Innovative Systems Design and Engineering
ISSN 2222-1727 (Paper) ISSN 2222-2871 (Online)
Vol 3, No 4, 2012

LED Light a futuristic Technology for African Rural Electrification

Godswill Ofualagba[1*] Igbinoba Kevwe Charles[2] Onyan Aaron Okiemute[2]

1. College of Technology, Department of Electrical and Electronics Engineering, Federal University of Petroleum Resources, P.M.B. 1221, Effurun, Delta State, Nigeria.

2. Faculty of Engineering, Department of Electrical and Electronics Engineering, University of Benin, Benin City, Edo State, Nigeria.

* E-mail of the corresponding author: swillas@ieee.org

Abstract

This paper considers the concept of very advanced technologies being developed in the West, to solve rural electrification problems in the developing world. The myth that poor quality is cheaper and therefore more affordable for rural electrification is dispelled. On the contrary this paper points to instances when problems of the rural poor have been solved by using cutting edge technologies where standard solutions had proved unworkable. In this paper a futuristic technology, the white light emitting diode (LED), for general lighting, is examined as a solution to African rural electrification. Comparisons are made with conventional technologies.

Keywords: Lumen, efficacy, incandescent, lifespan, lighting, lamp, illuminance, modeled.

1. Introduction

Sub-Saharan Africa constitutes the bulk of humanity that is still not electrified. The national power utilities in those countries are struggling to cope with the existing infrastructure, which are actually shrinking, in real terms. Many go by acronyms like, 'No Electric Power Again', to stand for 'National Electric Power Authority'! As a result the current trend is for communities to fend for themselves. Small remote power installations, especially from renewable energy are characterized by limited generation and storage capacities. These resource constraints call for effective demand side management that conserves energy but with minimal compromise on service delivery quality.

In these communities, lighting is dominated by smoky kerosene candles and is responsible for perennial respiratory and sight illnesses, in addition to the missed learning, business and other opportunities. This makes lighting a priority activity in rural electrification. Globally, electric lighting accounts for some one fifth of all electric energy consumed, and a similar percentage of electric energy related green house gas (GHG) emissions. Therefore any efficient electric lighting initiative is a subject of interest for all humankind.

Lighting loads are often inaccurately modeled due to omission of a number of relevant non-electrical parameters. Illumination as a technology has made its own advances, independently, that must be included in the ultimate electrical lighting solution [1]. High benefit lighting in the work place for example, optimizes sight dependent tasks while minimizing the energy used. Illumination experts [8] point out that over-lighting a space or task area degrades the lighting quality in addition to wasting energy.

Solutions for electrification or energy development in the developing world need not follow the same path as for the developed world. Instead relevant technical solutions for advanced applications in the developed world can be used to leapfrog intermediate technologies and applied directly, with benefit to the developing countries. One example is the use of cell phones, which do not require the costly physical infrastructure of regular land phones. Very remote rural locations that would have otherwise not dreamt of getting any communication are now just a push button away from the rest of the world.

In the field of lighting, recent developments in automotive electronics may yet launch another cutting edge technology into the rural communities. The red light emitting diode (LED) in the traffic and car tail light industries, in North America, reported a market penetration of 20%, rising from a mere 8% during an eighteen month period leading up to 2002. Energy savings of up to 80% are reported. This LED is fast evolving into the white LED for general lighting and may be applied directly to rural electrification problems.

This paper examines the lighting issue at depth. Section 2 has a description of how radiometric power output of a light source (in watts) relates to photometric or light power (in lumens) by incorporating the human eye frequency response. A range of attributes of a light source is described. How they contribute to the lighting quality and thus finally impacting on the electric power source is explained. Section 3 compares the energy consumption and cost, in a rural home, of incandescent lights vs LED light sources. Conclusions are then drawn on the possible impact of LEDs on rural electrification.

