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Lighting Industry: A Classical Case of Innovation

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LIGHTING INDUSTRY: A CLASSICAL CASE OF INNOVATION

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PREFACE

Exactly one hundred years ago Edison launched modern electrical lighting. He began studying the problem in 1877, and within a year and a half had made more than 1,200 experiments. Concurrently, recognizing that the series wiring systems then used for arc lights would not be satisfactory for incandescent lamps, Edison directed much more effort toward development of dynamos and other necessary equipment for multiple circuits.

On October 21st, 1879, Edison lighted a lamp containing a carbonized thread for the filament. The lamp burned steadily for two days. Later he learned that filaments of carbonized visiting card paper (Bristol board) would give several hundred hours life. Soon carbonized bamboo was found acceptable and was used as the filament material. Extruded cellulose filaments were introduced by Swan in 1883. The first complete incandescent lighting system was publicly demonstrated at Edison's laboratory in Menlo Park, New Jersey, on December 21st, 1879.

Edison was not only a great inventor, he was also a real innovator and entrepreneur. He determined the price of the lamp at a level of 40 cents despite the fact that the cost of one lamp at the beginning was 1.25 dollars. After three year's production he reduced the cost to 37 cents and more than compensated for all losses by an enormous turnover.

The case of the lighting industry is very informative for innovation and industrial policy. The lighting industry first became the mother of electrical engineering, but later it was a highly specialized industry of less importance. On the other hand it still satisfies a quite important need. What might the future of the lighting industry be?

ACKNOWLEDGMENTS

I would like to thank Dr. Horst Liewald in Berlin (GDR) for his productive suggestions and discussions, and Mrs. Ingrid Teply-Baubinder for her translation of the original German text.

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H.-D. Haustein

LIGHTING - AN ENERGY PROBLEM

One of the basic global problems is the further development of energy consumption and energy production. Our society has become increasingly aware of the fact that economic growth cannot rely on an extensive development of energy production in advance of the overall production scheme. The development in the past shows that on a global scale no significant reduction in energy intensity has been achieved during the decades following World War II (Table 1). In view of this situation many scientific institutions have been investigating in greater detail the wide spectrum of possible energy saving measures. Eighty years ago lighting technology was the main consumer in those advanced countries applying electro-energetic systems. The demand for electric light and the complex innovation process triggered by Edison's invention (lighting - energy transmission - energy production) gave rise to the development of an electricity economy. Even at the turn of the century the electricity consumed for lighting purposes still exceeded the power current consumption in Germany (Gross 1939). Table 2 shows the development since 1937. The rapidly rising lighting demand led to a considerable increase in electric energy consumption for lighting purposes. Since 1950 the German Democratic Republic has also experienced such a development (see Table 3).

In the future it will be necessary to cover the growing lighting demand by lower-growth resource consumption. The average efficiency of all existing light sources is at present only four to five percent. From 1909 to 1969 the lighting yield per unit lamp price increased on the average by six percent per year, and the useful life of lamps increased by 3.9 percent if we compare the carbon filament lamp and the flourescent lamp (Willoughby 1969). This gives a quality increase per unit purchasing power of 10.1 percent annually; in other words, the price per unit utilization value could

Table 1. Development of energy consumption and energy intensity, world, 1860-1980.

	World energy consumption*		World production	Energy consumption	Energy intensity of production
	Total mil tce	Per capita tce	index**	index	index
	(1)	(2)	(3)	(4)	(5)
1860	552	0.46	25	26	104
1900	959	0.59	70	45	64
1920	2117	1.15	100	100	100
1940	3152	1.47	169	149	88
1950	2700	1.16	194	128	66
55	3291	1.20	245	156	64
1960	4298	1.40	294	206	70
65	5222	1.59	369	247	67
1970	6864	1.90	506	325	64
75	8215	2.10	579	388	67
1980 (proj)	9200	2.25		435	

*See, Ekonomika i organisacija promyslennogo proizvodstva 6/75, p.214. (data up to 1950). Ukazatale Hospodarskeho Vyvoje v zahranici Praha 1976, pp.200-201 (data 1955-1970).

**See, Kuczynski, J.: Die Geschichte der Lage der Arbeiter unter dem Kapitalismus, Vol.37, Akademie Verlag Berlin 1967, p.31ff.

Table 2. Development of light generation and electric energy consumption, world, 1937-1975.

	World consumption of electric energy* TWh	Per capita consumption KWh	Lighting share percent	Lighting efficacy lm/W	Lighting efficacy percent	Light generation Total Tlmh	Light generation per cap. 1000lmh	Electric lighting energy Total TWh	Electric lighting energy per cap. KWh
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1937	405	292	28**	12	1.76	1361	642	113	53
1950	861	345	25	16	2.35	3444	1380	215	86
1960	2074	695	23	21	3.09	10017	3357	477	160
1970	4429	1225	21	26	3.82	24182	6689	936	257
1975	5795	1417	19	28	4.12	30829	7538	1101	269

*Production minus 10% transmission losses.
**See, Seeger, B.: Der Lichtverbrauch Europas. Technisch-wissenschaftliche Abhandlungen aus dem OSRAM-Konzern. Vol.4, Berlin Verlag von Julius Springer 1936, p.3.

Table 3. Development of lighting demand in the GDR, 1950-1975*.

	Electricity consumption GWh	Lighting share Percent	Electricity consumption for lighting GWh	Lighting yield lm/W	Light production T lmh
	(1)	(2)	(3)	(4)	(5)
1950	19466	12	2340	15	35.2
1955	28695	13	3730	20	74.5
1960	40408	13	5250	25	131.2
1965	54101	14	7570	32	242.0
1970	68880	15	10340	36	372.0
1975	85885	17	13800	38	524.4

*Columns (2) to (5) are estimates. The increasing share of energy consumption for lighting purposes is a historical peculiarity in the GDR economy which is related to the high share of electric energy-intensive technologies in 1950. The basic long-term tendency is the reduction of the lighting share in electric energy consumption, which will have to be enforced in the GDR as of 1980.

could be reduced by 9.2 percent annually. This figure is thoroughly in line with the productivity increase of other very dynamic technological sectors. As far as lighting yield is concerned, the reserves are still far from being exhausted. It is in particular the sodium high pressure lamp (at present 100-130 lm/W) and the halogen lamp (at present 30 lm/W) which present the major innovation processes of our time.

