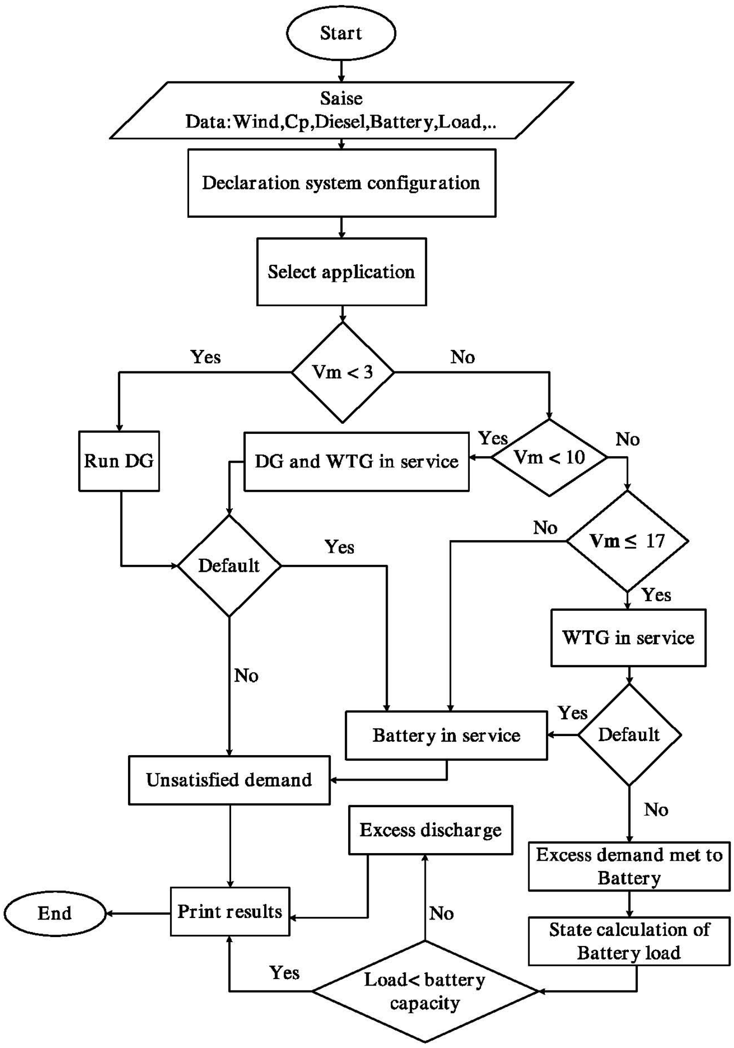
(V_m) and the power demanded by the consumer load. The power system has three operation modes, as follows (Ibrahim et al., 2011).

- weak winds ($V_m \leq 3$) m/s : (DO) in service
- moderate winds ($3 < V_m \leq 10$) m/s : (WD) in serviced
- strong winds ($10 < V_m \leq 17$) m/s : (WO) in service.

To adapt the production of the renewable source to the need for the load, we integrate a system of storage, such as the battery (BESS) to ensure the continuity of service; that is necessary to feed the load, in case when the generator diesel fails and the wind is insufficient (low) for the operation of the wind turbine.

The power management strategy used in this study is according to Figure 9:

Figure 9 Main flow chart



8 Results and discussions

To reveal the selection of good sites for implementation of this system in Algeria, we should have to choose the place that takes into account with the following parameters (wind speed, power demanded). In this study (Aguglia et al., 2010), the geographic location is considered the city of Adrar (Figure 1) south west Algeria with following coordinates: Longitude 0.28; Latitude 27.82 and an aggregate area of 427,968 Km^2. The majority of sites in the city of Adrar could be considered remote sites view that its area is huge and their distance from each other. The extremely difficult weather conditions are another parameter to be taken into account. All this leads us to think about the integration of hybrid systems for supplying this remote area.

The Matlab-Simulink (The MathWorks, Inc.) model of the WDHS of Fig. 2 is shown in Figure 10.

Figure 10 Renewable generation hybrid system (WDHS) (see online version for colours)

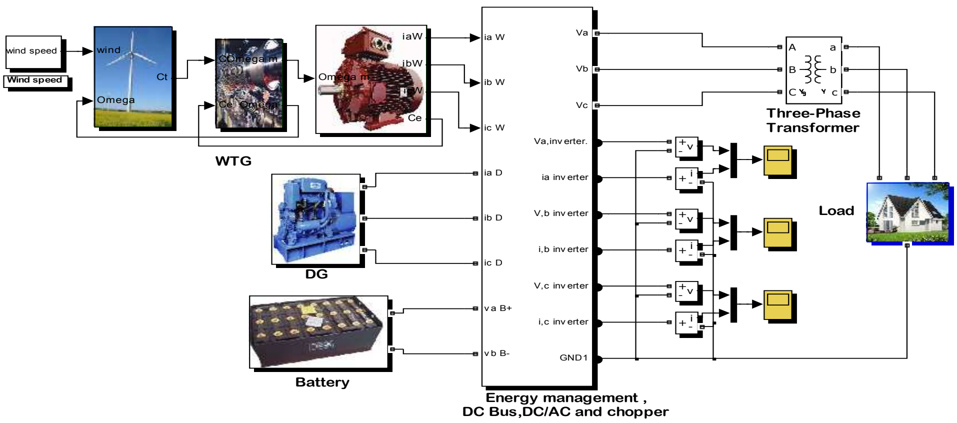
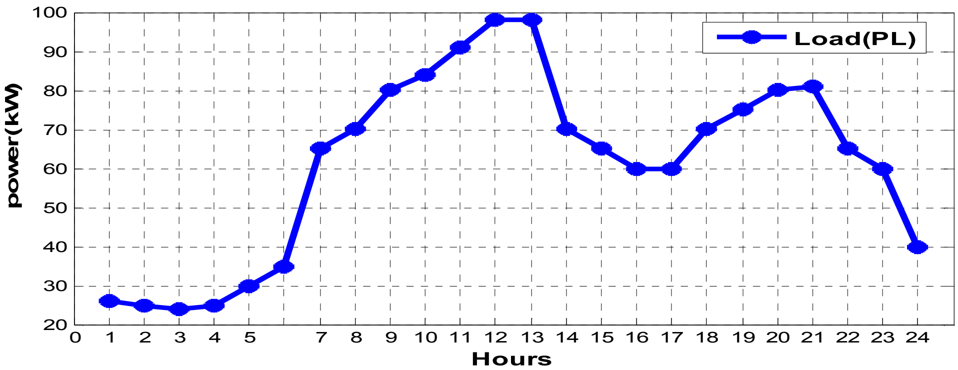


Figure 11 Daily distribution of electrical charge (see online version for colours)



Electrical load demand is an important element of a WDHS and any other power generating system. The daily consumption is assumed to be following the same profile over all the year with peak load as 99 kW and is shown in Figure 11. It shows that the consumption is important in the daytime (99 kW with 12h and 13h) and negligible at night (25 kW with 3h). It peaks at three points: at the early morning; at noon and at the beginning of the night as all the family members are around.

In this study, we seek to highlight the importance of the wind in the operation of the hybrid power system (WDHS) even to its role in reducing greenhouse gas emissions and global warming characterising the economic effect. Through the reduction of fuel consumption rate and the price which justifies reason of section studied. In this article we have studied the comparison of two months from the same region, the first month is characterised by a high ventilation rate (May) and the second month low ventilation (October).

Figure 12 represents the true wind speed measured in the city of Adrar for a year according to Table 2.

Figure 12 The average yearly wind speed for the studied site (Adrar) (see online version for colours)

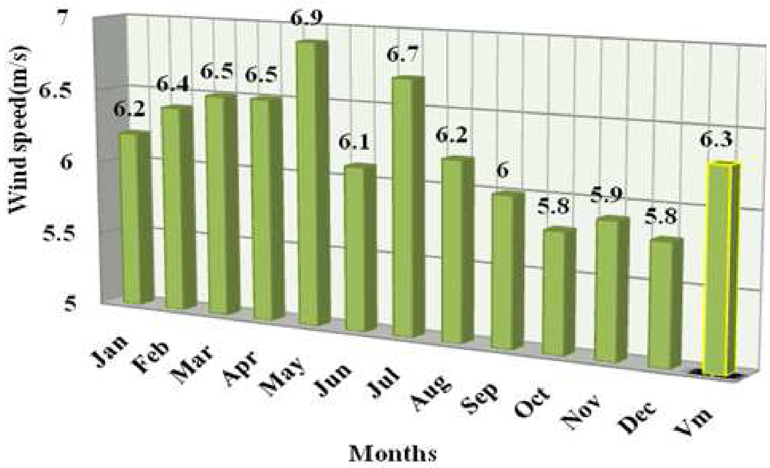


Figure 13 and Figure 14 represent the actual daily wind speed for the months of May and October respectively of the city of Adrar.

Figure 13 The average daily wind speed in May (see online version for colours)

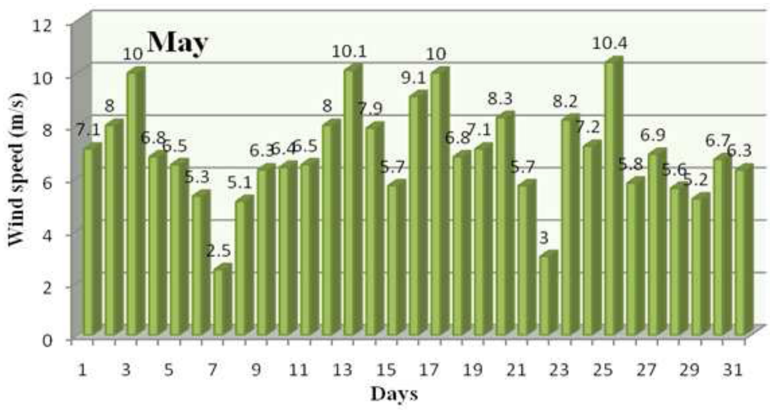


Figure 14 The average daily wind speed in October (see online version for colours)

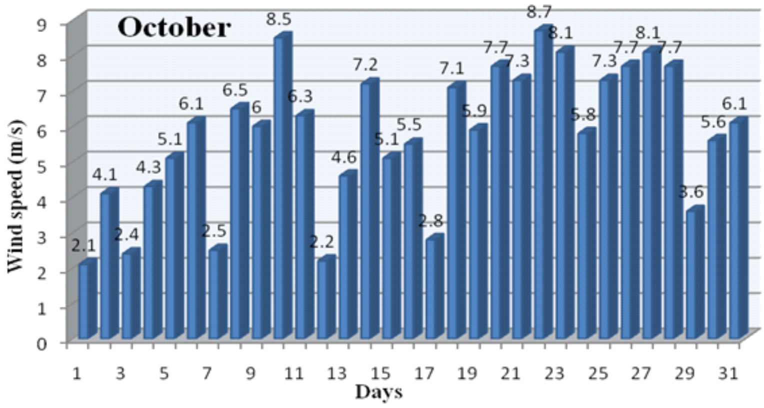


Figure 15 and Figure 16 show the daily power generated by the system (WDHS) according to wind speed for two months; May and October.