2. Background: Lighting Load Modeling

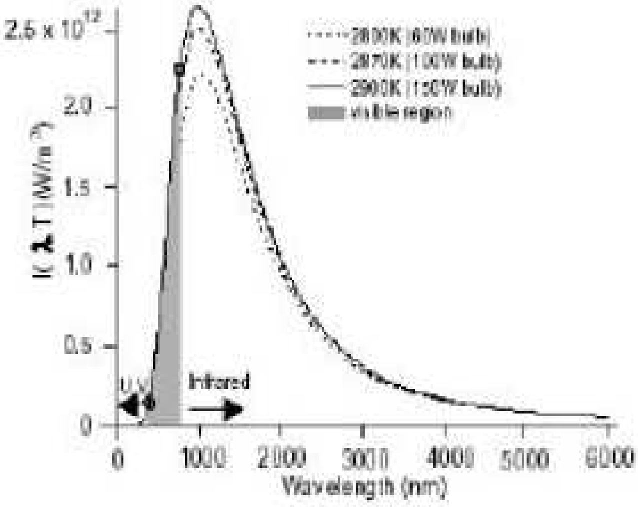

Figure 1. Output energy as a function of wavelength for an incandescent bulb.

When connected across a voltage source, an incandescent light bulb draws a current with a waveform that is a near replica of (and in phase with) the voltage and therefore at a near unity power factor. This is the classic criterion for an ideal electric load, yet this, apparently, ideal load is labeled as inefficient: infact, very inefficient.

Modeling lighting loads is unique as it involves the human eye as the ultimate load determining the required electric power input. Any losses prior to the eye constitute power delivery losses, and failure by light to reflect off an intended target and then to the reception of a normal eye constitutes system inefficiency.

In figure 1, the curve represents the radiometric output power, in watts, of a tungsten incandescent light source as a function of wavelength. The shaded area represents the visible output of the source, defined as the range from 360 nanometers (nm) to 830nm. This fraction determines the efficacy of the light source. However, since the human eye responds differently to different wavelengths (within the visible range), the light source efficacy is not (literally) the shaded area divided by the total area. In the above example with fog, a mere shift to a yellowish/orange headlamp may improve visibility and remove the necessity to increase headlamp power rating.

Figure 2 is an empirical curve, drawn by the International Commission on Illumination (CIE), of an average human eye response as a function of wavelength. This is the photopic curve. (The scotopic curve is the response during very low light levels and is not part of this illustration.).

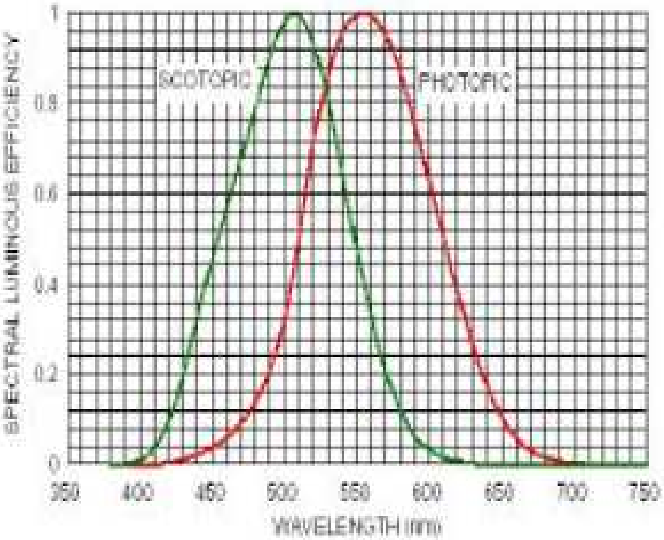

Figure 2. The human eye response plotted against wavelength

As seen on the photopic function the human eye responds best at 555nm. This point defines the full coefficient, 1, of the eye's response. The unit of light power is the lumen (lm). The eye receives radiometric watts and interprets them in lumens using the response function. For example, 1 watt of (monochromatic) radiometric power at 500nm will be interpreted, in lumens, as 0.3 in value compared to 1 watt at 555nm. (See figure 2)

The following is an elementally illustration of a general monochromatic case. The symbols used are not the authentic illumination symbols but merely serve to illustrate a point.

Let $y_1 = f_1(\lambda)$ watts, represent the radiometric function (due to light source) in figure 1

(where λ is the wave length)

And $y_2 = f_2(\lambda)$, represents the photopic function (of the human eye) in figure 2

Then the light power, L_γ, in lumens, of a monochromatic radiation of wavelength λ_γ is give by

$$L_\gamma = K f_1(\lambda_\gamma)\, f_2(\lambda_\gamma) \text{ lm} \qquad (1)$$

The constant K = 683 is the watt-lumen conversion constant. A lumen can then be defined as the (visual) power of monochromatic radiation of frequency 540 x 1012 hertz (which is 555nm in air or vacuum) equal to 683-1watts.