CLASSIFICATION OF BASIC AND IMPROVEMENT INNOVATIONS IN LIGHTING

All of the presently known technologies of light generation still do not guarantee the achievement of the very long-term goal in this field: the production of a light source of 250 lm/W (see Figure 1) and a useful life of 40,000 hours. The useful life of discharge lamps using electromagnetic induction instead of electrodes is already estimated to be five to ten years (Carnes 1978).

Therefore, the proportion of basic innovations and partial innovations is also significant in the field of light technology. Table 4 gives a classification and evaluation of the innovation processes.

The physical action principles for certain technological fields form a series of higher development stages or an increasingly deep penetration into the natural laws of the matter. An action principle is a lawful interrelation which explains a certain effect (Effect = energy × time = force × distance × time. Energy = performance × time) under given conditions. In 1802 the English physicist Davy discovered the effect that electric current can cause platinum wire to glow. The intensity laws of the Black Body governing the underlying action principle of temperature radiation were set up later by Wien (1893) and Planck (1900).

The historical sequence of the basic principles of light generation is as follows:

Principle	Time of discovery of the effect (or of the theory)*
1. Combustion processes	> 400,000 BC
2. Temperature radiation	1802 (1843)
3. Gas discharge processes	around 1900
4. Radiation transformation in solid states	1887 (1905 Einstein)

In view of our present situation it is also conceivable that plasma physics can be applied for light technology purposes.

*In principle, the theoretical perception may also precede the discovery of the effect.

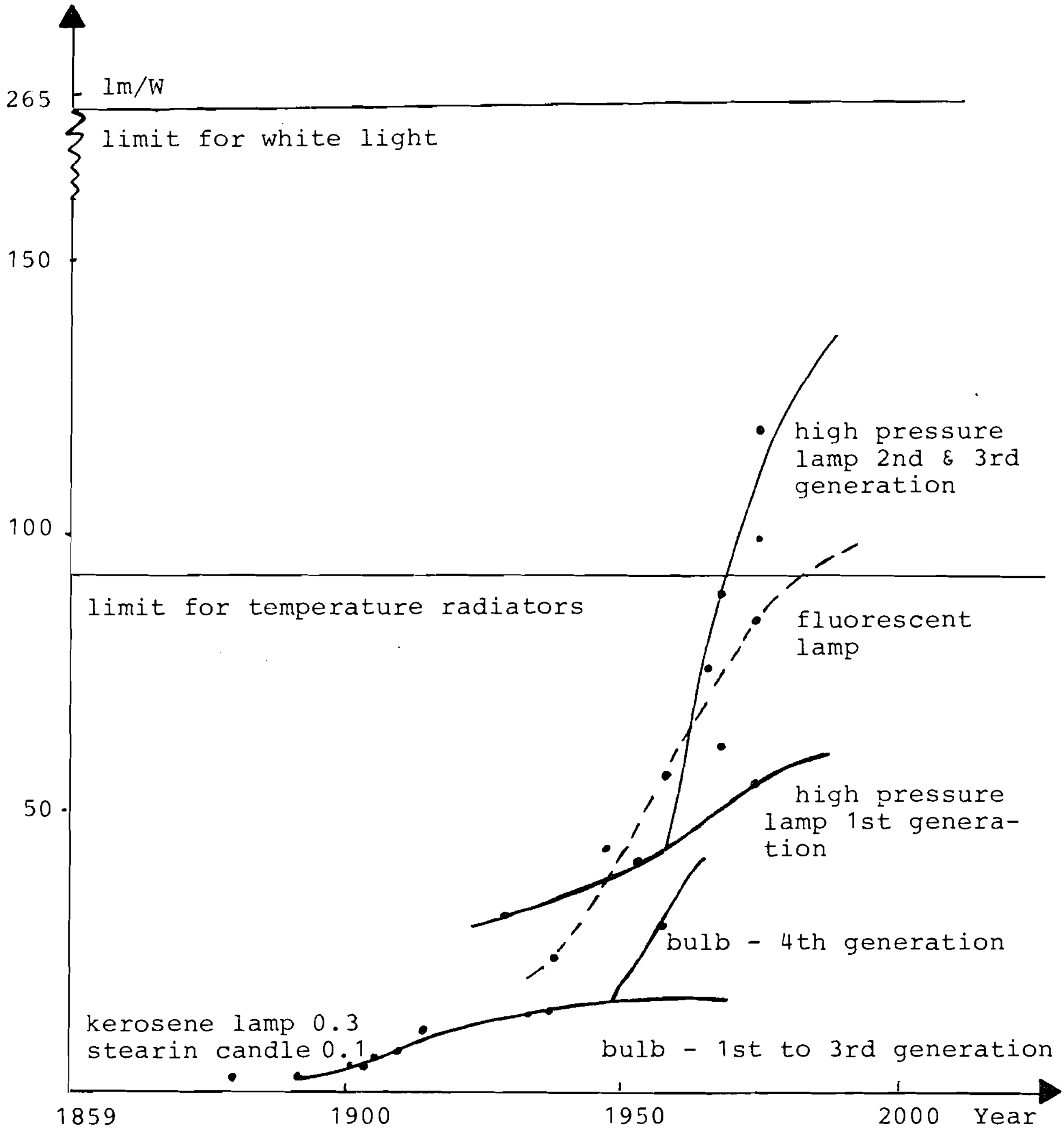

Figure 1. Development of efficacy for light sources I.

Table 4. Classification and evaluation of innovatin processes according to their scientific-technological level and their effect on meeting needs.

