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Forecasting OLED TV Technology Using Bibliometrics and Fisher-Pry Diffusion Model

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Abstract--**The market of flat panel displays is experiencing rapid growth with the advancement of digital technologies in broadcasting service. The next challenge of LCD is OLED in TV market. The study attempts to investigate the trends in advanced or emerging technologies by determining their technology diffusion rates due to the lack of experiential data. With the development of information and communication technology, one of the recent methods to assist in technology forecasting is data mining in bibliometric or textual data from various sources such as patents, journals, and research awards. The information extracted from diverse sources can be employed in technology diffusion models such as Fisher-Pry where emerging technologies substitute older ones. The study uses web of science and compendex for bibliometric analysis to forecast the growth of next-generation OLED technologies based on the analogous growths of LCD technologies.**

I. INTRODUCTION

Historically, the feasibility of a flat display has been successfully demonstrated with the Aiken tube, and since 1956 with the development of electro-luminescent panels [1]. In the latest years, Organic Light-Emitting Diode (OLED) technology has taking off substantially, and successfully penetrated into TV market, compared with previous years. Major drivers of this technology development are market demand for thin profile, bigger screen sizes and the needs of energy efficiency. Light-emitting diode (LED)- liquid-crystal display (LCD) technology TVs along with the trend to larger screen sizes are well underway. Over the last 10 years demand for bigger screen sizes in the household as well as commercial market, fuelled through such roll outs as High Definition (HD) Digital TV services, has led to the development of new display technologies such as LCD, LED-LCD, OLED, and plasma display panel (PDP). The study explores these technological development trends and progress associated with TV market. Included is some comparison of the energy use of OLED TV compared to other TVs such as plasma TV, LED-LCD TV, LCD TV, and traditional Cathode Ray Tube (CRT) TV.

The forecast of the next generation technology plays a significant role in research and development (R&D) planning to compete continuously in the saturated TV market. That is because TV industry is capital intensive and the speed of technological change for next substitutions has been increasing. The technology forecasting method used in this study offers a fairly and relatively accurate forecast for the measurement of OLED TV adoption in the market. The conclusion drawn from this study helps companies involved in OLED technologies to compete strategically and encourage the adoption of energy saving technologies in the market by forecasting the technological trends of the OLED TV. Another evidence regard to the increasing importance of OLED technologies includes the different Technology Roadmap programs developed by DOE and the recent increase in cooperative development by universities in areas such as materials and manufacturing equipment [2]. The study selects LCD technologies and build forecasting model to represent their market diffusion or growth curves using existing bibliometrics. The study uses multiple types of bibliometrics such as journals, conference proceedings, and patents for the purpose of forecasting OLED TV technologies in the university accessible databases. It is crucial that the method used to forecast OLED TV technology represents life-cycle of the OLED TV and provides as accurate outcomes as possible.

II. LITERATURE REVIEW

In history, technology forecasting (TF) is of much interest to government and to other research institutions. Around late 1960s, Erich Jantsch and Robert Ayres discuss that the company began to put some efforts in the integration of technological forecasting with long-range planning [3][4]. As information technology (IT) has gained more attention over several decades, data mining become a practical technique to identify early signs of technological change [5][6][7]. Cho and Daim [8] illustrate its origin, characteristics and extensions with other TF methods in detail [9]. Through literature review in Compendex and Web of Science, this paper investigate the first attempt to forecast technological change of television, which was made by Sidney Feinleib in 1971 employing morphological forecast and trend analysis [1]. Raymond Wilmotte [10], as a consultant, also discuss various technological change, broadcasting service and standards associated with TV, based on the report of "technological boundaries of television" funded by Federal Communications Commission in late 1974. Thereafter, over the last several decades, surprisingly little efforts has been made on the forecast of TV technologies in literature, even though TV, in the consumer area, is not only one of the best selling products in the world with large number of annual shipments, but also accounts for a significant residential electricity consumption. This is not simply because TV is out of lack of interest, but partly because TV technologies have been transferred from Western countries to Asian countries, and currently Asian countries such as Japan, South Korea, China, and Taiwan produce advanced TVs available to the market. Kreng and Wang [11] investigate the dynamic competitive relationship between PDP TVs and LCD TVs by means of their quarterly shipments employing the Lotka–Volterra model, which can incorporate the competitive relationship between the LCD TV as the prey (positive impact on the growth of PDP TVs) and the PDP TV as the predator (negative effect towards LCD TVs). They discuss the possibility for dropping the price of LCD TVs is an advantage of the attractiveness of the product which can be noted in higher growth rate than PDP TVs. Tseng et al [12] combine different technology forecasting techniques to improve the accuracy of the forecast. This study use the scenario analysis with the Delphi method and the technological substitution model to analyze the development of the organic light-emitting diode (OLED) TV from three perspectives: consumer, demand, and preference. Tsai [13] forecasts quarterly LCD TV shipments from the first quarter to the fourth quarter in 2009 using extended Gompertz models with the absolute price change value. The result show that market penetration rate is high for the smaller-sized LCD TVs while the market penetration rates is low for larger-sized LCD TV panels. Park et al [14] analyze the impact of the recent TV market transition from cold-cathode fluorescent lamps (CCFL)-LCD to LED-LCD in the LCD technology, and estimate global electricity savings potential in selected scenarios with the perspective of market transformation. Desroches and Ganeshalingam [15] measure the magnitude of the decline in cost and price for 42″ televisions, and investigate the evolution of incremental costs and prices of 47″ and 46″ 3D OLED televisions.