Figure 15 Daily power generated by WDHS in May (see online version for colours)

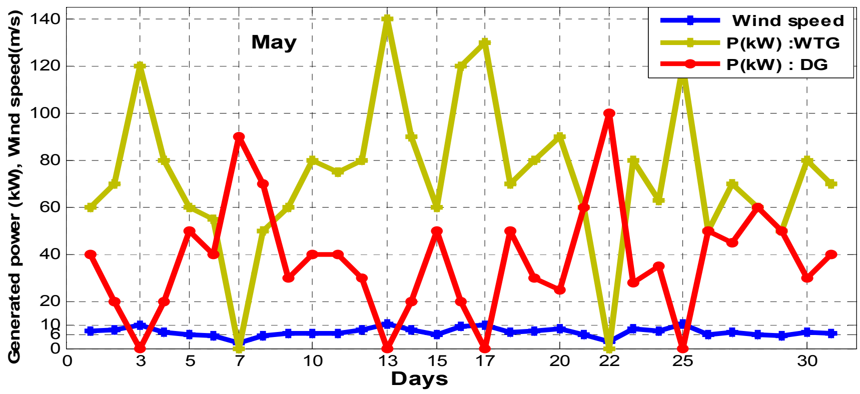
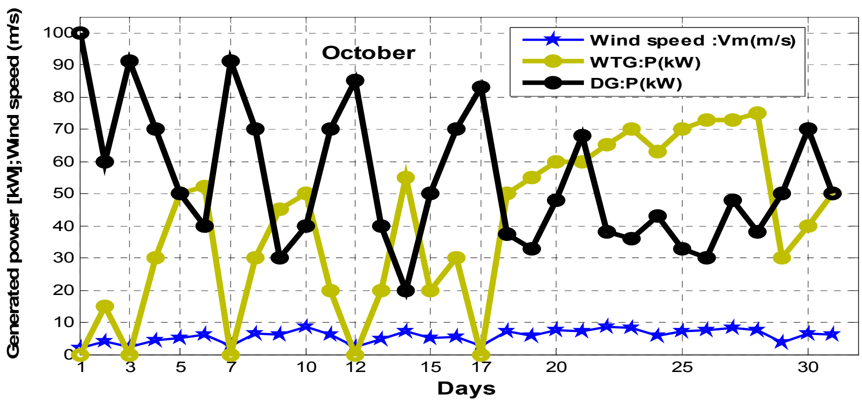


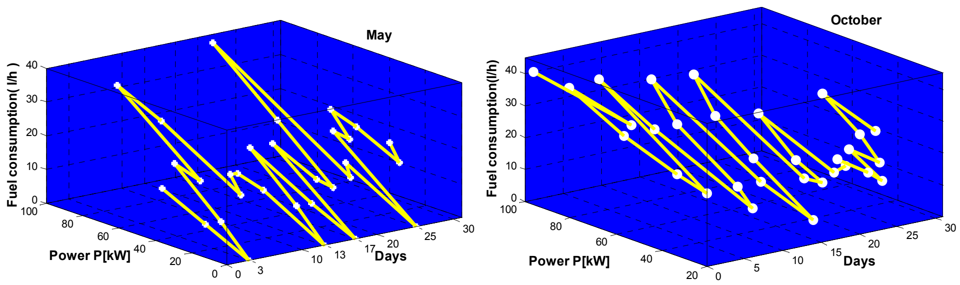
Figure 16 Daily power generated by WDHS in October (see online version for colours)



According to Figure 15, we note that during the days (3rd, 13th, 17th, 25th) power consumers (PL) are fed by the electric power generated by WTG because of the excellent wind speed exceeding ($V_m \geq 10$ m/s) where these days the DG is at rest, while the surplus of the electric power is stored in the batteries for it to be used to rescue the system according to the strategy of the energy proposed in Figure 9. On other hand, for days and particularly (7th, 22th) of the month, consumers are supplied by the DG due to weak wind rate ($V_m \leq 3$ m/s).

We notice in Figure 16, customer supply (PL) is generally provided by the diesel generator only (DO) where it works for the entire month. We also observe that wind has stopped working for five days during the months of October and particularly (1st, 3rd, 7th, 12th, 17th). On the other hand the month of May, it stopped for two days (7th, 22th), while the remaining days we use hybridisation (WD). Figure 17 represents the relationship of the daily consumption of fuel depending on the power generated by DG during the months of May and October respectively.

Figure 17 Daily fuel consumption depending on the power generated by DG (see online version for colours)



According to Figure 17, the quantity of the fuel consumption is zero during the day (3rd, 13th, 17th, 25th) because the wind speed is sufficient. On the other hand for days (7th, 22nd), the fuel consumption is maximal view that the site is too windy during this time.

Figure 18 presents the quantity of fuel saved for two months. Knowing that fuel consumption is higher on October than in May.

Figure 18 Gain of the fuel saved (see online version for colours)

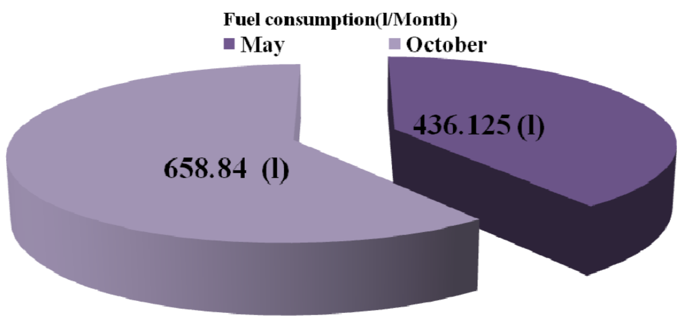
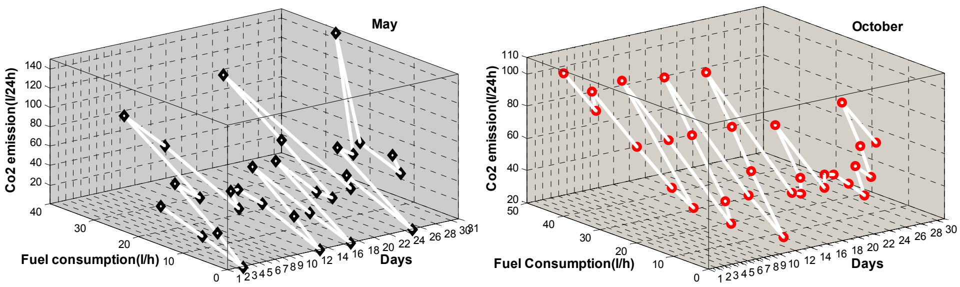


Figure 19 shows the fuel consumption effect generated by DG on CO_2 emissions.

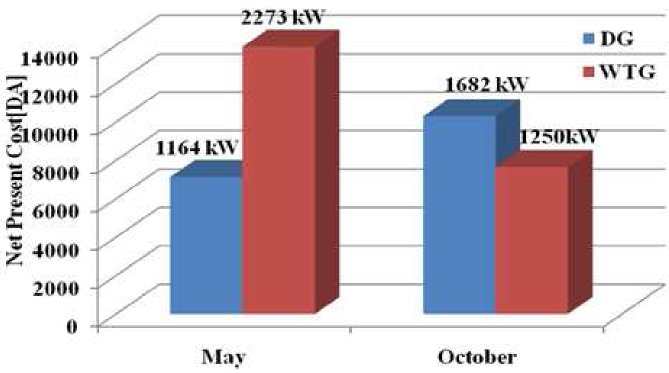
Figure 19 Emission of CO_2 depending on the fuel consumption (see online version for colours)



After comparising, we note that the CO_2 emission is higher in October corresponding to a volume of 1,779.2 emission (l/month).by what the DG generally provides power to the load (DO or DW). On the other hand for the month of May the total CO_2 pollution value is 1,280.7 (l/month).

The histogram of Figure 20 gives us a general idea about the total cost of kWh provided by the SWDH system for a month. Knowing that in the month of May the energy provided by the WTG is higher than DG which corresponds to the costs of 13,918 (DA/month) for wind and 7,131 (DA/month) for diesel, this will have a direct influence on the CO_2 emission rate and climate change.

Figure 20 Technical and economic gain of the system studied (see online version for colours)



In Table 4, we provide a summary of the daily calculations of economic costs generated by the system under study; knowing that the average price of electric energy consumption is 6.123 (DA/kWh) according to the source records SONELGAZ ‘The Algerian Society of Electricity Transmission System Management’.

To simulate the WDHS system, we have performed the simulation diagram in Figure 10 under the MATLAB/Simulink for supplying a load (AC) to a low voltage system knowing that at the beginning we use WO to power this load with a well controlled wind speed. After we use DO generator for the same load. The synchronisation will be established between the two sources of energise at t = 1.2s with a wind velocity ranging from 3 to 10 (m/s) (see Figure 21, Figure 22, Figure 23, Figure 24, Figure 25 and Figure 26).

Table 4 Daily summary calculations of economic costs generated by the system studied

Days	*DG energy price (6.123 DA/kWh)*		*Fuel consumption (l/24h)*		*Unit fuel prices (14. 2DA/l)*		*CO_2 emission (2.71 kg/l)*		*Energy prices WTG (6.123 DA/kWh)*	
	May	*October*	*May*	*October*	*May*	*October*	*May*	*October*	*May*	*October*
1	244.92	612.3	15	40.1	213	569.42	40.65	108.671	367.38	0
2	122.46	367.38	7.5	33.2	106.5	471.44	20.325	89.972	428.61	91.845
3	0	557.193	0	36.5	0	518.3	0	98.102	734.76	0
4	122.46	428.61	7.5	26.25	106.5	372.75	20.325	71.137	489.84	183.69
5	306.15	306.15	18.75	18.75	266.25	266.25	50.812	50.81	367.83	306.15
6	244.92	244.93	15	15	213	213	40.64	40.64	336.765	318.39
7	551.07	557.193	33.75	37	479.25	525.4	91.462	100.27	0	0
8	428.61	428.61	26.25	26.25	372.75	372.75	71.137	71.137	306.15	183.69
9	183.69	183.69	11.25	11.25	159.75	159.75	30.487	30.487	367.38	275.53
10	244.92	244.93	15	15	213	213	40.65	40.65	489.84	306.15
11	244.92	428.61	15	26.25	213	372.75	40.65	71.137	459.225	122.46
12	183.69	520.455	11.25	36	159.75	511.2	30.487	97.56	489.84	0
13	0	244.93	0	15	0	213	0	40.65	857.22	122.46
14	122.46	122.45	7.5	7.5	106.5	106.5	20.325	20.325	551.07	336.76
15	306.15	306.20	18.75	18.79	266.25	266.818	50.812	50.92	367.38	183.69
16	122.46	428.62	7.5	26.25	106.5	372.75	20.325	71.137	734.76	122.46

Table 4 Daily summary calculations of economic costs generated by the system studied (continued)

	DG energy price (6.123 DA/kWh)		*Fuel consumption (l/24h)*		*Unit fuel prices (14. 2DA/l)*		*CO_2 emission (2.71 kg/l)*		*Energy prices WTG (6.123 DA/kWh)*	
	May	*October*	*May*	*October*	*May*	*October*	*May*	*October*	*May*	*October*
17	0	508.209	0	35.5	0	504.1	0	96.205	795.99	0
18	306.15	229.61	18.75	14	266.25	198.8	50.812	37.94	428.61	306.15
19	183.69	202.06	11.25	13.5	159.75	191.7	30.487	36.585	489.84	336.765
20	153.075	293.904	9.375	16	133.125	227.2	25.406	43.36	551.07	367.38
21	367.38	416.364	22.5	25	319.5	355	60.975	67.75	367.38	367.38
22	612.3	232.674	37.5	13.75	532.5	195.25	101.625	37.262	0	397.99
23	171.444	220.428	10.5	15.75	149.1	223.65	28.455	42.682	489.84	428.6
24	214.305	263.289	13.125	15.5	186.375	220.1	35.568	42	385.749	385.749
25	0	202.06	0	13.5	0	191.7	0	36.585	734.76	428.61
26	316.15	183.7	18.75	11.25	266.25	159.75	50.812	30.487	306.15	446.97
27	275.535	293.904	16.875	16	239.625	227.2	45.731	43.36	428.61	446.97
28	367.38	232.674	22.5	13.75	319.5	195.25	159.75	37.262	367.38	459.225
29	306.15	306.5	18.75	19	266.25	269.8	50.812	51.49	306.15	183.69
30	183.69	428.62	11.25	26.25	159.75	372.75	30.487	71.137	489.84	244.92
31	244.92	306.5	15	19	213	269.8	40.65	51.49	428.61	306.15
The sum	7,131	10,303	436.125	658.84	6,193	9,327.1	1,280.7	1,779.2	13,918	7,659.8