	Quantitative extension of existing demand	Modification of existing types of demand. Qualitative improvement of existing products	Major modifications of existing types of demand (new properties of know utilization values)	Development of a new type of demand (of a new utilization value) within the existing demand structure	Major modification of the structure by the new utilization value	Development of a new structure. Major change of the proportions of demand	Reorganization of the existing system
	1.0	1.5	2.2	3.2	4.6	6.8	10.0
1. Quanitative development of the existing technological basis 1.0							
2. Further development within a known principle solution without major change 1.5		Improvement of wound coil filament lamp, 1950 2.3					
3. Further development within a known principle solution, however with major change of one factor (matter, technology, function, construction) 2.2		metallic filament lamp, 1905 wound coil filament lamp, 1935 crypton lamp, 1938 3.3					
4. Further development within a known principle solution, however with major change of several factors .2		gas-filled coiled-up filament lamp, 1915 4.8					
5. New principle solutions, 1st order, i.e. within the scientific action principle applied 4.6		halogen lamp, 1959 first applied for floodlight, cars, photography 10	halogen lamp, 1959 first applied for floodlight, cars, photography 10				
6. New principle solutions, 2nd order, i.e. replacement of the existing fundamental principle by a new one, however with the same motion pattern and structural level of the matter 6.8				carbon arc lamp, 1877 Jablockov 22			
7. New principle solution, 3rd order, i.e. transition to a different structural level of motion pattern of the matter 10.0			luminous condenser (excitation by electric field), effect discovered in 1921	chemi-luminescence bio-luminescence	gas discharge lamps 1930 46	bulb, 1881 temperature radiation 68	

Furthermore, the phenomena of tribo- chemi- and bio-luminescence have been known for a long time. But only the first three fundamental principles of action have so far been technologically exploited. Thus, only part of the total vector of light energy in the matrix of possible energy transformation processes has yet been used.

A decisive factor for the classification of innovation processes is the intensity of the innovation, i.e. its scientific and technological level. Here, the main point is the degree of change of the technological principle applied. A technological principle is a functional relationship which results from the application of physical action principles to a certain technological need; and one principle of action may be used for a great variety of technological principles. Thus, the action principle of underpressur, e.g., explains the technological principle of the windmill, of the hydraulic screw, of sailing, etc. The action principle of temperature radiation is applied in lighting technology, heat technology, and many other fields. Thus, a technological principle solution is understood to be the practical application of the technological principle. The light bulb is a principle solution, which is based on the technological principle of resistance heating of a wire. Within this principle solution various technological generations can be distinguished: carbon filament lamp, metallic filament lamp, gas-filled coiled-up filament lamp, halogen bulb.

Table 5 suggests a classification according the the degree of change of a technological principle.

In this classification, a transition towards the utilization of another fundamental principle of action rates highest. In this sense the light bulb and the gas discharge lamp are equivalent innovations. It shall, however, be noted that this is a very rough classification which does not take account of the various degrees of penetration into the laws of the matter and into new functional technological relationships of such innovations. An assessment of future prospects would therefore require a more detailed representation.

Figure 2 gives the possible action elements of light emission and their characteristic properties as well as the types of radiation energy in relation to known, conceivable or blank technological principle solutions.

The evolutionary development in this sector of light sources comprises a wide range within the field of temperature radiation and gas discharge principles.

The bulb serves as a good example to illustrate this phenomenon in its historical diversity. The corresponding historical data are given in Figure 1 and in the Appendix.

The light output of the bulb has grown since 1980 in the form of a logistic time function, which started at about 3 lm/W, then reached its turning point in 1913 at 8 lm/W (the highest increase), and did not exceed the 12 to 13 lm/W limit over the 1925-1960 period.

Table 5. Classification of innovations according to their scientific-technological level.

Main Categories	Categories		
	General	technological	material
A. PARTIAL CHANGES	1. Quantitative change of the elements of the inner system structure and their proportions.	Quantitative development of the existing technological basis.	Quantitative changes of material application.
	2. Restructuring of the elements of the inner system structure, supplementation and adaptation.	Further development within known principle solution without major changes.	Further improvement of known material properties without major changes.
	3. Qualitative changes of individual inner characteristics or functions.	Further development within known principle solution, however with major changes of one factor (matter, technology, function, construction).	Major change of one specific property of a known material, substitution by other known materials.
	4. Qualitative change of all inner characteristics, however without change of the fundamental functional concept.	Further development within known principle solution, however with major changes of several factors.	Major changes of several properties of a known material, new processes for known materials.
B. BASIC CHANGES	5. Qualitative change with change of basic concept, however without change of the principle of the concept.	New principle solutions, 1st order, i.e. within the scientific action principle applied.	Extraction of new materials from nature, empirical discovery and production of new elements and materials.
	6. Qualitative change with change of the basic functional principle in the same field of perception.	New principle solutions, 2nd order, i.e. replacement of the basic principle so far applied by a new one, however within the same motion pattern and the same structural level of the matter.	Development of new materials on the basis of molecular processes, major increase of the degree of material utilization.
	7. Qualitative changes of the basic functional principle by transition to a new field of perception.	New principle solution, 3rd order, i.e. transition to a different structural level or a different motion pattern of the matter.	Development of new materials on the basis of elementary processes in the atom range. Fundamental increase of the degree of material utilization.