III. TV MARKET TRENDS

Television is defined as "a telecommunication system that transmits images of objects (stationary or moving) between distant points" by Webster dictionary, which means any device such as mobile phone, laptop computer and tablet pc can be defined as television. Given the rapidly changing market for TVs, the study discusses historical TV market trend, investigates the supply chain of manufacture in South Korea, and illustrates the major trends in TV technology options in the near future with the perspective of market transformation. In history, there was a big transition from CRT TV to flat panel display (FDP) in around 1996. CRTs has been getting smaller as they have been displaced by FDPs in the larger screen categories and the small screen categories as well. Rear Projection technology has been commercially available since the 1970s, but it has a relatively low penetration in the market. Due to LCD and OLED technologies, it is not projected to improve upon this significantly in the future, in regard to the worldwide market. LCDs have widely been used in various electronics such as mobile phones, laptop computers, Personal Digital Assistance (PDAs), and computer monitors, which are the significant driving forces behind the remarkable growth of liquid-crystal displays. In recent years, LED-LCD has been emerged as a dominant design in the TV market. Flexible OLED TV has just emerged as next generation of it.

On the other hand, TV broadcasting service has been changed throughout the world as the transition from analog to digital era, while additional features such as digital contents storage, network function, and three-dimensional (3D) video capability are likely to increase the energy consumption of TVs. Korean, Japanese and Taiwan manufacturers are continuing to lead the TV market with intense competition. Illustrated in Figure 1 is the overview of historical TV market trends and roadmap in the near future, identified by expert panel as well as literature review.

Every industry typically has its own unique market structure. The study analyze the structure of television manufacturers from expert panel and literature review. Figure 2 illustrate the ecosystem of TV industry. The supply chain of TV industry seems to be vertically integrated with closed architecture and consists of specialized suppliers.