Figure 21 The evolution of the stator voltages: *WTG* [$10 \le V_m < 17$] (m/s) (see online version for colours)

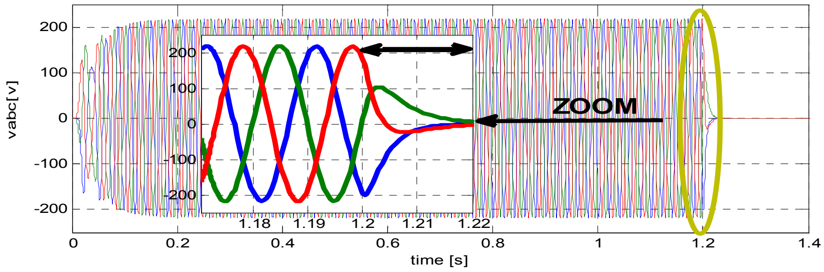


Figure 22 Voltages produced by DG: [$V_m < 3$] (m/s) (see online version for colours)

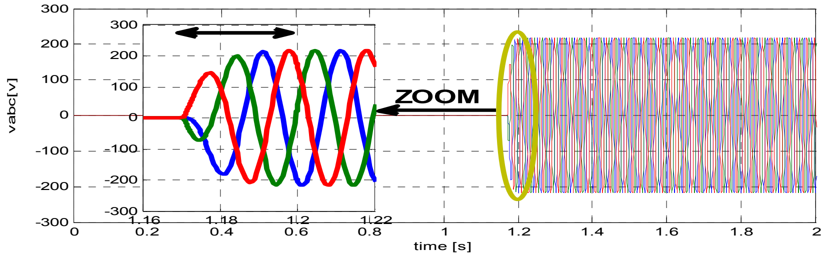


Figure 23 Currents produced by DG/WTG: [$3 \le V_m < 10$] (m/s) (see online version for colours)

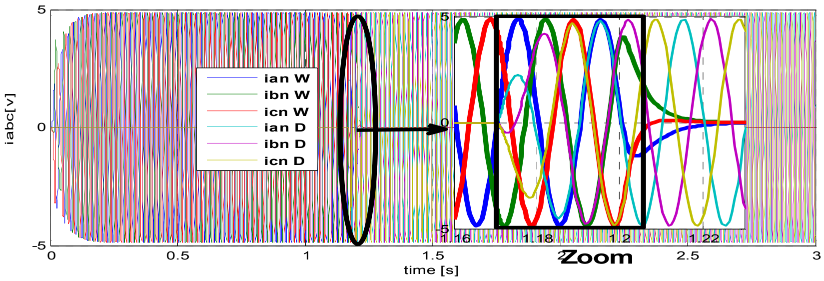


Figure 24 Overview of frequency (see online version for colours)

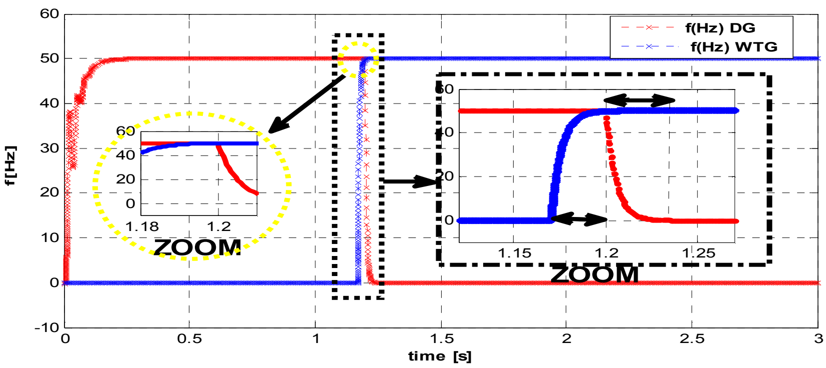


Figure 25 Simple tension of phase 'A' generated by inverter NPC (see online version for colours)

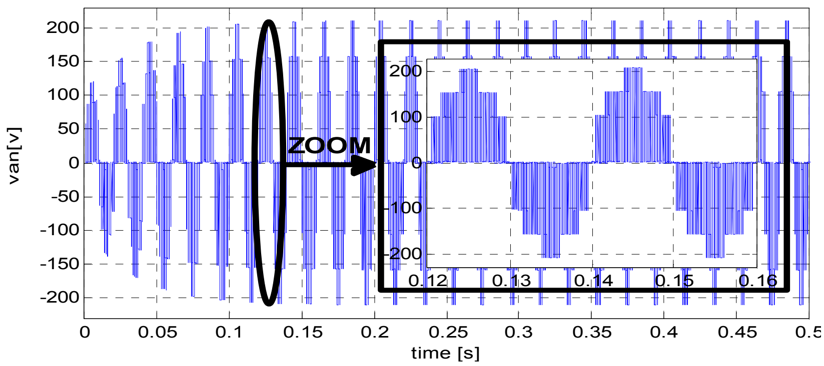
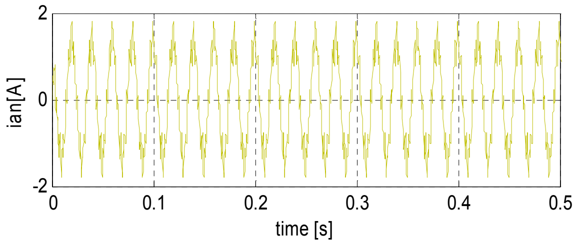


Figure 26 Simple current generated by inverter (see online version for colours)



According to Figure 21, representing the three-phase simple tensions where the feeding of the consumers is only assured by the wind generator (WO), when the speed of the wind is included [10 m/s with 17 m/s] until the time (t = 1.2 s) according to the condition of adapted management; for this mode, I note that a surplus of wind power which can be stored in the battery with a system of regulation to ensure the continuity of service: this is necessary to feed the load of which in the case when the power generator unit falls down and the wind insufficient for operation (see Figure 25 and Figure 26). In the case where ($t \geq 1.2$ s) the DG ensures only the feeding of the load concerned, knowing that the speed of the wind is lower than 3 m/s (see Figure 22).

9 Conclusions and perspectives

In this article, we have sized the integration of a hybrid system with a storage system located in a remote site. The hybrid system includes a wind turbine at variable speed controlled by the control maximum power point tracking (MPPT), a diesel generator and battery as an electrochemical storage system providing an essential role in the system studied. In this application, we have opted for the WDHS system located in the remote region of the city of Adrar, in the technical-economic study, we study the actual cost of fuel. Energy sources are connected to a bus (DC), under the MATLAB/Simulink environment. The results of our study have shown that the strategy we have proposed is profitable according to the configuration that have been used to help us gain an economic and technical as well as durability of our system. In addition, there is a continuous insurance of service and the elimination of part of the greenhouse gas when operating in wind. To have a permanent solution in power problems in isolated perspective (technical, economic and environmental) in Algeria the country is moving towards a new form of energy called 'renewable energy' by launching an ambitious program of these energies and including energy efficiency will have a strategic role. The program is to establish a renewable power in the order of 22,000 MW between 2011 and 2030 to face national demand for electricity. In this context, the city of Adrar has received a draft wind farm power generation capacity of 10 MW, the first of its kind nationally and 2020, the province of Adrar will be reinforced with a new 175 MW power plant which is in progress, and whose studies are in progress, too.

References

Aguglia, D., Viarouge, P., Wamkeue, R. and Cros, J. (2010) 'Determination of fault operation dynamical constraints for the design of wind turbine DFIG drives', *Mathematics and Computers in Simulation*, Vol. 81, No. 2, pp.252–262.

Alesina, A. and Venturini, M. (1988) 'Intrinsic amplitude limits and optimum design of 9 switches direct PWM AC-AC converter', *Proc. of PESC Con.*, Rec., April, pp.1284–1290.

Budinger, M., Leray, D. and Deblezer, Y. (2000) 'Eoliennes et vitesse variable', *The Review 3EI*, Vol. 21, pp.79–84.

Catalogue SONELGAZ, Algerian Management Company of Electricity Transmission System, specialised energy operator in the electricity generation, distribution and customer services, Algeria.

Chan, H.L. and Sutanto, D. (2000) 'A new battery model for use with battery energy storage systems and electric vehicles power systems', *Proc. IEEE PES Winter Meeting*, 23–27 January 2000, Vol. 1, pp.470–475.

Chedid, R.B., Karaki, S.H. and El-Chamali, C. (2000) 'Adaptive fuzzy control for wind-diesel weak power systems', *IEEE Transactions on Energy Conversion*, Vol. 15, No. 1, pp.71–78.

Chellali, F., Khellafb, A., Belouchranic, A. and Recioui, A. (2011) 'A contribution in the actualization of wind map of Algeria', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 2, pp.993–1002.

Ding, F., Li, P., Huang, B., Gao, F., Ding, C. and Wang, C. (2010) 'Modeling and simulation of grid-connected hybrid photovoltaic/battery distributed generation system', *China International Conference on Electricity Distribution (CICED)*, IEEE, September, pp.1–10.

Galdi, V., Piccolo, A. and Siano, P. (2009) 'Exploiting maximum energy from variable speed wind power generation systems by using an adaptive Takagi-Sugeno-Kang fuzzy model', *Energy Conversion and Management*, Vol. 50, No. 2, pp.413–421.

Hunter, R. and Elliot, G. (Eds.) (1994) *Wind-Diesel Systems: A Guide to the Technology and its Implementation*, Cambridge University Press, Cambridge, ISBN: 9780521434409.

Ibrahim, H. (2010) *Étude et conception d'un générateur hybride d'électricité de type éolien-diesel avec élément de stockage d'air comprimé*, University of Quebec with Chicoutimi.

Ibrahim, H., Younès, R., Basbous, T., Ilincac, A. and Dimitrova, M. (2011) 'Optimization of diesel engine performances for a hybrid wind diesel system with compressed air energy storage', *Energy*, Vol. 36, No. 5, pp.3079–3091.

Merzouk, N.K. and Merzouk, M. (2006) 'Estimation du potentiel énergétique éolien utilisable application au pompage dans les Hauts Plateaux', *Review of Renewable Energies*, Vol. 9, No. 3, pp.155–163.

Sebastian, R. (2011) 'Modelling and simulation of a high penetration wind diesel system with battery energy storage', *Electrical Power and Energy Systems*, Vol. 33, No. 3, pp.767–774.

Sebastián, R. (2013) 'Reverse power management in a wind diesel system with a battery energy storage', *Electrical Power and Energy Systems*, Vol. 44, pp.160–167.

Seyoum, D., Rahman, M.F. and Grantham, C. (2003) 'Terminal voltage control of a wind turbine driven isolated induction generator using stator oriented field control', *Applied Power Electronics Conference and Exposition, APEC'03, Eighteenth Annual IEEE*, IEEE, Vol. 2, pp.846–852.