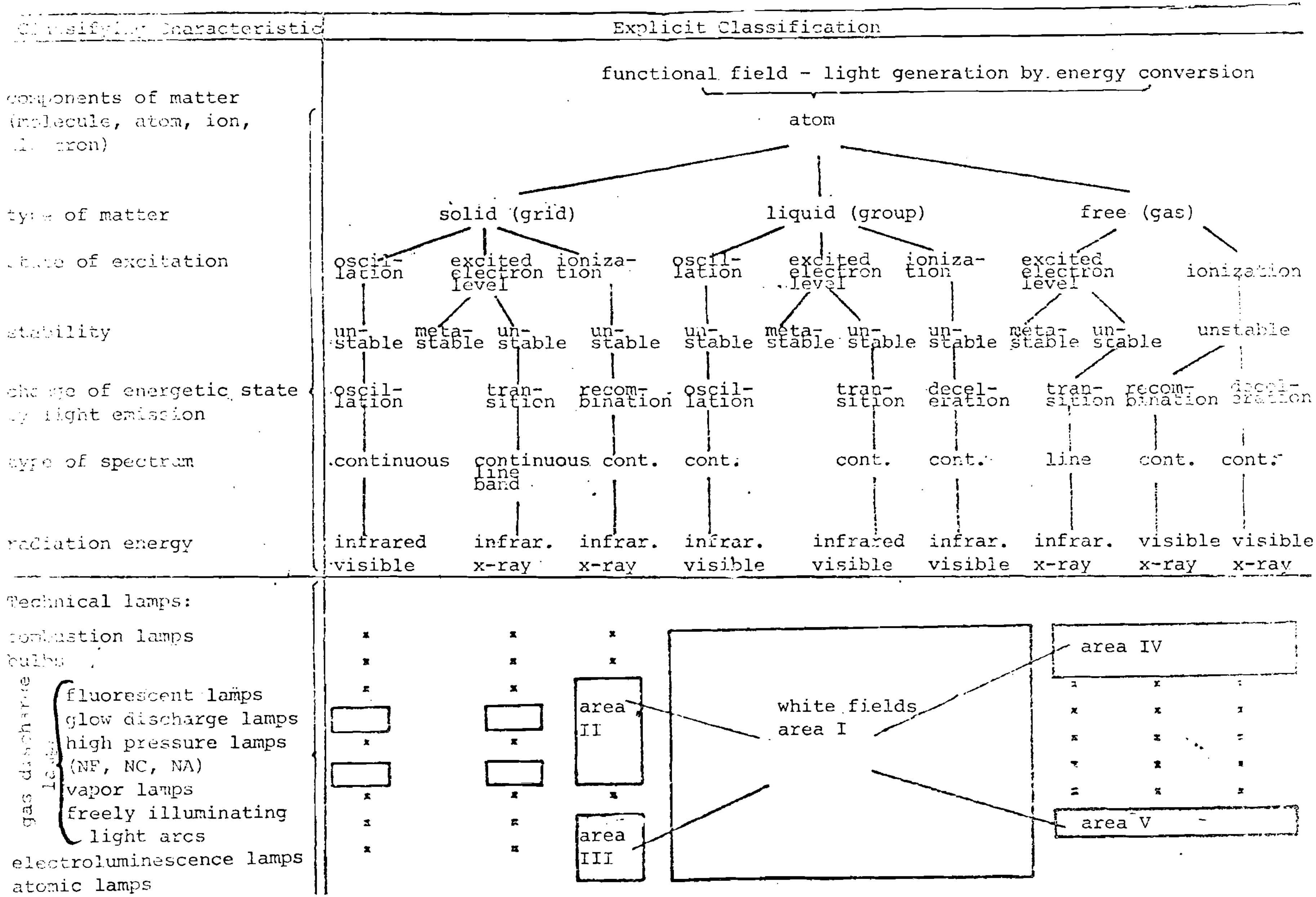

Figure 2. Classification of possible scientific-technological principles.

All partial improvements within the course of this S-shaped curve are to be characterized as evolutionary or partial changes. They were mostly related to the availability and utilization of new, suitable, and fairly inexpensive materials (krypton lamp, 1938).

In 1959, however, a new technological solution was found: the halogen lamp. It presented a breakthrough to a light output two or three times higher than that of the conventional bulb. It is based on two earlier patents of 1882 (Scribner, USA) and 1933 (van Liempt, Netherlands). By means of this technological principle a maximum of 58 lm/W can be obtained. For the bulb in general, 95 lm/W are assumed to be theoretically feasible. (Theoretical limit of the Planck radiator at 6000°K)

The halogen lamp presents a step ahead in bulb development. Thus it is regarded to be a principle solution of the first order, i.e., within the action principle of temperature radiation, as has so far been known and applied.

Similarly, fluorescent lamps are only a new principle solution of gas discharge lamps, which were later produced in the form of high pressure lamps, at first exceeding the former in light output, and consequently lagging behind.

Of course, there is a chance of new technological principles to be discovered in the field of the gas discharge system. In such a case the corresponding innovation would have to be classified as a principle solution of the second order.

In view of the historical development of light technology the carbon arc lamp can be specified as a principle solution of the second order.

MEASUREMENT AND EVALUATION OF TECHNOLOGICAL AND ECONOMIC LEVEL INNOVATIONS

It can be assumed that the scientific-technological level will develop exponentially beyond the seven stages described above. The relative increase in light output in the seven stages is (in %):

1.	1 - 10	5.	200 - 300
2.	10 - 30	6	-
3.	30 - 80	7.	1000 - 2000
4.	60 - 100		

From 1890-1975 the light output developed according to the function of time

$$y(t) = \frac{265}{1 + \exp - \{\frac{(t-1977)}{22.12}\}} \ \text{lm/W} \quad .$$

Thus, in the year t = 2000 a light source of an output of 196 lm/W will be available (see Figure 3).

It must, however, be taken into consideration that the useful life is another essential parameter in the scientific-technological level of light sources. While a higher light output saves energy, a longer useful life may contribute to a reduction of manpower, material requirements, financial means, and raw material resources.

The scientific-technological level presents, however, only one side of the innovation process. Its economic counterpart is the actual extent of application or the effect on meeting demands (see Table 6). From an historical point of view the bulb has created a new demand structure and has contributed to qualitative changes in the national economies.

The gas discharge lamp, on the other hand, has led to a major modification of the existing demand structure.

Both sides, the scientific-technological level and the level of application, together characterize the valency of an innovation. Accordingly, Table 4 distinguishes 7 × 7 = 49 kinds of innovation processes. Their valency shall be defined as

$$V = i_k \cdot v_k$$

i_k = scientific-technological level of the k^{th} degree;

v_k = extension volume of the k^{th} degree.