The conversion of radiometric power of a general non-monochromatic light source to luminous quantity, however, involves a lot of other illumination functions that are beyond the scope of this illustration. Fortunately, light source manufacturers normally indicate the efficacies (in lumen per watt) of their products.

3. Light Source Performance

As mentioned, efficacy is given as the number of lumens of light output of a light source per input watt of electrical power (lm/w). This is, however, just one of the indices of lighting quality. For a more comprehensive light source design one requires more data. Initially the task for which light is required must be defined and the required amount of light quantified.

As an example one may consider an incandescent light source and a light emitting diode (LED), which have practically the same lumens per watt (efficacies) rating. It would therefore be reasonable to assume that the two light sources would consume the same amount of energy to perform the same task. How then could the traffic and signal lights industry report such massive energy savings of up to 80% by just replacing the incandescent lights with LEDs?

In the case of a 'stop' traffic light, for example, the required task is the production of red light and only to the view of the car driver. The key words are color and directivity. True efficiency must therefore be the amount of power successfully converted for the task per unit watt of input of electric power. In order to perform this task the incandescent light must use a reflector and a red filter. A 140 watt incandescent lamp with an efficacy of 15 lumens per watt will produce 2100 lumens but after the red filtering and reflector the amount of red light that is finally available to the driver may be only 200 lumens, which happens to be adequate. A red LED, on the other hand, is a monochromatic device and has directivity with an appropriate angle. It is task specific: requiring neither filter nor reflector. Therefore a replacement LED assembly for the same traffic light function only requires 200 lumens. Having the same efficacy as the incandescent, the LED ends up consuming only 10% of the power. Moreover the LED has other superior attributes like shock resistance; a problem that causes premature failure in incandescent traffic lights and vehicle and tail lights.

Light sources have a variety of other attributes in varying degrees as illustrated in the appendix. These determine the suitability and therefore efficiency of a light source for a given task. In addition the color of the surroundings having unique reflective properties which will affect the amount of light required and ultimately impact on the required generation and/or storage capacity in an electrification design. “In some cases enhancement of these influencing factors can improve performance without the need to raise illuminance” [2].

As mentioned earlier in the case of traffic lights, confining light to a specific purpose does improve on energy efficiency. The effectiveness of this technique, called 'tasking', has also been demonstrated by Philips engineers. A set of specially constructed LED street lights performed at par with sodium lamps despite the overwhelmingly superior efficacy of the sodium.

If the purpose for a light source is reading it would appear reasonable to infer that energy would be most conserved if the light is confined to a target area, namely the book. Illumination experts, however, caution that this may cause discomfort due to glare [4], if the background is pitch dark. Other symptoms include annoyance and reduced productivity. Some mild ambient lighting, of the order of at least 10%, which would otherwise be inadequate on its own, is recommended [8].

Finally there are special circumstances that call for higher lamp lumen levels than would be required ordinarily. These include provision for visually impaired persons, or special age groups of occupants.

4. Solid-State Lighting (SSL)

SSL has taken a foothold and is certain to revolutionalise lighting energy consumption. Cynics refer to traditional electrical lighting as a process of heating of a medium by the application of electricity until it's hot enough to give out some light. A grossly energy-squandering scenario!

In contrast LED technology involves a quantum process to convert dc current to light. Conversion efficiencies nearing 100% have been achieved in laboratory results with certain materials. However it is the extractability of this light that is still one of the stumbling blocks. In fact it appears as though the materials with the most efficient quantum conversions have the poorer extractability efficiencies. This is part of what research will address and should be awaited for with much anticipation by the African rural communities. Historically the LED efficacy has been doubling every 18 to 24 months since the beginning of the 1970's. Such evolution is highly dependent on funding. In July 2001 the US Senate launched, 'the Next Generation lighting Initiative' with an ambitious goal to achieve 25% market penetration by the year 2012.

Subsequently a bill was passed in April 2002, committing over a billion dollars per year for research and development (R&D) for the next generation of lighting technologies.

LEDs have superior life spans to incandescent light sources. However, like other light source types they suffer from lumen depreciation and one has to exercise caution with hyped figures like 100,000 hours. This gradual deterioration, once understood, could be factored into scheduled maintenance. Unlike the abrupt failures by incandescent lamps it would be an added advantage.