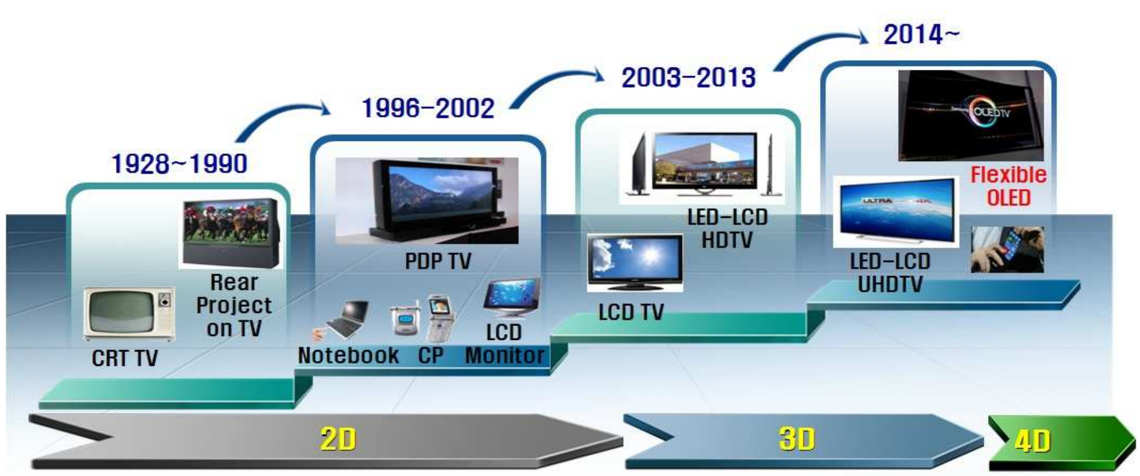


Fig. 1. TV market trends

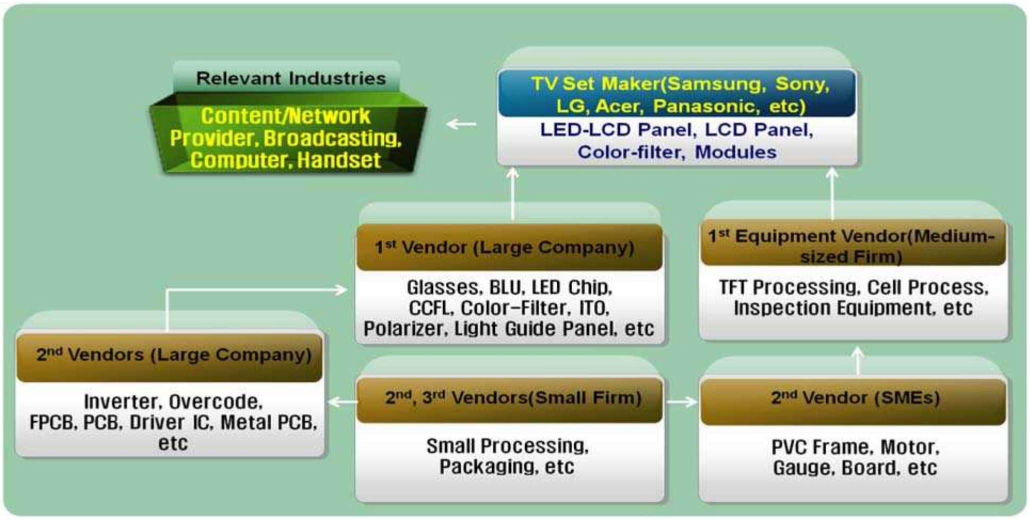


Fig. 2. The value chain of TV industry

With sales growth in diverse applications of LCD driven by laptop computer, mobile phone, and LCD monitor, LCD has successfully taken up the large-screen TV category with the aid of the rapid technology development, producing high-resolution images. On the other hand, since the introduction of PDP TV in 1995, many Korean and Japanese companies such as Samsung, LG, Panasonic, and Toshiba began to produce PDPs. They, however, recently have ceased producing PDP panels altogether in order to invest in LED-LCDs and OLEDs. Finally, PDP would be expected to lose its market position in large-size TV in sooner or later (See Table 1).

After the introduction of first color OLED display by Kodak in 1998, since 2007, several Korean and Japanese companies such as Sony, LG, and Samsung have made large commitments to developing OLED displays, having upgrading their R&D lines to commercialize OLEDs in large-size TV category. For the large sized OLED TV and lighting application, white organic light-emitting diode (WOLED) technology has been developed and constantly improved [16][17]. OLED has great image quality, higher contrast, larger viewing angle, thin and consume less energy with a thin layer of organic material which emits light, since it does not require backlight unit. Current market barriers for large-sized OLED TV are product price and performance.

TABLE 1. THE END OF THE ERA OF PDP

Country	Company	Timeline	Event
Japan	Panasonic	1995	Introduction of PDP TV
		2006	Pledged to fully focus on PDP business
		Oct-11	Announcement of trimming PDP TV plant capacity
		Mar-12	Phase-out of R&D on PDP
		Jan-13	Announcement of closing down PDP fab in Shangha
		Mar-14	Ceases PDP production and PDP TV sales
	Toshiba	2004	Disposed PDP business
	Hitachi	2008	Disposed PDP TV business
	Pioneer	2009	Disposed PDP TV business
Korea	LGE	2008	Switched PDP production to solar battery in A1
		2012	Discontinued PDP production in A2
		2013	Launched to 4 PDP TV models
	SDI	2012	Lower investment in PDP module to KRW 20bn from KRW 33.5 in 2011
		Jun-13	CEO says to dispose PDP business by 2015
		Dec-13	Write-off of PDP business assets