For an exponential assessment

$$V = e^{ak} \cdot e^{bk}$$

$$V = e^{(a+b)k} \quad .$$

If we assume symmetry of both factors (a = b) for reasons of simplification, then

$$V = e^{2ak} \qquad k = 0,1,\ldots,6 \quad .$$

Since V is defined as

$$1 \leqq V \leqq 100 \text{ (percent)} \quad ,$$

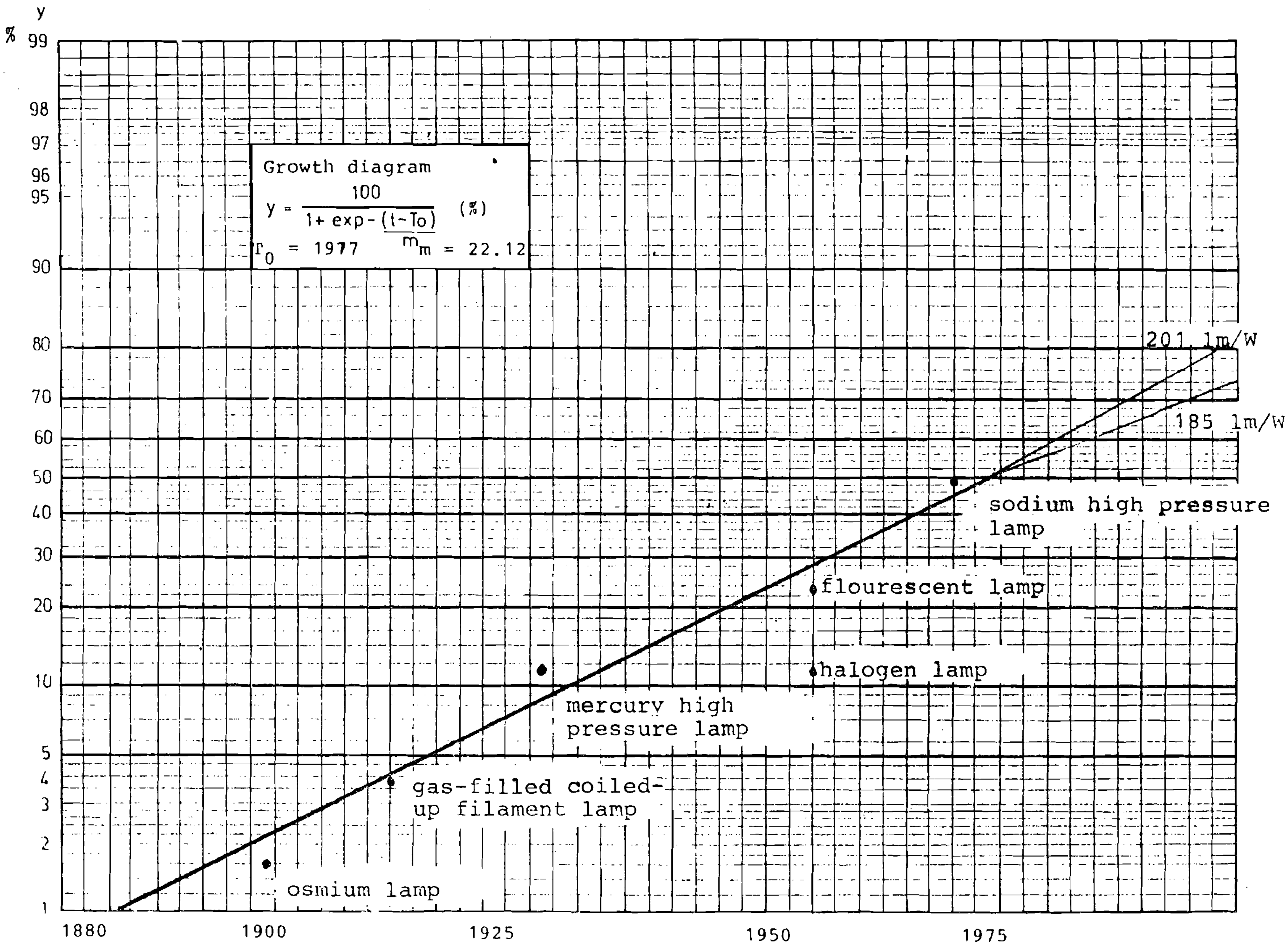

Figure 3. Development of efficacy of light sources II (265 lm/W = 100%).

Table 6. Classification of innovations according to their range of application or their effect on meeting needs.

Main Categories	Categories: General	Categories: Meeting Demand
A. Partial changes	1. Simple qualitative extension of existing elements or processes	Quantitative extension of existing demand
	2. Quantitative extension of existing elements or processes	Modification of existing types of demand Quality improvements of existing products
	3. Changed proportions and new characteristics of known elements or processes	Major modification of existing types of demand (new characteristics of known utilization values)
	4. Development of individual new processes and process results in existing economic sectors	Development of a new type of demand (of a new utilization value) in the existing demand structure
B. Basic changes	5. Qualitative changes of economic sectors (development of new industrial sectors and subsectors)	Major modification of the structure by the new utilization value
	6. Qualitative changes of the total economy Development of new groups of industrial sectors	Development of a new need structure. Major changes of proportions
	7. Qualitative changes of the total social and natural environment	Reorganization of the existing system

we find via

$$100 = e^{12a}$$

$$a = \frac{\ln 100}{12} = 0.38376 \quad ,$$

which is the basis for calculating the evaluation coefficient V in Table 4.

Valency is a general historical and not an operational characteristic. For a comprehensive evaluation of light-technological solutions the following factors have to be considered (see Table 7):

-- the age of a technological solution;

-- the average annual development of the scientific-technological level;

-- the average annual decrease of expenditure per unit of performance;

-- the scientific-technological level achieved;

-- the actual extent of the overall effectivity;

-- the future prospects of the respective principle.

The table clearly shows that the two new types of high pressure lamps had obviously reached or exceeded the technological level and the effectivity of other technological solutions already seven to eight years after their introduction.

The effectivity of the various technological principle solutions in one field, at a certain point of time, is not identical with their historical valency. This is due to the effect of the time factor, i.e., the actual effectivity of a principle solution is the result of the following factors:

-- original validity;

-- scientific-technological level at the point of introduction and its development;

-- specific expenditure at the point of introduction and its reduction;

-- level and development of other, competing principle solution with respect to technological characteristics and expenditures;

-- resources and productivity development of the economy.

Table 7. Evaluation index of technological principle solutions of the lighting industry.