The time it takes to start a light source can in certain instances be important. Currently, CFLs are very popular in off grid systems. There is a time delay to get to full brightness. So the incandescent lamp still ends up standing in for that odd function like closet lighting. The LEDs are not only as fast as the incandescent lights to start but even faster when going off.

5. Lighting Requirements of a Rural Home

In Nigeria and Kenya, as in most sub- Saharan countries, the overwhelming majority of the populations live in the rural areas with official grid electrification close to 1% or virtually non-existent. Current privatization trends of public corporations have led to further divesture from the rural areas and dashing any hopes for further grid extensions. As a result, recent developments have been mainly driven by self -help initiatives. The available means to harness the all -vital electric energy are small and costly. All efforts must be made to economize the meager resources without compromising quality of service.

As mentioned earlier a light source may produce a large amount of light and with a good electricity to light conversion efficiency (efficacy) but how well it targets a particular the intended task will impact on its overall efficiency. Currently the efficacies of incandescent lamps and white LEDs are of the same order.

Household lighting applications are in three general categories. Ambient lighting is a basic minimum amount of illumination for living. This level should be adequate for sitting rooms, corridors and for more public utilities like restaurants and hospital wards. General lighting provides a relatively higher illumination level than ambient. It is for such purposes as reading, cooking and security. Task lighting is the illumination required for very detailed viewing, like an operating theater. Regulations, guide lines and on occasions legislation specify these illumination requirements in lumens per flat surface area. In SI units 1 lumen per square meter is a lux.

In South Africa, a code of practice [8] gives the minimum lux for a whole range of locations and activities. For example, kitchens are allocated 200 lux, 100 lux for bathrooms and 500 for study and reading. Like other standards, there may be variations from country to country. In the following illustration the specification of the South African Bureau of Standards will be assumed.

An incandescent lamp and a white LED for reading are compared below. If the reading area is 0.25m and the required light density is 500 lumens per square meter, then the lamp should give (500 x0.25) =125 lumens.

As of 14th April 2002 Lumileds produced LUXEON-5W, a 120 lumen white LED light source with a power consumption of 5 watts. As mentioned earlier, LEDs have directivity and it is reasonable to assume that all the light can be confined to the required area.

The incandescent lamp will use a reflector (luminaire) to attain the directivity. A good quality luminaire has a coefficient of utilization (CU) of 0.55 [8]. CU is the indication of the proportion of useful light emitted by a luminaire. Therefore in order to create the same effect as the Luxeon-5 the incandescent light must produce 120/0.55 = 218lumens . The efficacy of a typical incandescent lamp is 15lumens per watt. The wattage of this lamp will be 218/15 =14.5 watt. Incandescent lamp efficacies rise with filament temperature, which in turn rises with lamp wattage. So in reality a lamp of such low wattage will have an efficacy closer to 10 lumens per watt. This will make its wattage closer to 20watts and hence will require 4 times the amount of power as the Luxeon.

6. The Future

Typical indicator LEDs are designed to operate with no more than 30–60 milliwatts (mW) of electrical power. Around 1999, Philips Lumileds introduced power LEDs capable of continuous use at one watt. These LEDs used much larger semiconductor die sizes to handle the large power inputs. Also, the semiconductor dies were mounted onto metal slugs to allow for heat removal from the LED die.

One of the key advantages of LED-based lighting sources is high luminous efficacy. White LEDs quickly matched and overtook the efficacy of standard incandescent lighting systems. In 2002, Lumileds made five-watt LEDs available with a luminous efficacy of 18–22 lumens per watt (lm/W). For comparison, a conventional incandescent light bulb of 60–100 watts emits around 15 lm/W, and standard fluorescent lights emit up to 100 lm/W. A recurring problem is that efficacy falls sharply with rising current. This effect is known as droop and effectively limits the light output of a given LED, raising heating more than light output for higher current.[14][15][16]]

In September 2003, a new type of blue LED was demonstrated by the company Cree Inc. to provide 24 mW at 20 milliamperes (mA). This produced a commercially packaged white light giving 65 lm/W at 20 mA, becoming the brightest white LED commercially available at the time, and more than four times as efficient as standard incandescents. In 2006, they demonstrated a prototype with a record white LED luminous efficacy of 131 lm/W at 20 mA. Nichia Corporation has developed a white LED with luminous efficacy of 150 lm/W at a forward current of 20 mA.[17] Cree's XLamp XM-L LEDs, commercially available in 2011, produce 100 lumens per watt at their full power of 10 watts, and up to 160 lumens/watt at around 2 watts input power.