source: company, media sources

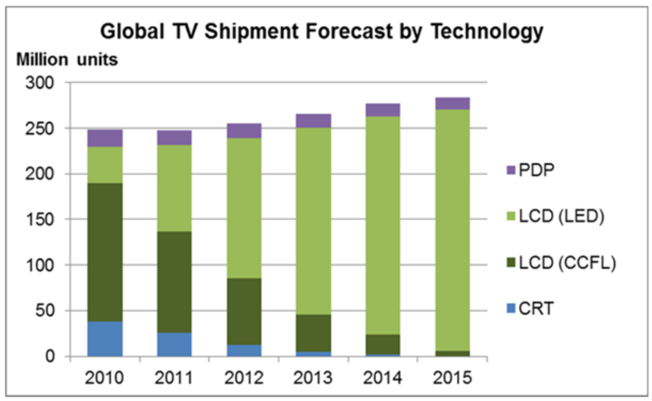
TABLE 2. THE EMERGENCE OF OLED

	Dev. Year	Size	Company	Note
Commercialization	Sep-2007	11"	Sony	$3600
	Dec-2009	15"	LGE/LG Display	$3000
Major Product Lines	Jan-2007	27.3"	Sony	
	April-2007	21"	Toshiba MD	
	Oct-2007	25"	CMEL	CMO subsidiary
	Jan-2008	31"	Samsung SDI	
	Oct-2008	19"	LGE/LG Display	
	Oct-2008	40"	Samsung SDI	
	Jan-2009	21"	Sony	
	Oct-2009	30"	SMD	3D
	May-2010	19"	SMD	
	Aug-2010	31"	LGE/LG Display	3D
	Jan-2011	24.5"	Sony	3D without Glasses

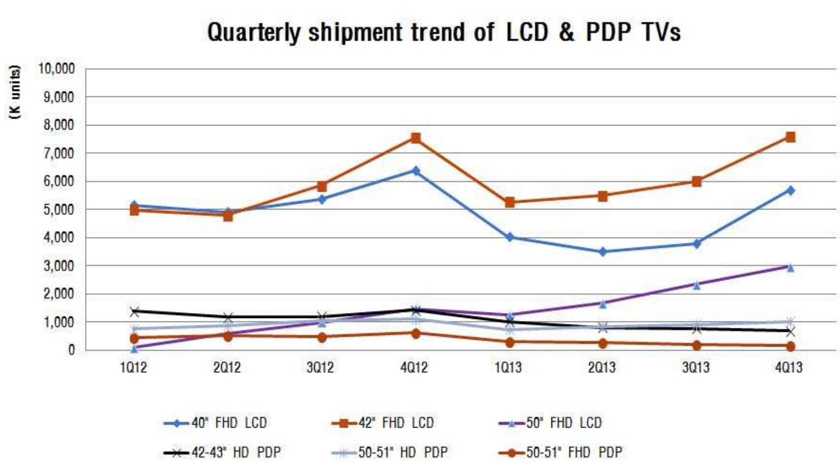
source: company, media sources

Shown in Figure 3 is how the adoption of LCD and LED-LCD offering the improvement in energy efficiency, screen size, and thin profile was expected to grow worldwide from 2010 to the predicted levels of 2015. DisplaySearch predicted that LCD TVs was expected to account for more than 85% of the global TV market through 2012 (CCFL-LCD TV : ~29%, LED-LCD TVs : ~60% in 2012). Global shipments of rear projection TVs were 0.17 million units in 2010 and were expected to decrease, and Organic Light Emitting Diode (OLED) TVs were expected to reach 2.7 million units in 2015.

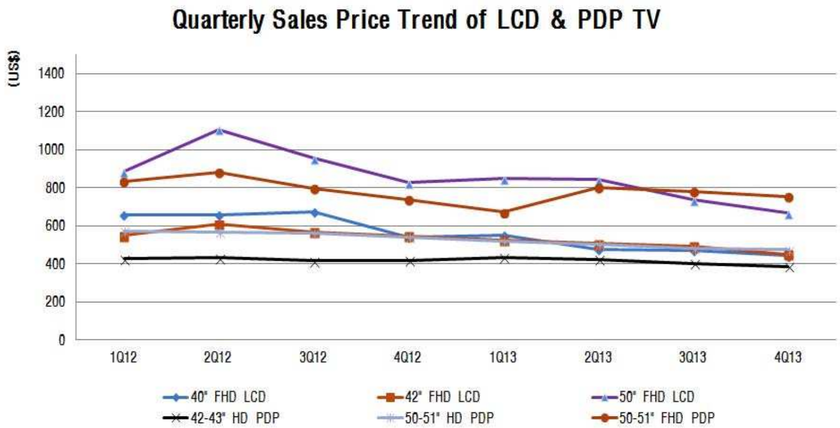
As to the screen sizes, Figure 4 presents the trend for the major technologies such as LCD and PDP. The shipment of PDP TVs has been decreasing slowly, and LCD TVs has been growing in large size TV category in both 42" and 50".