		Valency acc. to Table 4 %	Valency standard %	First year of production	Annual growth rate of tech level % (1)	Prod. per unit of expenditure annual growth rate % (1)	Annual effectivity increase % (1)	Tech level at the point of introduction (2)	Tech level in 1975	Relative effectivity 1975 % (3)
		1	2	3	4	5	6	7	8	9
1	Bulb to halogen lamp	68	100	1881	4.6	2.2	6.9	0.43	32	20
2	Gas discharge lamp									
2.1	Low pressure discharge lp (flourescent lamp)	46	68	1935	8.9	3.9	13.9	23	638	77
2.2	High pressure discharge lp mercury without 2.2.1 and 2.2.2	46	68	1930	7.2	3.4	12.9	31	660	100
2.2.1	Halogen metal vapor lamp	10	15	1967	22.2	3.7	26.7	140	570	105
2.2.2	Sodium high pressure lp	10	15	1968	32.2	2.8	35.9	180	960	125
TOTAL		-	-	-	8.5	2.4	22.2	-	-	-

1) All annual growth rates are measured from the first year of production up to 1975
2) Measured here as the product of light output and useful life of the lamp, divided by 1000 W (lmh/1000W)
3) Based on the social costs, calculated by Liewald 1977. The social costs calculations include the following quantities: lighting current, useful life, lighting efficiency, lamp costs, installation expenditures, service life, price of light source, annual duration of burning, lamp replacement costs, costs of current, maintenance costs.

In the initial or introductory stage the technical level of new solutions (level of production) develops more rapidly than the technological level; i.e., the later extension phase of the innovation is typically characterized by a more rapid technological development.

In the field of light sources a uniform effectivity measurement has reached a relatively high stage of development. In a technically simplified way the level of meeting demand is also measurable in lux. But it is not only the volume that has to be considered. The historical transition towards qualitatively higher demands is a dimension of change relating to people. Thus the lighting demand has furthermore been determined by qualitative physiological parameters.

The effort to find suitable measuring quantities for the valency or effectivity of innovations in a certain technological field could well be a heuristic stimulus for further development.

In this sense the efficacy of a lamp may also be defined in a different way:

$$\eta = \frac{\text{useful energy released}}{\text{energy absorbed}}$$

$$\eta = \frac{\text{useful energy released } E_u}{\begin{matrix}\text{Industrially} & & \text{Naturally} \\ \text{supplied} & + & \text{supplied} \\ \text{energy } E_{SI} & & \text{energy } E_{SN}\end{matrix}}$$

Accordingly, three variants of light sources are possible: (Haustein 1964)

-- E_{SN} (e.g. environmental heat) is not utilized. This applies to our present light sources.

-- E_{SN} is utilized in addition to E_{SI}. This light source withdraws heat from its environment. This principle can be utilized by application of the thermoelectric effect to the electroluminescence in solid bodies.

-- The logical continuation of this thought is $E_{SI} = 0$, i.e., a light source operating independently of the mains supply.

A light source which is independent of the mains supply and which has a nearly unlimited useful life is the ideal aim of the technological development in this field.

SEQUENCE OF PRODUCT AND PROCESS INNOVATION IN THE CASE OF INCANDESCENT LAMPS

At present the innovation coefficient is rather low in the sector of light technology as compared with the share of innovation of higher historical valency in the production complex.

The improvements of the multi-purpose lamp correspond to a valency of a maximum of 10% (halogen lamp), and the same applies at best, to discharge lamps. So this sector has a lower historical innovation coefficient than the total field of electrical engineering. And it is not by coincidence that the annual profit increase of the US lamp industry is 20% below the average profit increase (1954-1977).

With the example of the incandescent lamp we can also study the sequence of product innovation and process innovation (Figure 4 and Table 8). The product innovation began in 1881 and up to 1891 the technical level of the product measured by linear hours had a rising annual increase. The progress between 1890 and 1900 was not so important and at the same time gas lighting became competitive with electric light. However from 1900 to 1915 a series of major improvements (mainly ductile tungsten) ensured the success of the new principle. At the same time process indicators behaved differently. Productivity gain was very high at the time when mass production was established (1882-1886) however it was rather low during the next fifteen years because it was mainly a manual process. Mechanization introduced a higher increase in productivity in the following years from 1900 to 1915. Due to automation the main process innovations came before the second world war. Product innovation in incandescent lamps declined after 1910-1915 but had a small upswing before the second world war.

In 1960 the first halogen lamp was produced, but this lamp is still not comparable with the general purpose lamps. Therefore we find that the basic innovation "incandescent lamp" was realized through three upswings of major improvement innovations as well as through many minor improvements. The length of this improvement cycle was about 25-30 years. It had reached an absolute maximum in 1910-1915, but after this peak we have a decline in the increase of product level. Process innovations also went through improvement cycles and they became higher after the peak in product innovation. In more than 40 years of relatively low product development the bulb production process was technological revolutionized. While only 83 lamps were produced per man-hour in 1939, the corresponding figure was 750 in 1969 (Caines 1978).

The innovation process "discharge lamp" began in 1830. The relative increase of light output was lower than that of the bulb, which should, however, be seen against an essentially higher technological level and a considerable improvement in useful life. The production rate of a plant could be increase from 1,000 (1954) to more than 3,000 pieces per hour in 1977.