Practical general lighting needs high-power LEDs, of one watt or more. Typical operating currents for such devices begin at 350 mA.

Note that these efficiencies are for the LED chip only, held at low temperature in a lab. Lighting works at higher temperature and with drive circuit losses, so efficiencies are much lower. United States Department of Energy (DOE) testing of commercial LED lamps designed to replace incandescent lamps or CFLs showed that average efficacy was still about 46 lm/W in 2009 (tested performance ranged from 17 lm/W to 79 lm/W).[18]

Cree issued a press release on February 3, 2010 about a laboratory prototype LED achieving 208 lumens per watt at room temperature. The correlated color temperature was reported to be 4579 K.[19]

On the 25th of April, 2002 the US Senate passed bill S.517, and committed over 1 billion US dollars per annum for research and development (R&D), for “such areas as next generation lighting technologies”. This is cause for optimism. The same forecast projects that at 50 lumens per watt the per kilo lumen price will still be US$ 8.30 against the incandescent lamp’s current US$ 0.56. Cost is by far the major disadvantage of the LED. If the accelerated track should be followed a price breakthrough of US$ 0.50 is projected at 120 lm/w of component efficacy.

It should be noted that the Sandia model focused on efficacy as the major index for market response. There are other possibilities. The market could, for example, be impressed by other improving attributes like, the life span or color rendering index CRI and realize a price break through much earlier.

Life spans of incandescent lamps average about 800 hours. Independent researchers have pegged the 50% lumen depreciation life span of a white LED to a more realistic figure of 6000 hours [10, 11]. This is a far cry from the manufacturers, frequent claims of 100,000 hours, which is probably when the LED finally shuts down. It is nonetheless far superior to the incandescent lamp and matches the CFLs, while at the same time not being completely out. (CFLs have additional shortcomings like disposal.) This gives an 8:1 advantage of cost over life span of the white LED against the incandescent lamp. It means that for every time one buys an LED lamp one requires to buy at least 8 incandescent lamps to last as long, giving a much better cost effectiveness scenario in favor of the LED. It also means that even at the projected lower end value of 50 lm/w the LED will be far more cost effective to buy than the incandescent lamp while LED power consumption will be less than a third.

At the current levels of technology the white LED’s advantage over the incandescent lamp would appear to be mainly in task applications, like reading and perhaps the kitchen. Additionally when considering lumen depreciation (also called light loss factor, LLF), the LED scores yet another point. Because the reflectance of the reflector deteriorates as well, the incandescent lamp has two depreciation factors to contend with against the LED’s one. Otherwise with virtually the same efficacies elsewhere in the rural household, power consumption levels are matched.

Consider a rural African household comprised of two bedrooms, a kitchen, a bath room with a toilet and a lounge/dinning at the far end. One may assume over 80% of the full lighting load for the four hours per evening and only incandescent lamps in use. Assuming also, that the room sizes and surrounding wall reflectance are such that specified lux levels can be achieved using, 60W in the kitchen, 40W in each of the bedrooms 25W in the bathroom, 60W for ambience in the lounge/dinning room and an additional 20W for the table reading lamp. The total peak load would be 225W. At the assumed load factor of 80% for the period of usage the average rating would be 180W. During a 4 hour evening a total of 720 watt hours (Wh) would be consumed. With a simple automobile lead acid battery system that permits only a 40% depth of discharge (DOD) one would require a storage capacity of 720/40% = 1800 Wh.

Under the current circumstances replacing the incandescent lamps with white LED's would only affect the reading light and reduce the peak load by 15W. Given that batteries are only available in certain sizes, it should be reasonable to assume that there would be no difference on the storage capacity.

If one should consider the same LEDs having an average efficacy levels of 120 lm/w then the average load would become (180 x incandescent efficacy)/ (LED efficacy)

Average load = (180 x 15)/120 = 22.5watts

This would yield a required storage of 90 Wh and a lead acid battery size of 225 Wh. By that time the life span could have possibly exceeded the 100,000-hour mark and the CRI perhaps at 100.

7. Conclusion

This paper has examined the concept of applying first world innovative technologies to the problem of rural electrification. In particular, white LEDs can electrify rural Africa, with minimal power requirements.