Source: Quarterly Advanced Global TV Shipment and Forecast Report, Third Quarter 2011, DisplaySearch
Fig. 3. The trends of TV shipment by technology



Source: DisplaySearch
Fig. 4. The trends of TV shipment by screen sizes



Source: DisplaySearch

Fig. 5. The trends of TV shipment by technology

As to the price, Figure 5 indicates that price will ensure that LCD TVs appear compelling enough to cannibalize PDP purchases. CRTs just have a presence in developing economies where the TVs that can be afforded in the smaller screen size category.

IV. ENERGY EFFICIENCY OF TVS

The paper briefly discusses the shift in the market has an impact on the energy consumption. Presented in Table 3 is the power consumption of TVs by screen size and technology type based on the assumption of the same per-kWh cost and usage as the Energy Guide labels. LED-LCD TV is energy efficient with fast response rate, high resolution, and the brightest TV in the market. In regard to power consumption, LED-LCD consumes lesser power about 70% compared to PDP and 40 % power as compared to traditional CCFL-LCD. This analysis is only an estimate and many other factors are associated with it.

TABLE 3. THE POWER CONSUMPTION BY MAKE AND MODEL

Make and model	Size (inches)	Type	Energy cost/year	Energy cost/month
Samsung UN32EH4000	32	LED	$9.76	$0.81
LG 47LM7600	47	LED	$9.83	$0.82
Sony KDL-55W900	55	LED	$13.26	$1.11
Toshiba 50L5200U	50	LED	$15.72	$1.31
Sony KDL-46EX640	46	LED	$15.98	$1.33
Vizio E601i-A3	60	LED	$17.62	$1.47
Panasonic TC-L55DT60	55	LED	$20.78	$1.73
Sharp LC-80LE632U	80	LED	$26.39	$2.20
Samsung PN51E450	51	plasma	$27.48	$2.29
Panasonic TC-P50S60	50	plasma	$44.14	$3.68
LG 50PM9700	50	plasma	$44.65	$3.72
Panasonic TC-P55ST60	55	plasma	$54.73	$4.56
Panasonic TC-P65VT50	65	plasma	$81.22	$6.77

source: [18]

With the increased energy consumption that is associated with increased screen size, some of key features have been highlighted in energy efficient TV market segment. Energy efficient TVs have been developed to encourage the adoption of more energy efficient TVs in the market, which have power saving mode such as a trio of sensors to optimize the intensity of the LCD's backlight by detecting the relative darkness and brightness of the room and adjusting how much light it uses to illuminate the picture. In 2008, Philips launched Eco TV 42 inch model for people who seek TV for their home that is energy-sipping and relatively environmentally friendly.

Fig. 6. Eco TV; Philips LCD 42PFL5603D [19].

V. METHODOLOGY

A number of growth curves have been developed and continuously gained popularity to predict technological advance due to relative simplicity, long history of use in various fields, and the modality of the assumption that historical data can be a good guidance to technology trajectory [20]. Logistic and Gompertz curves among them are most commonly used methods with the long history of their inception in demography field and later applied to technology forecasting. In 1925, Lotka introduced the model of stable age-distribution of a population and of natural rate of increase of a population based on a logistic curve in ecology [21]. Volterra independently developed the same mathematics of population growth [22]. Thereafter, Lotka-Volterra model has been used to model population dynamics and ecological competitive diffusion, and later extended to illustrate technological change in a competitive market [23][24]. Since 1960s, Fourt and Woodlock suggest mathematical model of penetration [25]. Rogers, as a seminal work, provides a wealth of knowledge on the diffusion of innovations in a variety of disciplines [26]. Since Mansfield, as a pioneer, proposed technology diffusion model incorporating the rate of imitation and technology adoption, a variety of growth curves such as the Mansfield-Blackman model, the Fisher-Pry model, the Extended Riccati model, the Bass model, and etc, have been developed to forecast S-shaped pattern of technological advance [27]. Selecting an appropriate equation of growth curve depends on data and technology characteristics and is somewhat arbitrary. That is the reason why most forecasters experiment various growth curves to find the most relevant curve fitting to predict the technological change [28].

The Bass model [29] has been applied to investigate product diffusion and demand forecasting in the marketing literature [30][31]. It essentially consists of two parameters that represent innovation (sales influenced by desire for novel products) by consumers and imitation (sales influenced by the interactive portion of the adoption) coefficients to model the diffusion of new product. The Mansfield and Bass models more focus on the customer's adoption behavior based on the market data and imitation process in a social system. They, however, do not take into account substitution effects. Later, Norton and Bass created a model to incorporate substitution for multi-generations of high-technology products [32].