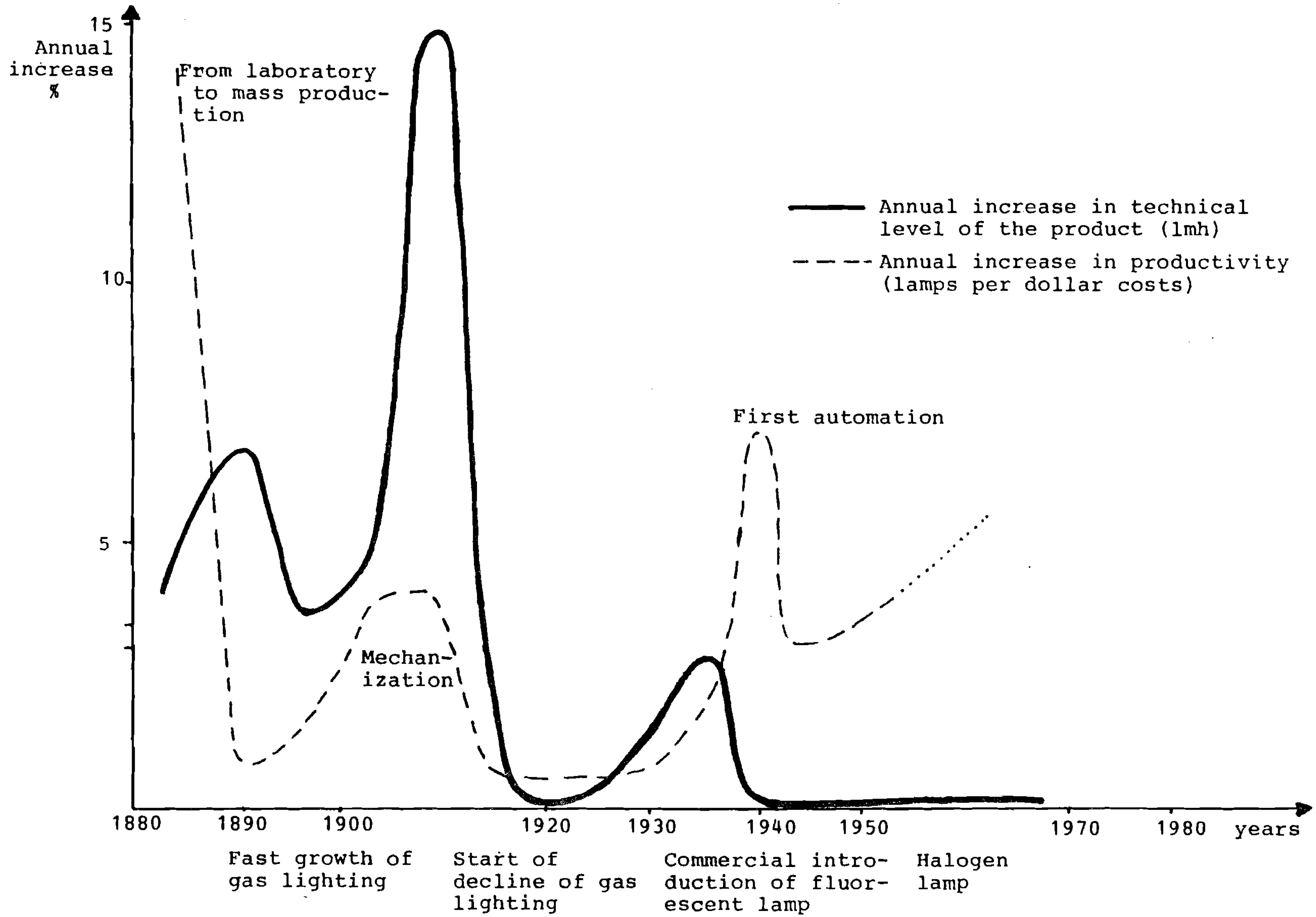

Figure 4. Sequence of product and process innovation in the case of incandescent lamps.

Table 8. Annual increase in percent of the product level, of productivity and efficiency of incandescent lamps 1882-1960.

Years	Lumen hours per 100W lamp	No. of lamps for cost of 1 dollar	Efficiency lumen hours per dollar cost
1882-1888	4.9	13.6	19.2
1888-1894	6.7	0.7	7.4
1894-1900	3.7	1.6	5.4
1900-1906	4.9	3.8	8.9
1906-1912	14.7	4.0	19.3
1912-1915	3.2	0.9	4.1
1915-1923	0	0.6	0.6
1923-1933	1.0	0.7	1.7
1933-1937	2.8	1.9	4.8
1937-1942	0.1	7.1	7.2
1942-1945	0	3.1	3.1
1945-1960	0.2	3.9	4.1

Source: Calculated according to historical data, given in Bright (1949) and Liewald (1977).

As we do not know of any new technological principle of light generation, it is very difficult today to assess the time or extent of maximum discharge lamp production.

The bulb reached its maximum share in the lighting system around 1930 in the leading countries. The commercial utilization of discharge lamps started at the same time.

Only after 1985 can discharge lamps be expected to reach a 95% share in total electric lighting in the leading countries (see Appendix B and C).

SOME THOUGHTS ABOUT THE FUTURE OF THE LIGHTING INDUSTRY

Let us now return to our starting point. In principle, the technological development of specific fields is not unlimited. There are physical and technological limits to action principles which cannot be exceeded. Sooner or later this leads to a reduction in effectivity increase, to the transition of a sector from growth to stagnation or recession; the situation is, however, quite different if we turn away from the limited technological aspects towards such issues as meeting demands or resource availability.

On one side we have the qualitatively and quantitatively growing lighting demand and on the other side there is the total of resources available to meet this demand, with lighting production and application systems (LAS) of various orders inbetween (Table 9). From an historical view light technology developed as a complex field, including current production, current distribution and lighting. In the course of increasing industrial specialization light technology developed into a relatively narrow special field which centered its productional interests mainly on lamps (LAS of the first order). At a later point auxiliary devices (main connecting devices) and new forms of application were added (LAS of the second order).

Today the development tends towards a new and higher degree of complexity (LAS of the third order), which also includes--apart from lamp manufacture--planning and application of new utilization systems. Not only lamps are sold, but--to a growing extent--whole lighting systems, especially on the international market. In 1978 the light technological industry of the German Democratic Republic started to follow up on the development of LAS of the third order, which is assumed to yield much higher effectivity. The combinat VEB NARVA comprises today light sources, lamp production, main connecting devices, and other non-production activities.

There might be a future LAS of the fourth order, which would return to the starting point of the light source industry on a higher level. If we succeed in developing some form of lighting system which is independent of the central mains supply, a qualitatively new step will be reached in the field of production and application systems.

Table 9. Components of lighting production and application systems LAS.

	Light technological production and application systems			
	1st order,	2nd order,	3rd order,	4th order
1. Source of current				x
2. Distribution of current				x
3. Light source	x	x	x	x
4. Glass and lamp component		x	x	x
5. Lamp-shades			x	x
6. Auxiliary devices		x	x	x
7. Contracting work for lighting installations			x	x
8. Application		x	x	x
9. Lighting projects			x	x
10. Planning and consultancy			x	x

The effectivity of the LAS is a complex quantity, and not just the sum of the effectiveness of its components, as specified in Table 9.