8. References

[1] Arthur D. Little, Inc, "Energy saving potential of solid state lighting in general light applications". US Department of energy.

[2] "Discomfort glare in interior lighting," Publication CIE 117 - 1995 ISBN 3 900 734 70 4

[3] Glover, J. D. and Sarma, M., (1995). "Power system analysis and design" 2nd edition, PWS - Kent Publishing, Boston.

[4] "Lighting Education (1983 - 1989)," Publication CIE 99 - 1992. ISBN 3 900 734 36 4

[5] "Lighting of indoor work places," Publication CIE Standard: S008/E - 2001

[6] "Maintenance of indoor electric lighting systems," Publication CIE 97 - 1992 ISBN 3 900 734 34 8

[7] N Narendran et al. (2000). "Characterizing white LEDs for general illumination applications." Proc. SPIE 3950

[8] N Narendran et al. (2001). "What is useful life for white light LEDs?" J. Illum. Eng. Soc. 30(1) 57.

[9] "Proceedings of the first CIE symposium on lighting quality" C1998 ISBN 3 900 734 91 7

[10] SABS 0114-1:1996. Interior Lighting. (Part 1: Artificial lighting of interiors). South African Bureau of Standards.

[11] SABS 0114-2:2002. Interior Lighting. (Part 2: Emergency lighting). South African Bureau of Standards.

[12] T. Drennen, R. Haitz, J . Tsao, "A market diffusion and energy impact model for solid-state lighting. SAND200 1 – 2830." Sandia National Laboratories, Agilent Technologies, E20 Communications and Hobar & William Smith Colleges.

[13] William H. Casting, (2002). "Distribution system modeling and analysis" CRC Press LLC.

[14] Efremov; A. A.; Gorbunov, R. I.; Lavrinovich, D. A.; Rebane, Yu. T.; Tarkhin, D. V.; Shreter, Yu. G.

(2006). "Effect of the joule heating on the quantum efficiency and choice of thermal conditions for high-power blue InGaN/GaN LEDs". Semiconductors 40 (5): 605. Bibcode 2006Semic..40..605E. doi:10.1134/S1063782606050162.

[15] Smart Lighting: New LED Drops The 'Droop'. Sciencedaily.com (2009). Retrieved on 2012-03-16.

[16] Richard Stevenson "The LED's Dark Secret: Solid-state lighting won't supplant the lightbulb until it can overcome the mysterious malady known as droop". IEEE Spectrum, August 2009

[17] "Nichia Unveils White LED with 150 lm/W Luminous Efficiency". Tech-On!. December 21, 2006. Retrieved 2007-08-13.

[18] DOE Solid-State Lighting CALiPER Program Summary of Results: Round 9 of Product Testing.. U.S. Department of Energy. October 2009.

[19] Cree Breaks "200 Lumen Per Watt Efficacy Barrier" (Press release). Durham, N.C: CREE. February 3, 2010.

[20] Adoniya Ben Sebitosi and Pragasen Pillay (2007) "New Technologies for Rural Lighting in Developing Countries: White LEDs" IEEE Transactions on Energy Conversion, Vol. 22, No. 3, Sept. 2007.

This academic article was published by The International Institute for Science, Technology and Education (IISTE). The IISTE is a pioneer in the Open Access Publishing service based in the U.S. and Europe. The aim of the institute is Accelerating Global Knowledge Sharing.

More information about the publisher can be found in the IISTE's homepage:
http://www.iiste.org

The IISTE is currently hosting more than 30 peer-reviewed academic journals and collaborating with academic institutions around the world. **Prospective authors of IISTE journals can find the submission instruction on the following page:** http://www.iiste.org/Journals/

The IISTE editorial team promises to the review and publish all the qualified submissions in a fast manner. All the journals articles are available online to the readers all over the world without financial, legal, or technical barriers other than those inseparable from gaining access to the internet itself. Printed version of the journals is also available upon request of readers and authors.

IISTE Knowledge Sharing Partners

EBSCO, Index Copernicus, Ulrich's Periodicals Directory, JournalTOCS, PKP Open Archives Harvester, Bielefeld Academic Search Engine, Elektronische Zeitschriftenbibliothek EZB, Open J-Gate, OCLC WorldCat, Universe Digtial Library , NewJour, Google Scholar