On the other hand, like life cycle, substitution curves (e.g. Fisher-Pry model) are a type of growth curve that project the substitution of one technology for another or the rate of penetration of some technology into a market [33][34]. Growth curves presume a technology will finally reach its upper limit at a certain time. It reflects that growth is slow initially until difficulties are overcome, then growth is more rapid until the limit is approached with growth slow down again. Therefore, it is critical to estimate the upper limit using historical analogies. At this juncture, the previous experience with respect to a similar technology is a key element to forecast technologies more accurately [35]. In this regard, the study uses Fisher-Pry's substitution model of technological change in that it is more appropriate to investigate the similarities and differences in the rate of technological change of competing technology based on the data in place such as literature and patents.

TABLE 4. TYPES OF GROWTH CURVES.

Types	Equations	Inception	Reference
Logistic or Pearl	$Y = \frac{L}{1 + ae^{-bt}}$	1923, 1957	[36][37]
Lotka-Volterra	$\frac{dM}{dt} = (a_m - b_m M + c_{mn} N)M,$ $\frac{dN}{dt} = (a_n - b_n N + c_{nm} M)N$	1925, 1931	[21][22][23]
Gompertz[1]	$Y = Le^{-b-kt}$	1932	[38]
Mansfield- Blackman	$\ln\left(\frac{Y_t}{L - Y_t}\right) = \beta_0 + \beta_0 t$	1961, 1972	[27][20]
BASS	$y_t = \frac{\left[1 - e^{-(p+q)t}\right]}{\left[1 + (\frac{q}{p})e^{-(p+q)t}\right]}$	1969	[29]
Fisher-Pry	$\frac{Y_t}{1 - Y_t} = e^{2a(t-t_0)}$	1971	[33]
Extended Riccati	$\frac{y_t}{Y_{t-1}} = \beta_0 + \beta_1 Y_{t-1} + \beta_2 \left(\frac{1}{Y_{t-1}}\right) + \beta_3 \ln(Y_{t-1})$	1976	[39]
Weibull	$\ln\left(\ln\left[\frac{L}{L - Y_t}\right]\right) = \beta_0 + \beta_1 \ln t$	1980	[40]
NSRL[2]	$\ln y_t = \beta_0 + \beta_1 \ln(Y_{t-1}) + \beta_2 \ln(L - Y_{t-1})$	1981	[41]
Harvey	$\ln y_t = \beta_0 + \beta_1 t + \beta_2 \ln(Y_{t-1})$	1984	[42]

source: adapted from [8]

[1] Gompertz named after Benjamin Gompertz, an English demographer, who originally proposed the model as a law governing mortality rates in 1825
[2] NSRL: Non-Symmetric Responding Logistic

A. Fisher-Pry Diffusion Model

The pioneering work by Fisher and Pry [43] has set the stage for the study of forecasting technologies where "technological advances can be considered as competitive substitution of one method of satisfying the need for another." Fisher–Pry model forecasting is similar to biological system growth. It is also referred to as the "substitution model" because of its application in forecasting the rate of the replacement technology. This model represents substitution technologies when substitution is driven by superior technology and new product presents some technological advantage over the old one. It analyzes the penetration process of new technologies. The Fisher Pry model expresses the fractional rate of fractional substitution of the old technology by the new in terms of what is left to be substituted. The Fisher-Pry model - with its transformation to linear form for ease in regression analysis - can be represented by the equation below.

$$\frac{Y}{L-Y} = 10^{A-Bt}$$

L: Normalized Upper Growth Limit (100),
t: Year.

Use of data mining and bibliometrics such as patents, journal citations, and research awards has been gaining popularity due to the availability of data and the emergence of Information Technology. Illustrated in Figure 7 is one of the patterns and relationship between the different types of S-Curves, either it represents the R&D awards, Conferences, Journals or Patents.

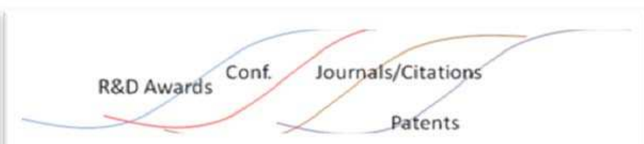


Fig. 7. Patterns of different S-Curves.

A study of OLED TV is one of substitution of existing TV. In this case, the study regards the analogy of replacing LED-LCD component by OLED. Consequently, the study assumes that OLED technology follow Fisher-Pry diffusion model, and use analogy technique from LED-LCD technology in existing TV market. It seems obvious to first look at trends in similar electronic technology. The study use established databases such as Web of Science, Compendex as data source. The model determine percentage of cumulative penetration for OLED technology and for each type of bibliometrics by fitting Fisher-Pry curves to existing data and extending to 2027 to forecast penetration rates.