Slotine, J-J.E. and Li, W. (1991) *Applied Nonlinear Control*, Vol. 60, Prentice-Hall, Englewood Cliffs, NJ.

Stoyanov, L., Notton, G. and Lazarov, V. (2007) 'Optimisation des systèmes multi-sources de production d'électricité à énergies renouvelables', *Review of Renewable Energies*, Vol. 10, No. 1, pp.1–18.

The MathWorks, Inc., *Simulink (Built Upon Matlab)* [online] http://www.mathworks.com/access/helpdesk/help/toolbox/simulink/ (accessed 16 April 2014).

Tudorache, T. and Roman, C. (2010) 'The numerical modeling of transient regimes of diesel generator sets', *Acta Polytechnica Hungarica*, Vol. 7, No. 2, pp.39–53.

Academic landscape of hydropower: citation-analysis-based method and its application

Hajime Sasaki*

Policy Alternatives Research Institute,
The University of Tokyo,
7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
Email: sasaki@pari.u-tokyo.ac.jp
*Corresponding author

Liu Zhidong

Department of Technology Management for Innovation,
Graduate School of Engineering,
The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Email: wotrump@gmail.com

Ichiro Sakata

Policy Alternatives Research Institute,
The University of Tokyo,
7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan
Email: isakata@ipr-ctr.t.u-tokyo.ac.jp

Abstract: Hydropower has superior storage capacity and speedy response to meet sudden fluctuations in electricity demand. According to a recent estimate by International Energy Agency (IEA), its generation capacity could double by 2050. Nevertheless, no great picture of academic knowledge exists in relation to hydropower. This study was undertaken to reveal the academic landscape in this field by analysing the citation network of papers published in academic journals. We collected 7,521 target papers from the Web of Science using a specific search query. Using a topological-based method, all the papers were categorised into clusters according to their own characteristic topics. Results show the existence of six principal research clusters: renewable energy, optimisation of system operation, environmental impact, fish management, water governance and hybrid solutions. Combining the analysis results, clusters were found related to 'small hydropower', 'Mekong Basin hydropower' and 'pumped-storage' are developing, as indicated by the recent increasing trend. Even in developing countries, policymakers should make policy with full access to that knowledge. Governments must prepare environments in which policymakers can access the latest knowledge and information related to their own countries.

Keywords: renewable energy; hydropower; academic landscape; emerging field; citation network analysis.

Reference to this paper should be made as follows: Sasaki, H., Zhidong, L. and Sakata, I. (2016) 'Academic landscape of hydropower: citation-analysis-based method and its application', *Int. J. Energy Technology and Policy*, Vol. 12, No. 1, pp.84–102.

Biographical notes: Hajime Sasaki is a Project Researcher at the Policy Alternatives Research Institute, The University of Tokyo. His research interests include innovation policy, management of technology and data-driven decision-making.

Liu Zhidong completed his graduate studies in Technology Management for Innovation from the University of Tokyo in 2014.

Ichiro Sakata is a Professor at the Department of Technology Management for Innovation, the Director of Innovation Policy Research Centre and the Co-Head of Presidential Endowed Chair for Electricity Network Innovation by Digital Grid at the University of Tokyo. He received his Bachelor's degree and PhD from the same university, and Master's degree from Brandeis University. He has 20 years of working experience at the Japanese Ministry of Economy, Trade and Industry (METI). His research interests include technology management, technology roadmap and innovation network. He has published more than 100 papers in peer reviewed journals and conference proceedings.

This paper is a revised and expanded version of a paper entitled 'Study on the academic landscape of hydropower: a citation-analysis based method and its application' presented at the Portland International Conference on Management Engineering and Technology 2014 (PICMET'14), Kanazawa, 27–31 July 2014.

1 Introduction

Hydropower, or more precisely speaking, hydroelectricity as discussed in this study, refers to electricity derived from the potential energy of water captured when moving from higher to lower elevations. Categories of hydropower projects include run-of-river, reservoir-based capacity, and low-head in-stream technology (the least developed). Hydropower encompasses a wide continuum of project scales from large (usually defined as more than 100 MW installed capacity, while the definition varies by country) to small, mini, micro, and pico (widely used in rural electrification) sizes. Being technology related to concepts first put forward by a French engineer in the mid-1770s, hydropower remains a popular interdisciplinary research field today. With thousands of academic papers published annually on this subject, the fast-changing and complicated situation has made it impossible for researchers, even those experts in this domain, to comprehend the whole picture by reading all the papers. Empirical knowledge, case studies, and brief surveys are no longer sufficient, although grasping the current status of hydropower research and development has become imperative.

To meet the challenge created by this huge scale of information, a computer-based approach can be introduced to complement the expert-based approach (Börner et al., 2003; Boyack et al., 2005). This approach is based on the assumptions that citing and cited papers have similar or at least related research topics and that the interrelationships among thousands of papers constitute a complex citation network. By analysing the citation work, we can elucidate the structure of a research domain consisting of numerous academic papers without reading all of them.

After grasping the academic landscape of hydropower, this research can benefit society in several ways. First, for academia, researchers in this domain can benefit from understanding the fundamental framework of the current status in this research without needing to read such numerous papers. Additionally, it is easier to as certain trends in research topics indicated by groups of newly published papers around central topics. For industry, hydropower itself as a renewable energy with lower technological requirements and lower cost can be found operating almost throughout the world. With the rapid economic growth of emerging countries in recent years, meeting increasing energy demands with limited budgets has led to severe social and political problems. Our research can also contribute to the technology acquisition roadmap for those emerging countries. With an accurate guide to the academic landscape, energy planners can grasp the current status and determine the general direction. They can also find better alternative methods that have recently become available or wait for new solutions in development. In this way, the distance between academia and industry can be shortened. Ultimately, society as a whole can benefit from our research.

Our research examines previous papers using the two approaches of a literature review of hydropower and a citation network analysis. In the literature review under the topic of hydropower, most papers concentrate on certain topics under hydropower, such as small hydropower (Okot, 2013; Oliver, 2002), hydropower plant operation (Kishor et al., 2007; Labadie, 2004), and pumped-hydro energy storage (Yang and Jackson, 2011). Most papers present discussion of the current progress in the research of hydropower related by listing and classifying various technologies with detailed analysis. However, they might be unable to provide a comprehensive picture of research on hydropower because they tend to emphasise some trendy topics specifically while omitting others. In addition, some papers discuss the present situation and future prospects of hydropower in certain countries or areas, which also include discussion covering a series of proper technologies according to local conditions (Huang and Yan, 2009). However, they do not provide analysis of a global scale or information related to the development of technologies in other countries. Although citation-based approaches have been applied to studies of various fields such as nanotechnology (Li et al., 2007) and water resource management (Thelwall et al., 2006), and although some earlier studies have examined other types of renewable energy such as solar power (Shibata et al., 2010), no similar research has been conducted for hydropower. The major objective of this paper is to grasp the academic landscape of hydropower-related studies and to forecast future development.

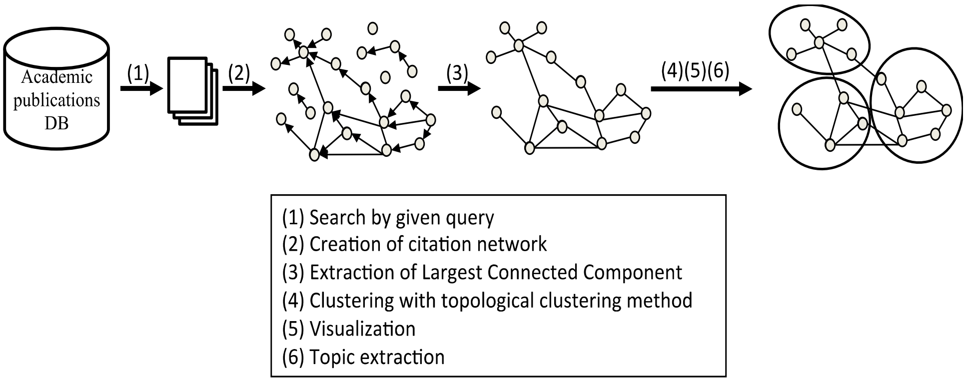
2 Methodology

The overview of the methodology used for this study is illustrated schematically in Figure 1.

To conduct citation network analysis, we collected a set of academic papers related to hydropower (including ‘hydropower’ or ‘hydroelectricity’ in their titles, abstracts, and keywords). We obtained citation data of hydropower-related publications from the science citation index (SCI) and the social science citation index (SSCI) compiled by the Institute for Science Information (ISI) because both are the comprehensive sources for citation data. We used the Web of Science, an online subscription-based scientific citation indexing service maintained by Thomson Reuters, to access these databases.

First, we searched the papers using the query of [(‘power’ or electric*) near ‘hydro’] or hydro-power or hydropower or hydroelectric*. The asterisk * represents a wildcard, and using specific search operators ‘NEAR’, the system can be told to find records where the terms joined by NEAR are within 15 words of each other. Both can help to locate the right results. In all, 7,521 papers were retrieved, which contain a keyword of interest [(1) search by given query in Figure 1].

Figure 1 Overview of methodology



The citation network was converted to a non-weighted, non-directed network using respective papers as nodes and citation relations as links as shown [(2) creation citation network in Figure 1]. Direct citation is the most effective method for detecting research frontiers because core papers will always be included in the largest component.

In fact, not all the retrieved papers are closely relevant to the major topic of hydropower. Therefore, we specifically examined the largest connected component, which accounted for about 43.2% of all papers (3,250 out of 7,521 papers). We regarded papers having no citation relation with other papers as digressional and ignored them in this research [(3) extract largest connected component in Figure 1].

Next, using the topological clustering method (Newman, 2004), the network was divided into several clusters (Newman, 2004; Newman and Girvan, 2004). Each cluster will represent their contents as well as the important terms extracted the frequently cited academic papers with in each cluster [(4) clustering with topological clustering method in Figure 1].

After clustering the network, the visualisation is converted to infer a relation among these clusters intuitively. We use a large graph layout (LGL) that is based on a force-direct layout algorithm (Adai et al., 2004). This layout can display minimal spanning trees of the network to generate coordinates for the nodes in two dimensions. We visualise the citation network by expressing inter-cluster links as the same colour [(5) visualisation in Figure 1].

Next, we analysed the characteristics of each cluster by the titles and abstracts of papers that are frequently cited by the other papers in the cluster, as well as journals in which the papers in the cluster were published. We named each cluster and also listed the keywords for each cluster from the titles and abstracts of the top 20 most cited papers in the cluster [(6) topic extraction in Figure 1]. The average publication year of papers in each cluster was calculated to ascertain trends in the research field in hydropower research, which might engender emerging technologies in the near future.

3 Results

3.1 Results of the academic landscape

By entering the search query into the search engine of Web of Science, we retrieved 7,521 related papers from the whole database (up to 2013 September 29). As presented in Figure 2, as an academic field with a long history, the earliest publication recorded in the database dates back to 1904. Different from the slow increase in the early years, there exists a sharp increase in the rate of annual publication starting from around the 1990s, at which time the concept of sustainable development was proposed in Our Common Future by World Commission on Environment and Development (1987). Because of the lack of sufficient publication data of 2013, a decline is apparent in the number of academic papers between 2012 and 2013.