B. Key words and Sources of Data

Experts in OLED Technology provide the keywords to search in the different database sources. Summarized in Table 5 is an important set of both old and emerging flat panel display technologies along with acronyms.

TABLE 5. KEYWORDS FROM EXPERTS

Keywords	Acronym
"OLED" or "organic light-emitting diode"	OLED
"LCD" or "liquid-crystal display"	LED
"Television" or "TV" or "Display"	TV

Data mining for issued patents globally was performed using Patentscope in World Intellectual Property Organization (WIPO), which includes the following national and international patent data bases: United States (USPTO), International (PCT), Europe (EPO), Japan (JPO), Korea (KIPO), and China (CPTO). A period from 1990 to 2014 is used for the search. Due to the inconsistency and difficulty in using patent classifications (both U.S. and International), this method was not used for this broad patent survey.

VI. RESULTS

A. Basic Research

Based on the search from Web of Science database, the cumulative number of publications in basic research area regarding OLED technologies have been drastically growing. In total, 2098 articles are found from database. Compound Average Growth Rate (CAGR) appears to be 37.5% since 1990, which represents that OLED surely seems to be the next generation technology.

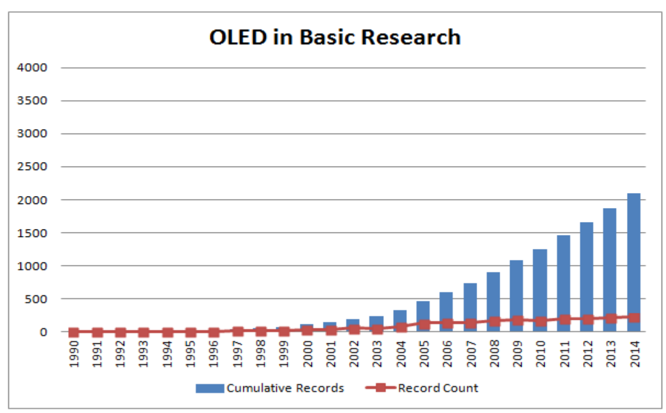


Fig. 8. Growth Curves for Basic Research

TABLE 6. DATA SOURCE FOR DATA MINING

R&D Stage	Typical Source	Database
Basic Research	Science Citation Index	Web of Science
Applied Research	Engineering Index	Compendex
Development	Patents	USPTO, PCT, EPO, JPO, KIPO, CPTO

B. Applied Research

The cumulative number of publication searched in Compendex database for each year is shown in Figure 9 for OLED technologies. As it was found in basic research analysis, OLED lead the next generation TV technologies for applied research activities as well. This trend also represents an aggressive growth, showing a very strong research activity in this area in recent years. CAGR appears to be 37.9% since 1990, similar to basic research activities.

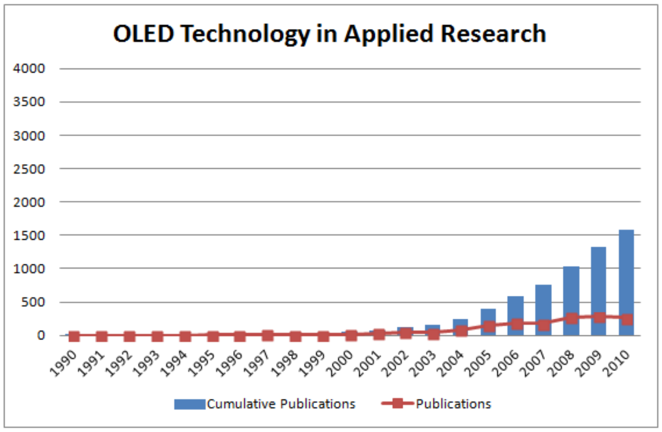


Fig. 9. Growth Curves for Applied Research

C. Patents

Finally, presented in Figure 10 is the patent growth curve (overall patents per year) for OLED technologies. For the Fisher-Pry technology diffusion model the LCD technologies patent count is used. It is inherently assumed that LCD technologies would be analogous to the cumulative OLED technologies counts at maturity. In this study, LCD is selected because it is a similar technology and has already reached a level of maturity where the patent count peaked in 2011 and has been currently decreasing. OLED technologies present a clear behavior of emerging technologies in the future TV market. Figure 10 represents a very similar growth behavior compared with Journal publication analysis. Patents, however, are behind compared with literatures in number of publications.