Figure 2 Time series plot of the retrieved papers

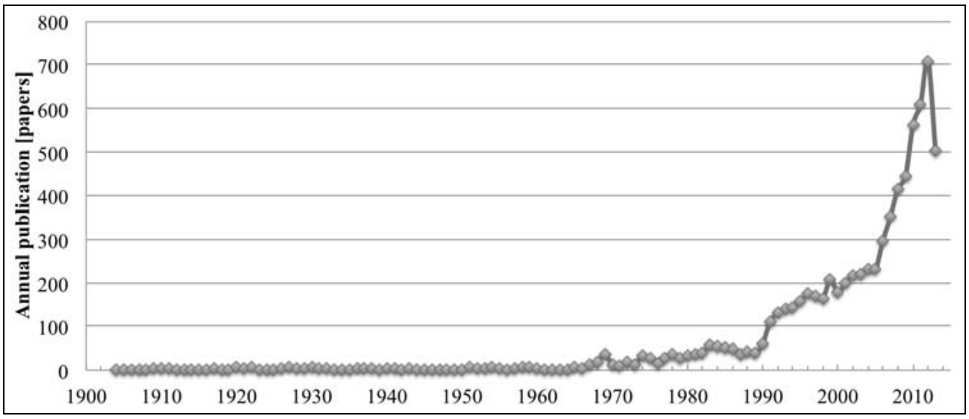
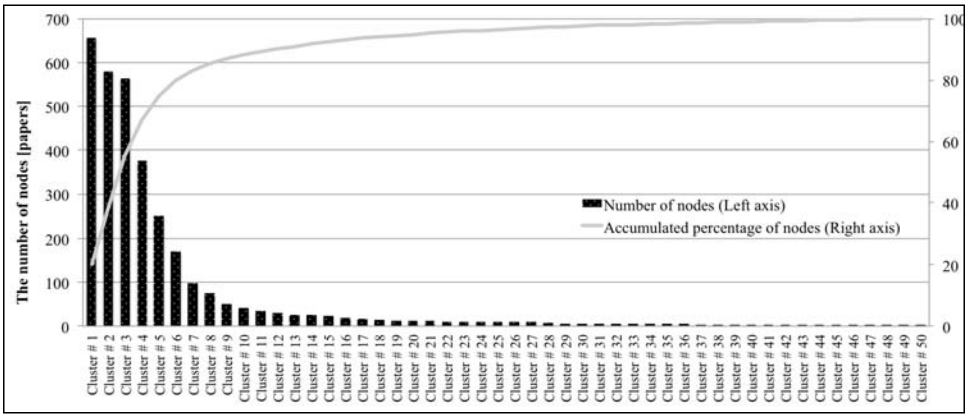


Figure 3 Cluster size and accumulated percentage

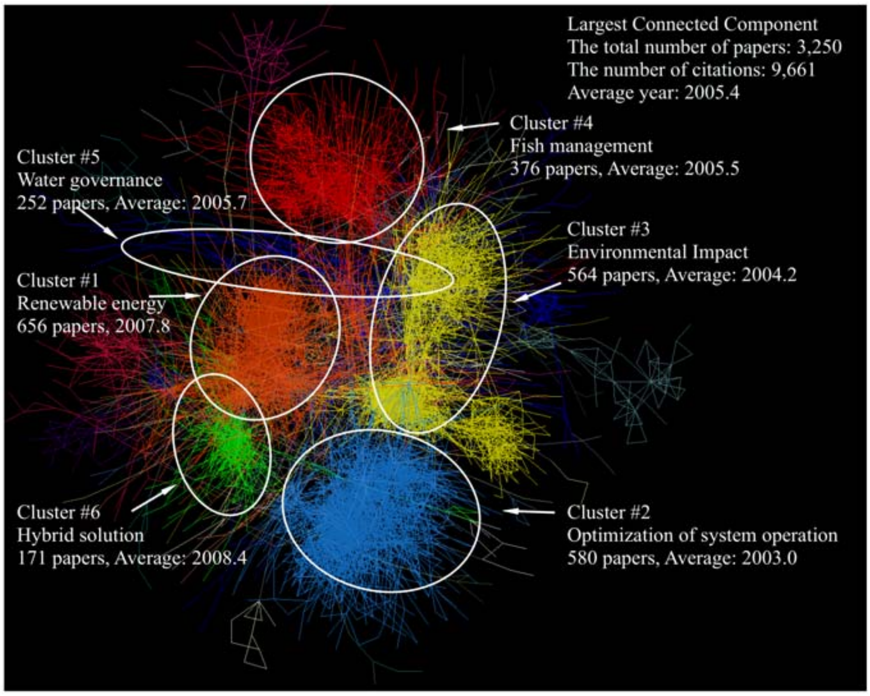


Notes: Black bar and gray line respectively represent the number of nodes in each cluster and the accumulated percentage of nodes.

In the next step, the citation network is converted to a non-weighted, non-directed network. Because not all the retrieved papers are closely relevant to the major topic of hydropower, we specifically examined the largest connected component. This component accounted for about 43.2% of the total papers (3,250 out of 7,521 papers). Therefore, we regarded papers showing no citation relation with other papers as digressional and ignored them in this research.

After the process of clusterisation, the whole citation network of hydropower is divisible into 50 clusters, where the number of nodes in each cluster varies mutually with the largest cluster (cluster #1) of 656 nodes and the smallest one (cluster #50) containing only three nodes. As explained in the last chapter, papers in each cluster are strongly coupled by intra-cluster citation. As shown in Figure 3, the number of nodes in each cluster decreases sharply until the ninth cluster. After the 20th cluster, the number becomes trivial. In this way, we can neglect the clusters after the cluster #7 because the top six clusters account for about 80% of the total papers as nodes in this network as depicted in Figure 3.

Figure 4 Visualization of the structure of hydropower (see online version for colours)



By assigning different colours to intra-cluster links in different clusters, we can obtain the visualised structure of the citation work, as portrayed in Figure 4. Some clusters' structures are compact and round like cluster #2, whereas some others are stretched like cluster #3. Usually, the former ones stand for clusters that consist of papers with a strong tendency to cite other papers in the same cluster, whereas the latter ones are related closely to the clusters located in the corresponding direction. When clusters are mutually close, meaning that there exist close citation relations among the papers in those clusters. Table 1 presents characteristics of the top six clusters and sub-clusters in each cluster.

Table 1 Summary of academic paper clusters and sub-clusters

Cluster no.		*Cluster name*	*No. of papers*	*Average year*	*Top keyword*
#1		Renewable energy	656	2007.8	Turkey
	#1-1	Small hydropower	171	2008.3	SHP
	#1-2	Hydropower in Turkey	152	2006.9	Turkey
	#1-3	Effect of climate change on hydropower	117	2007.9	Climate
#2		Optimisation of system operation	580	2003.0	Programming
	#2-1	Optimisation of system operation	180	2003.4	Reservoir
	#2-2	Scheduling	137	2004.9	Scheduling
	#2-3	Stochastic optimisation	67	2002.2	Scheduling
#3		Environmental impact	564	2004.2	Fish
	#3-1	Impact on aquatic fauna	117	2002.5	Fish
	#3-2	Greenhouse gas emissions	141	2005.6	Ch4
	#3-3	Mercury in the river	108	2003.7	MeHg
#4		Fish management	376	2005.5	Fish
	#4-1	Fish passage survival	73	2006.2	Fish
	#4-2	Migration of eels	65	2005.8	Eel
	#4-3	Migration of salmon	55	2006.7	Salmon
#5		Water governance	252	2005.7	River
	#5-1	Mekong Basin hydropower	38	2009.1	Cambodia
	#5-2	Channel changes	28	2004.0	Snowy
	#5-3	River regulations	26	2005.0	Free flowing
#6		Hybrid solution	171	2008.4	Wind
	#6-1	Pumped hydro storage system	39	2010.4	PHES
	#6-2	Hybrid solution	24	2007.5	Wind
	#6-3	Renewable energy scenario	24	2009.8	WWS

As shown in Table 1, cluster #1 has 656 papers in it and is the largest among the 50 clusters. The top keywords of cluster #1 turn out to be quite general and slightly different because the top keyword is the name of a country, ‘Turkey’, which is apparently not so closely related to the central topic of hydropower. To elucidate the contents of this cluster, we further conducted an in-depth clusterisation of the papers in cluster #1. The top three sub-clusters include research reports related to small hydropower, hydropower in Turkey, and the effect of climate change on hydropower. Although ‘’Turkey’ ranks no. 1 among all keywords of cluster #1, the largest sub-cluster is sub-cluster #1-1, which is about small hydropower. It is also the youngest one among the sub-clusters of cluster #1, corresponding to the current trend of exploiting small hydropower. One cannot ignore the fact that Turkish researchers have contributed the most to the study in this field according to the country rank. According to a recent report, Turkey is increasing its hydropower capacity at a rapid rate to address chronic shortages of electricity and frequent power outages, which is approximately 2 GW in 2012, second only to China (REN21, 2013). Currently, hydropower is Turkey’s major renewable energy source, supplying approximately 25.0% of the country's annual electricity generation and the Turkish government has an extremely impressive target to use all technically available hydroelectric potential by 2023 (Melikoglu, 2013). This market need for hydroelectricity is making a major contribution to the funding for related research in Turkey.

Cluster #2 is mainly inclusive of methods and algorithms for optimising the system operation of hydroelectricity generation. Furthermore, cluster #2 is the oldest cluster among the major clusters. According to the top cited (within cluster) papers, cluster #2-1 tends to represent cluster #2; therefore, we named the same topic with cluster #2. Cluster #2-2 is about optimisation methods particularly addressing the scheduling of hydropower operation considering head dependency. Head dependency is regarded as a nonlinear problem. However, cluster #2-3 consisted of papers related to the same topic using a stochastic method. This sub-cluster is the oldest among all sub-clusters in this field.

As for cluster #3, this cluster mainly deals with environmental issues directly associated with the construction of hydroelectric reservoirs, such as greenhouse-gas emissions, influence on fish behaviour, sediment problems. Cluster #3-1 discusses the impact on aquatic fauna by hydropower generation. Because this sub-cluster is also an old one among all sub-clusters, it is apparent that topics related to the impact on aquatic fauna have been discussed for a long time in the hydropower context. Cluster #3-2 consists of papers discussing efficiency for decreasing greenhouse gas emissions. Cluster #3-3 is also about environmental issues, but most of the papers in this sub-cluster specifically examine residual mercury in reservoirs. Cluster #4 discusses fishery matters in the context of hydropower generation. Many papers have reported impacts on ecological systems as a result of the construction and operation of hydropower plants. Not only stakeholders but also designers of hydropower generations are required to contrive ways of avoiding wasteful killing.

Cluster #5 is about water governance. Because cluster #5-1, which discusses the Mekong Basin hydropower, is a young sub-cluster, we can understand that hydropower generation in eastern Asia has been drawing attention in recent years.

Cluster #6 is the youngest major cluster, in which wind and pumped storage are the key topics. Wind-hydro, solar-hydro, and other similar types of hybrid renewable energy systems are discussed in this cluster. Unlike hydropower, the generation of wind or solar energy bears a stochastic nature. Simultaneously, the process of consumption is also uneven and depends on the rhythm of people's lives, type of energy consumption, etc. To balance supply and demand, some energy in times of surplus can be stored and then output in times of deficit, which is a feature of hydropower. Rather than the USA, researchers from Croatia and Greece contribute the most papers to this cluster.

3.2 Results of top cited paper within each cluster

We extracted the six most cited papers within each cluster in Table 2. The top cited (within the cluster) paper in cluster #1 is titled 'small hydropower: technology and current status' (Oliver, 2002). This paper presents a discussion of the classification of small hydropower plants without reservoirs, the history, mechanism, economics and problems to be solved when these small hydropower generation plants are installed. The publication year of this paper is 2002, which is six years before 2007.8 as the average year of publication in cluster #1. The author of this paper is a senior engineer with IT Power Ltd., an international energy consultancy firm specialising in renewable energy engineering. It is interesting that the top cited paper is written by a person who is in the industrial domain, not an academic person. A paper titled ‘optimal operation of multi-reservoir systems: state-of-the-art review’ is the top cited paper (within the cluster) in cluster # 2 (Labadie, 2004). This paper is a review related to the optimal methodology for operation of a multi-reservoir system. The number of times cited within cluster, 57, exceeds the number of times cited within cluster in cluster #1. From the number of citations of this paper (742 papers are cited in this paper), it is apparent that this paper is a comprehensive review paper. In cluster #3, the top cited (within the cluster) paper is titled ‘are hydroelectric reservoirs significant sources of greenhouse gases’. This paper explains a hypothesis, the amount emitted is positively related to the area flooded, and is supported by actual data that is retrieved in northern Canada (Rudd et al., 1993). As for cluster #4, the title of the paper that is top cited (within the cluster) is ‘the development of advanced hydroelectric turbines to improve fish passage survival’. Technological progress in hydroelectric generation refers not only toimprovement of power generation efficiency but also environmental considerations. This paper organises studies of the design and operation of turbines designed not to damage fish passing dams (Cada, 2001). The top cited paper in cluster #5 is ‘Mekong hydropower development’, a paper posted on science. With an increase in the significance of energy supply in eastern Asian countries over the years, multiple donors have promoted cooperative frameworks including UN brokered sustainable energy for all (SE4All). Because the area along the Mekong has high potential in hydroelectric generation, neighbouring countries tend to avoid large-scale fossil electric power generation considering public sentiment. Hydroelectric generation, one means of using renewable energy, involves rural electrification using small hydropower even along the branch of the Mekong. The paper most frequently cited in cluster #6 is titled ‘combining hydro and variable wind power generation using pumped-storage under economically viable terms’, which verifies the economic relevance of the pumped hydro storage (PHS) systems located in the Aegean Sea island, Lesbos (Kapasali and Kaldellis, 2010).

Table 2 Top cited papers within each cluster

Cluster no.	*Top cited paper (within cluster)*	*Authors*	*Times cited**
#1	‘Small hydropower: technology and current status’, *Renew Sust Energ Rev*, Vol. 6, p.537.	Paish (2002)	41
#2	‘Optimal operation of multi-reservoir systems: state-of-the-art review’, *J Water Res PL-ASCE*, Vol. 130, p.93.	Labadie (2004)	57
#3	‘Are hydroelectric reservoirs significant sources of greenhouse gases’, *AMBIO*, Vol. 22, p.246 (1993)	Rudd et al.	51
#4	The development of advanced hydroelectric turbines to improve fish passage survival, Fisheries, V26, P14 (2001)	Cada	23
#5	‘Mekong hydropower development’, *Science*, Vol. 332, p.178.	Grumbine et al. (2012)	10
#6	‘Combining hydro and variable wind power generation by means of pumped-storage under economically viable terms’, *Appl. Energ*, Vol. 87, p.3475.	Kapasali and Kaldellis (2010)	16

Note: *Times cited within each cluster.

3.3 Results from time series plot

By plotting the annual publication data (1963–2013) of each cluster in one graph, we obtain Figure 5. Although varying from each other, the top six major clusters still share several traits in common: first, there are few papers published before the 1980s, indicating that the current dominant research topics are still young compared with the long history of hydropower. Furthermore, there has been a rising tendency in recent years, this trend might be explained using the rapid development of research on sustainability science, which has become a significant issue in contemporary society (Kajikawa et al., 2007). Hydropower is no longer simply a method to produce electricity, increasingly attention is being paid to other related studies, such as the environmental impact of hydropower in clusters #3, #4, and #5 (Rudd, 1993). This growth trend is classifiable into three types. The first type is the rapid increase after 2008 as seen in clusters #1 and #6. The second type is the smooth increase as shown in clusters #3, #4, and #5. The third type is the fluctuation in the quantity of academic publications as in cluster #2, for example, the number of publications in cluster #2 drops from the late 1990s and increases again in the late 2000s.

Figure 5 Time series plot of each cluster

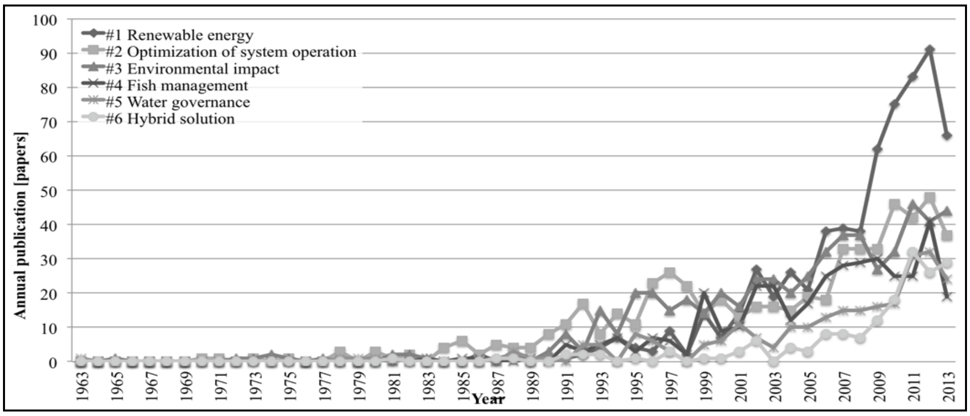
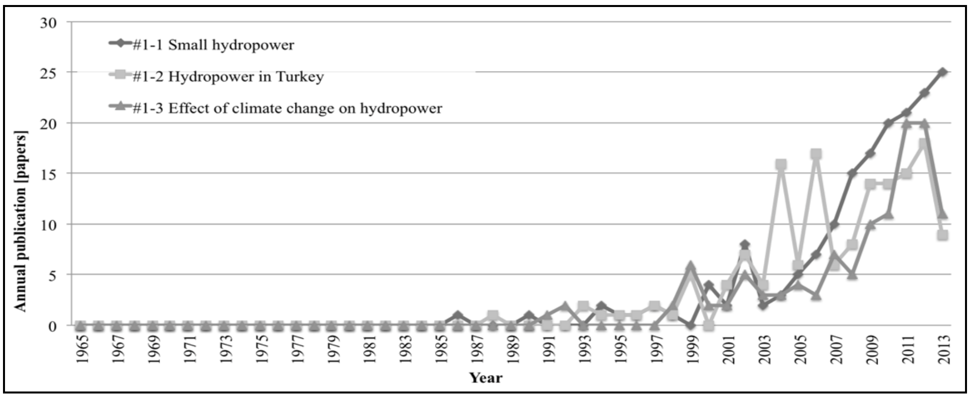


Figure 6 Time series plot of sub-clusters in cluster #1



However, by plotting the annual publication data (1965–2013) of each sub-cluster in each figure, we can obtain Figure 6 (cluster #1) to Figure 11 (cluster #6). These figures identify the areas attracting most attention in recent years. Figure 6 demonstrates that the papers on sub-cluster #1-1: small hydropower has increased in a steady manner since 2004. Figure 10 shows a rapid increase in the number of papers on #5-1: Mekong Basin hydropower. Particularly the number of papers published in 2013 increased to 220% over the last year (five papers in 2012 to 12 papers in 2013), which indicates the popularity of hydroelectric generation in eastern Asian countries. In addition, Figure 11 shows that all sub-clusters (#6-1, #6-2, and #6-3) experienced rapid growth after 2000, although the absolute number of papers published is small. Those sub-clusters demonstrating an increasing trend in recent years are expected to continue attracting attention for a certain period of time in the future. In contrast, the number of recent papers in some sub-clusters including #2-3: stochastic optimisation remains unchanged despite their nature as upper clusters. Therefore, these clusters are less attractive in the area of academic study of hydroelectric generation.