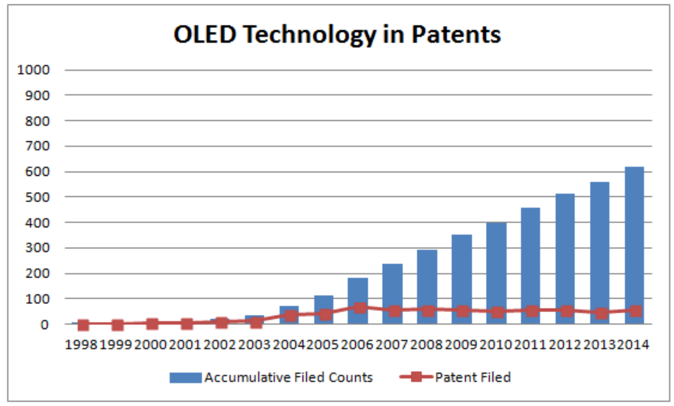


Fig. 10. Growth Curves for Patents

D. Compilation of Growth Curves

After the analysis of the different sources separately, this section focuses in putting together all the growth curves for OLED technologies. Illustrated in Figure 11 are the compiled growth curves for OLED technologies respectively. According to the graph, basic research leads applied research Journal publications, and both are close each other. Patent filings are following up closely. The forecast using Fisher-Pry curve follows an expected trend - where the process of applied research and patent is preceded by basic research. In 2027, OLED technology would seems to reach closely 99 percent level of maturity in technology development.

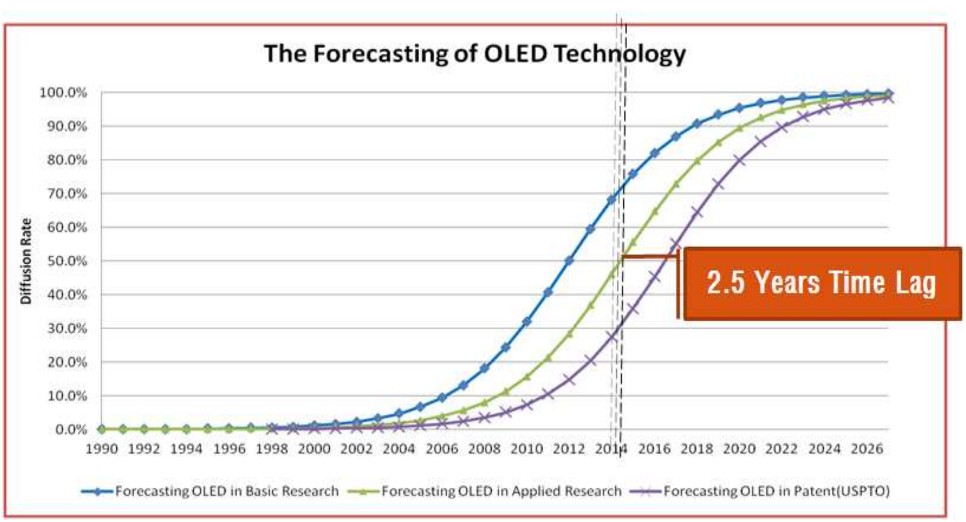


Fig. 11. Compilation of Growth Curves for OLED Technology

The narrow gap between Journals and Patents indicates not only the intensive research efforts made by universities, but also the high interest of the industry to develop and apply OLED technology to a variety of products. A number of experts consider OLED technology as the next generation technology for TV. Hence, this interest from companies to develop and exploit it commercially has been continuously growing. As for OLED technology, Journals and Patents are developed almost at the same time (2-3 years of lag-difference). Currently, Journals lead initially followed by patents and lead after 50% growth (2014) until maturity level is reached.

VII. CONCLUSIONS

Fisher-Pry growth curves for Journal publications, and Patents follow the expected sequence. Specially, Journal publications and Patents growth curves are close for OLED technologies indicating strong industry adoption. In recent years, there is a drastic reduction of patents related with LCD technologies, which suggests next generation OLED technology penetrate into TV market. Strong industry adoption for OLED has been found. High level of maturity is expected by 2025. For OLED technologies that are closely tied to industrial applications such as electronic display devices, it may be better to use more industry oriented data mining such as patents, market data, trade shows, number of companies or startups, etc. Fisher-Pry model does not address the level of sales for each technology. Therefore, the comparison between Bass model and Fisher-Pry model would be useful to investigate the market trends of OLED TVs further. Another step for forecasting could include using industry experts and a Delphi model for forecasting (and further validation).

ACKNOWLEDGEMENTS

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