Figure 7 Time series plot of sub-clusters in cluster #2

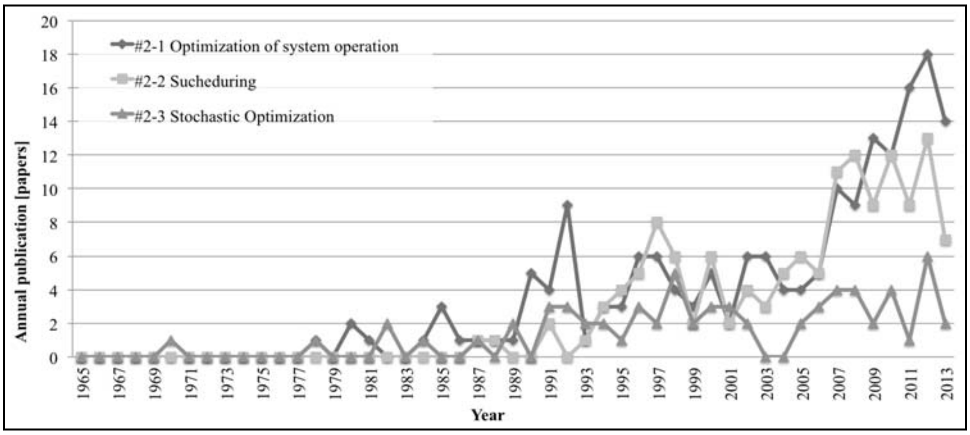


Figure 8 Time series plot of sub-clusters in cluster #3

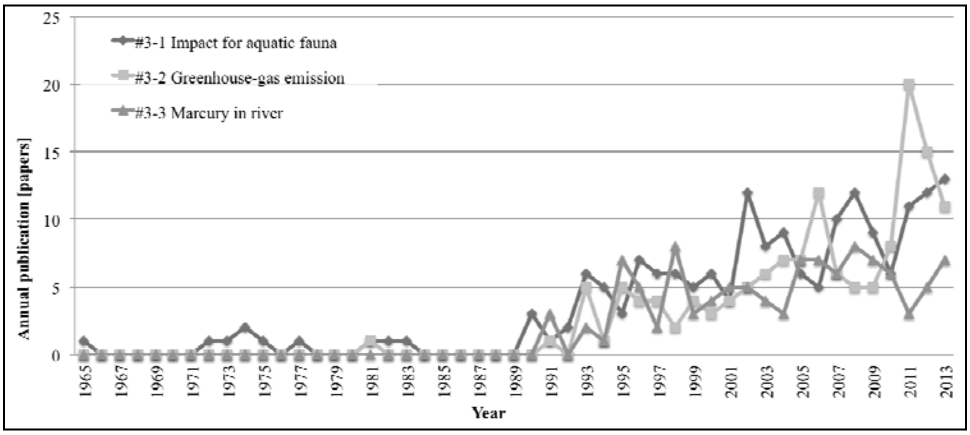


Figure 9 Time series plot of sub-clusters in cluster #4

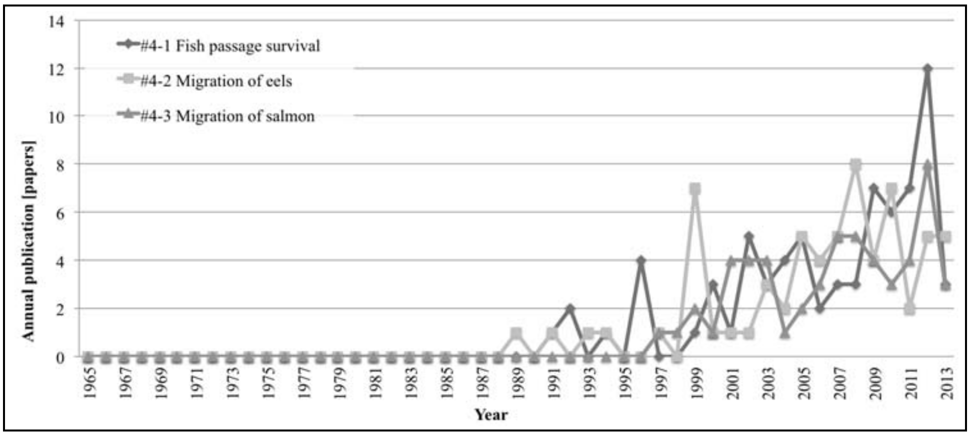


Figure 10 Time series plot of sub-clusters in cluster #5

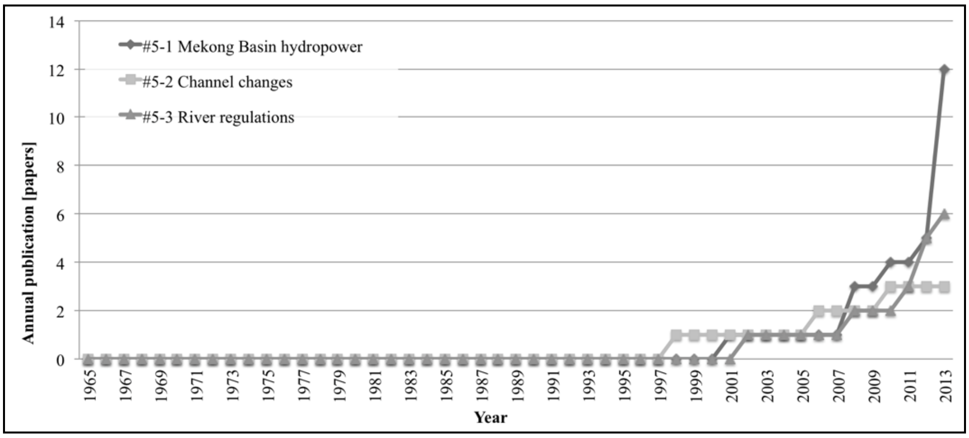
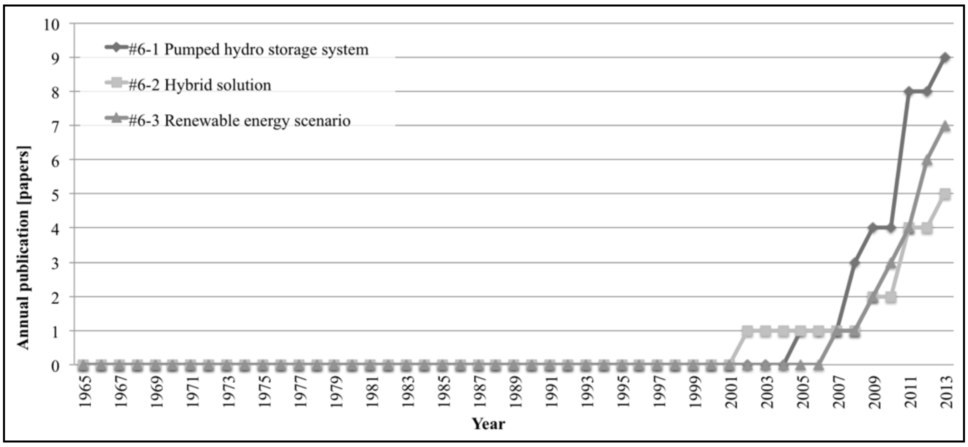


Figure 11 Time series plot of sub-clusters in cluster #6



3.4 Oligopoly structure by sub-cluster

Next, the variations in each sub-cluster were calculated using each country. The results were obtained by calculating the Herfindahl-Hirschman index, which generally indicates the oligopoly situation in the market. In this instance, the extent to which each sub-cluster is in the oligopoly situation was calculated based on the share of publications in each sub-cluster in each country. The Herfindahl-Hirschman index *HHI* is given as shown below.

$$HHI = \sum_{i=0}^{N} s_i^2$$

Therein, s_i stands for the publication share of country *i* in the sub-cluster, and *N* signifies the number of countries. According to US Department of Justice and the Federal Trade Commission (2010), *HHI* is divided into the following three criteria:

- unconcentrated: HHI below 1,500
- moderately concentrated: HHI between 1,500 and 2,500
- highly concentrated: HHI above 2,500.

Table 3 Herfindahl-Hirschman index of each cluster

Sub-cluster no.	*Cluster name*	*Herfindahl-Hirschman index*
#1-1	Small hydropower	534
#1-2	Hydropower in Turkey	8,266
#1-3	Effect of climate change on hydropower	1,272
#2-1	Optimisation of system operation	1,328
#2-2	Scheduling	703
#2-3	Stochastic optimisation	652
#3-1	Impact on aquatic fauna	1,094
#3-2	Greenhouse gas emissions	1,280
#3-3	Mercury rivers	1,693
#4-1	Fish passage survival	5,112
#4-2	Migration of eels	884
#4-3	Migration of salmon	5,926
#5-1	Mekong Basin hydropower	826
#5-2	Channel changes	1,578
#5-3	River regulations	1,872
#6-1	Pumped hydro storage system	929
#6-2	Hybrid solution	752
#6-3	Renewable energy scenario	1,568

Based on these criteria, sub-clusters #1-2, #4-3, and #4-1 might be classified as Highly Concentrated. As seen from the name, #1-2: hydropower in Turkey suggests that many papers are written about hydroelectric generation in Turkey. Therefore, the classification is not in doubt. The three countries producing the largest number of papers on # 4-1: fish passage survival includes the USA with 55 papers, Canada with six papers, and the People's Republic of China with five papers. Similarly, #4-3: migration of salmon includes 47 papers, seven of which are from Canada and four from Japan. All those exhibit the US dominance in the number of papers. The sub-clusters in which a number of countries are uniformly interested (unconcentrated) might be #1-1: small hydropower (HHI = 534), #2-2: scheduling (HHI = 703), #2-3: stochastic optimisation (HHI = 652) and #6-2: hybrid solution (HHI = 752). They all could be sub-clusters in competition.

4 Discussion

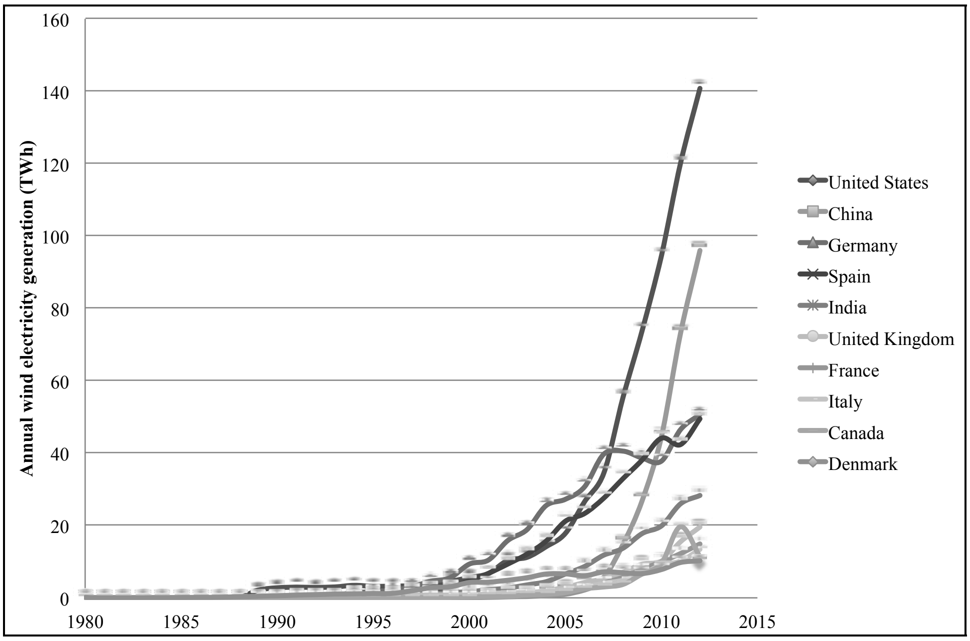
4.1 Characteristics of each cluster.

As described in the results section, sub-cluster #1-1 (small hydropower), #5-1 (Mekong Basin hydropower), and cluster #6 (hybrid solution) are young and rapidly developing among the major clusters. The appearance and development of these three topics is closely related to contemporary social needs. In the case of sub-cluster #1-1 (small hydropower), hydropower on a small-scale is not only an extremely cost-effective energy technology that is appropriate for rural electrification in developing countries; it is also the main prospect for future hydropower development in Europe, where large-scale opportunities have either been exploited already, or would now be considered environmentally unacceptable (Oliver, 2002). How to make electricity generation more efficient and how to strike a balance to maintain both the ecological health of the stream and the economics are the main topics of this research field.

Regarding sub-cluster #5-1 (Mekong Basin hydropower), it is well known that the Mekong River and its tributaries have a large potential for hydropower. Moreover, eastern Asian countries surrounding the river are gathering attention as rapidly developing countries. They have huge demand for current and future electricity. Lao PDR is therefore called the 'Battery of Southeast Asia' because this country has large hydro power generation along Mekong River and its tributaries. This country exports electricity to Thailand and other neighbouring countries. Myanmar is an emerging country associated with the wider Mekong. This country also needs enormous hydropower capacity to meet their large demand. In such a situation, not only China but also other countries find opportunities to construct a series of hydropower in the upper and lower stream. It is easy to expect that biodiversity and ecosystem service values will be reduced after constructing them. They also affect the food security of millions of people (Grumbine and Xu, 2011). In that sense, regional governance issues of Mekong hydropower decision-making are complex and transnational (Grumbine et al., 2012), addressing social, ecological, economic, and political matters, in addition to ongoing regional governance issues. Although the papers in this sub-cluster #5-1 (Mekong Basin hydropower) are fewer than for other sub-clusters, its growth rate is radical. Base on social and economic situation, this topic might grow now and in the future.

In cluster #6 (hybrid solution), hydropower acts as a large energy container to stabilise the output of electricity. Although the concept of pumped-storage hydroelectricity dates back to the 1930s, it is the rapid development of wind, solar, and other renewable energy that is leading to the research and application of pumped-storage systems in wind and solar power plants. The following Figure 12 is based on wind electricity generation data from the US Energy Information Administration (2015). The chart shows that for most countries listed here, growth starts around 2000 and then continues at an almost constant increasing rate. Especially for the USA and China, growth accelerated in 2007; it has been increasing rapidly ever since. Compared with hydropower, wind and solar power are young technologies. We consider one reason for cluster #6 (hybrid solution) being the youngest cluster is the progress of other renewable energy.

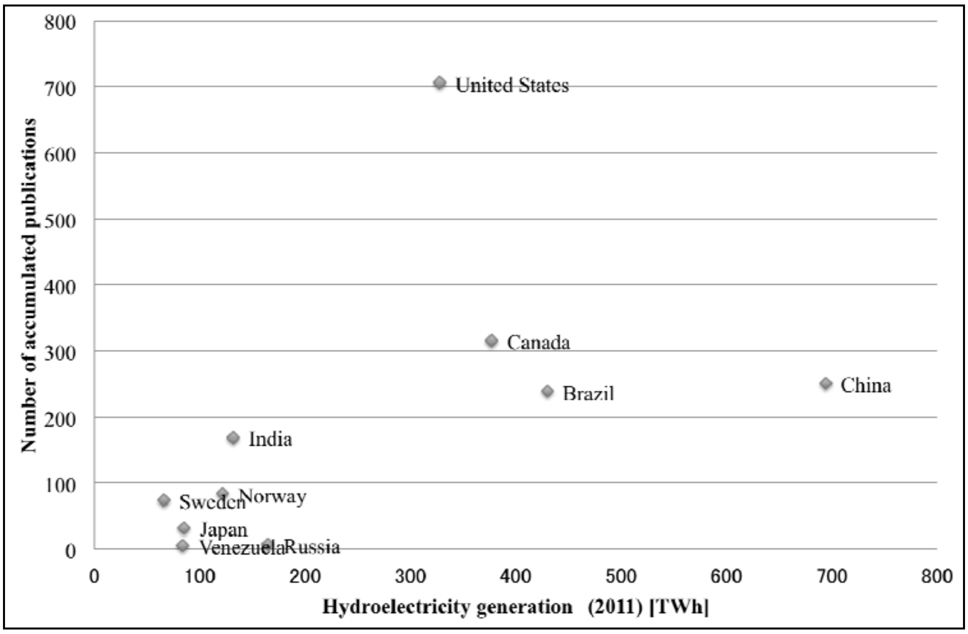
Figure 12 Top 10 countries generating electricity from wind (1980–2011)



An estimated 30 GW of new hydropower capacity came on line in 2012, increasing the global installed capacity by about 3% to an estimated 990 GW. The top countries for hydro capacity are China, Brazil, the USA, Canada, and Russia, which together account for 52% of total installed capacity (REN21, 2013). We managed to obtain hydroelectricity generation data of 2011(US Energy Information Administration, 2015). By combining it with the academic publication data, we obtained Figure 13, indicating a close relation between industry and academia.

As presented in Figure 13, except for Russia and Venezuela, countries with large electricity generation also possess a high rank among academic publications. Furthermore, the top four countries of both ranks are the same, despite some trivial difference in the order, which is subject to many other factors such as the natural environment. Actually, clusters #2 (optimisation of system operation), #3 (environmental impact), and #4 (fish management) are all related closely to the practical development of hydropower, these four clusters are dominated by China, Brazil, Canada, and the USA, which are also the top four hydropower generating countries in the world (REN21, 2013). Therefore, for hydropower, we regard the relation between industry and academia as extremely close.

Figure 13 Scatter chart showing hydroelectricity generation and academic publication of leading countries



4.2 Policy implications

We inferred correlation between the trend of academic studies and that of industrial development. Although hydroelectric generation is a mature technology, proper social implementation of that technology requires collection and analysis of academic knowledge in that field.

All of clusters #1-1, #5-1, and #6 are growing rapidly in publication of academic papers. All are attracting social attention.

Developing eastern Asian countries with huge potential for hydroelectric power can benefit from collection of information about the introduction of hydroelectric generation. Access to that knowledge by policymakers of renewable energy in economically developing countries is becoming easier recently. In that sense, policymakers should not make policy without gaining full access to that knowledge. Determining the direction of energy policy influenced by older and less than reliable data or limited information from neighbouring countries might engender the adoption of ineffective or short-sighted policy, making the policy they proposed difficult to evaluate a few years later.

Policymakers in these countries are asked to send information about their own countries to the rest of the world, explaining the recent uses of small hydroelectric power generation and their problems comprehensively (#1-1), what challenges are confronting neighbouring countries (#5-1), and the proper composition of electrical resources to establish a stable supply of electricity on and off grid (#6). In these contexts, governments of developing countries must prepare such environments in which policymakers can access the latest knowledge and dispatch information related to their own countries.

4.3 Limitations of this research

Below, we explain some limitations of the approach applied in this research. We collected a corpus of academic publications by making a query, which failed to include some related papers and which excluded some unrelated papers. Results obtained by citation network analysis indicate that the top six major clusters account for most of the total papers, among which small hydropower and pumped-storage system are emerging research fields with an acute increase in recent years. Furthermore, many papers discuss the social and environmental influence that this technology has had or might have on society. As a mature technology, there are lower expectations for new breakthroughs. Therefore, increasing numbers of researchers are now dealing with non-technology issues related to hydropower. However, even though a close relation between academic research and practical applications, not all scientific progress can be commercialised to meet social needs. The bibliographic analysis might be unable to offer sufficient grounds for predicting how emerging technologies will evolve without information related to the application side. Still, the citation network approach is a powerful tool for assisting experts in their construction of fundamental frameworks in domains such as hydropower where the number of annual publication far exceeds the capacity to read all papers.

5 Concluding remarks

Hydropower, as an important renewable energy resource, is indispensable for the development of the economy and society. To meet the rapidly increasing demand for electricity, a growing body of research assesses and explains hydropower. Although is it impossible to read all the papers published each year, planners of energy research and energy researchers must grasp broad trends in hydropower research, and make decisions on effective investment with limited resources. The computer-based approach is expected to offer supplemental information.

This paper visualised the structure of hydropower by analysis based on citation relations among relevant publications, and used a topological clustering method to detect the major topics of hydropower (Newman, 2004; Newman and Girvan, 2004). Our citation analysis extracted six main research domains: renewable energy, optimisation of system operation, environmental impact, fish management, water governance and hybrid solution. Among these major clusters, small hydropower, Mekong Basin hydropower and pumped-storage system are currently developing topics that correspond to the development of small hydropower and hybrid power plants on the application side. A comparison of the data of hydroelectricity generation and academic publication shows that the relation between academia and industry of hydropower is quite close.

The analysis produces concise summary of the overall structure of the target research field and emerging research topics. However, we discarded most contents of the papers during analysis. For instance, each cluster is named after the title and abstracts of the top 20 most cited papers in the cluster. By this process, information from less-cited papers is ignored, which in some situations might have great potential as new technologies. Furthermore, our analysis is determined greatly by the pile of publications we extracted in the first step. It is not an easy task to define a research domain using queries. The method of query selection to define a research domain effectively is beyond the scope of this paper. It leaves room for future improvement. The last shortcoming of this approach is the existence of a time lag. It takes time for a paper to be recognised by academia; it also takes time from the completion of research to the publication. Without amendments based on experts' opinions, the so-called current status might not be so current. Moreover, it can be difficult to grasp the current landscape correctly.

Although the computer-based approach is a powerful tool for summarising and visualising the overall structure of a target research domain in a way that even cannot be done by experts, the results obtained using this approach provide only a reference point for those who contribute to hydropower development. We hope that the obtained landscape can help to promote research on hydropower by enabling the current status to be grasped quickly and clearly.

Even in developing countries, recently, policymakers should make policy with gaining full access to that knowledge. Governments must prepare such environments in which policymakers can access the latest knowledge and dispatch information related to their own countries.

References

Adai, A.T., Shailesh, V.D., Shannon, W. and Edward, M. (2004) 'LGL: creating a map of protein function with an algorithm for visualizing very large biological networks', *Journal of Molecular Biology*, Vol. 340, No. 1, pp.179–190.

Börner, K., Chen, C. and Boyack, K.W. (2003) 'Visualizing knowledge domains', *Annual Review of Information Science and Technology*, Vol. 37, No. 1, pp.179–255.

Boyack, K.W., Klavans, R. and Börner, K. (2005) 'Mapping the backbone of science', *Scientometrics*, Vol. 64, No. 3, pp.351–374.

Cada, G.F. (2001) 'The development of advanced hydroelectric turbines to improve fish passage survival', *Fisheries*, Vol. 26, No. 9, pp.14–23.

Grumbine, R.E. and Xu, J. (2011) 'Mekong hydropower development', *Science*, Vol. 332, No. 6026, pp.178–179.

Grumbine, R.E., Dore, J. and Xu, J. (2012) 'Mekong hydropower: drivers of change and governance challenges', *Frontiers in Ecology and the Environment*, Vol. 10, No. 2, pp.91–98.

Huang, H. and Yan, Z. (2009) 'Present situation and future prospect of hydropower in China', *Renewable and Sustainable Energy Reviews*, Vol. 13, No. 6, pp.1652–1656.

Kajikawa, Y., Ohno, J., Takeda, Y., Matsushima, K.,and Komiyama, H. (2007)'Creating an academic landscape of sustainability science: an analysis of the citation network', *Sustainability Science*, Vol. 2, No. 2, pp.221–231.

Kapasali, M. and Kaldellis, J.K. (2010) 'Combining hydro and variable wind power generation using pumped-storage under economically viable terms', *Applied Energy*, Vol. 87, No. 11, pp.3475–3485.

Kishor, N., Saini, R.P. and Singh, S.P. (2007) 'A review on hydropower plant models and control', *Renewable and Sustainable Energy Reviews*, Vol. 11, No. 5, pp.776–796.

Labadie, J.W. (2004) 'Optimal operation of multireservoir systems: state-of-the-art review', *Journal of Water Resources Planning and Management*, Vol. 130, No. 2, pp.93–111.

Li, X., Chen, H., Huang, Z. and Roco, M.C. (2007) 'Patent citation network in nanotechnology (1976–2004) *Journal of Nanoparticle Research*, Vol. 9, No. 3, pp.337–352.

Melikoglu, M. (2013) 'Hydropower in Turkey: analysis in the view of Vision 2023', *Renewable and Sustainable Energy Reviews*, Vol. 25, pp.503–510.

Newman, M.E. (2004) 'Fast algorithm for detecting community structure in networks', *Physical Review E*, Vol. 69, No. 6, p.066133.

Newman, M.E. and Girvan, M. (2004) 'Finding and evaluating community structure in networks', *Physical Review E*, Vol. 69, No. 2, p.026113.

Okot, D.K. (2013) 'Review of small hydropower technology', *Renewable and Sustainable Energy Reviews*, Vol. 26, pp.515–520.

Oliver, P. (2002) 'Small hydropower: technology and current status', *Renewable and Sustainable Energy Reviews*, Vol. 6, No. 6, pp.537–556.

Paish, O. (2002) 'Small hydropower: technology and current status', *Renew Sust. Energ. Rev.*, Vol. 6, No. 6, p.537.

REN21 (2013) *Renewables 2013: Global Status Report*, REN21 [online] http://www.unep.org/pdf/GSR2013.pdf (accessed 21 January 2015).

Rudd, J.W., Hecky, R.E., Harris, R. and Kerry, C.A. (1993) 'Are hydroelectric reservoirs significant sources of greenhouse gases', *International Atomic Energy Agency*, Vol. 22, No. 4, pp.246–248.

Shibata, N., Kajikawa, Y. and Sakata, I. (2010) 'Extracting the commercialization gap separating science and technology – case study of a solar cell', *Technological Forecasting and Social Change*, Vol. 77, No. 7, pp.1147–1155.

Thelwall, M., Vann, K. and Fairclough, R. (2006) 'Web issue analysis: an integrated water resource management case study', *Journal of the American Society for information Science and Technology*, Vol. 57, No. 10, pp.1303–1314.

US Department of Justice and the Federal Trade Commission (2010) *Horizontal Merger Guidelines*, US Department of Justice and the Federal Trade Commission.

US Energy Information Administration (2015) *International Energy Statistics, Renewable Electricity Generation*, International Energy Statistics, Renewable Electricity Generation [online] http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=12 (accessed 21 January 2015).

World Commission on Environment and Development (1987) *Our Common Future Vol. 383*, Oxford University Press, Oxford.

Yang, C.J. and Jackson, R.B. (2011) 'Opportunities and barriers to pumped-hydro energy storage in the United States', *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 1, pp.839–844.