Therefore any projection of the scientific-technological development must not be confined to individual components. It has to reveal those strategic deficiencies which limit effectivity growth within the overall production and application system.

Vertical and horizontal combination of production in the production and application system is the best way of promoting the dynamic progress of industrial sectors in the interest of the national economy. In this sense the concept of the complex innovation process is clearly defined: it is an innovation process which is not confined to individual components of the production and application process, but which comprises several of all of these components.

APPENDIX A: Historical data illustrating the technological means of meeting the lighting demand (for white light)

Year	Event	Efficacy lm/W	Life-time hours
	Hearth fire		
7000-8000BC	Terracotta oil lamps in Mesopotamia		
2700 BC	Egyptian and Persian copper and bronze lamps		
1000 BC	Wick of vegetable fibre burning in a saucer-type vessel holding olive or nut oil		
500-400 BC	Oil lamps had come into general use		
230 BC	Lamps with automatic refill - Philon of Byzantium		
200 BC	Candles		
100 BC	The Romans developed the first true lantern of horn, cylindrical in form with a perforated top		
ca. 300	Street lighting (Asia) Stearin candle	0.13	
1650	Otto von Guericke discovered that light was produced by electricity or by electrical excitation. He also invented the vacuum pump		
1783	Kerosene lamp with flat wick - Leger Paris. Kerosene lamp with hollow wick and glass cylinder - Argand, Paris	1.00	

Year	Event	Efficacy lm/W	Life-time hours
1792	Gas lighting - Murdoch		
1802	Davy made a platinum filament glow by galvanic current		
1836	"Courier belge" first mentioned the possibility of using a vacuum for electric lighting		
1840	Grove. First experiments with platinum incandescent lamp		
1845	Starr - English patent for a "continuous metallic or carbon conductor intensely heated by the passage of electricity for the purpose of illumination"		
1845	Thomas Wright, London. First patent for arc lamp		
1848-1860	Swan - Several experiments in England		
1850	H. Geissler, Germany, discovered that an electric current passing through a rarefied gas, causes the gas to glow		
1854	Goebel - bulb with bamboo filament	0.80	
1859	Discovery of petroleum. The crude oil lamp was superseded		
1859	A.E. Becquerel - First electric lamp containing flourescent materials very low efficiency and short life		
1866	Werner von Siemens developed the dynamo-electrical machine		
1872	Hodyguine, Graphite lamp		
1976	Jablochkov candle (arc lamp)		
1877	Beginning of Edison's experiments		
1877	Edison began his work on electric lamps		
1879	Edison's first lamp (carbon filament)	1.60	300
1880	Steamer "Columbia" was equiped with 115 Edison lamps with Edison sockets. Lamp price 1 dollar		
1881	Edison's improved lamp cost 70¢ Johann Kremenezky, Vienna - Bulb with carbon filament	1.68	600
1882	Edison lost a patent infringement action against Swan		

Year	Event	Efficacy lm/W	Life-time hours
1883	Edison and Swan founded a company		
1884	Edison lamp cost 22¢	3.4	400
1885	Auer von Welsbach invented the gas mantle, a strong competitor to electric lighting		
1885	Sprengel mercury pump reduced exhaust time from 5 hours to 30 minutes		
1888	Asphalt-treated filament	3.0	600
1891	Tungsram Austria founded		
1892	Incandescent gas light Auer von Welsbach	1.50	
1892	Invention of mercury-vapour lamp by L. Arons		
1893	Fast growth of gas lighting with Auer gas mantle lamp price 12-18¢	3.5	
1896	Phosphorus exhaust method reduced exhaust time to less than a minute		
1901	Mercury arc lamp, Peter Cooper Hewitt 19 lm/W, remained a popular light source for factories for 40 years		
1902	Osmium lamp - Auer von Welsbach (Osmium too expensive and rare)	4.40	
1904	Metallized carbon	4.0	600
1904	Non-ductile tungsten	7.85	800
1904	Moore tube first used commercially Commercially successful high-voltage gaseous-discharge lamp		
	with nitrogen yellow light	5.0	
	with carbon-dioxide white light	2.00	
1904	Steinmetz, US arc lamp, remained a popular street lighting source in US until 1930		
1904	Just, Hanamann, Austria Tungsten filament lamp		
1905	Production of lamps in flexible job-shop configuration, involving more than 11 separate operations with mainly manual labor		
1905	Tantalum lamp, W. Siemens (on the market 1906-1913)	3.70	800
1906	Tungsten filament lamp	5.50	800

Year	Event	Efficacy lm/W	Life-time hours
1907	Edison patent on fluorescent lamp		
1908	W.D. Coolidge, US - developed ductile tungsten by drawing it through a series of dies		
1909	Beginning of reduction in gas lighting		
1910	Ductile tungsten	6.3	1000
1911	Tungsten drawn filament lamp	10,0	1000
1913	Langmuir developed the use of inert gases inside the incandescent lamp (nitrogen and later argon).		
1915	First gas-filled coiled-up filament lamp	10.30	
1920	100 Watt filament lamp Lamp price 37p Living costs 51% (1940 = 100)	10.0	1000
1930	100 Watt filament lamp Price 22p Living costs 72% (1940 = 100)	11,0	1100
1931	High-intensity sodium-vapour lamp not satisfactory for commercial use		
1932	Mercury lamp	31.0	
1935	Wound coil filament lamp	13.2	
1935	Phosphors with good response to ultraviolet radiation had been developed		
1935-1938	Development work by General Electric and Westinghouse		
1938	April 1st - first commercially successful flourescent lamps were introduced in the US		
1938	20,000 fluorescent lamps in the US		
1938	Krypton lamp	13.9	
1939	Productivity: 1250 bulbs per hour (15 man hours) highly mechanized process		
1939	Fluorescent lamp - 80Watts	23.0	2000
1940	100 Watt filament lamp Price 10p Living costs 100%	11.6	1160
	80 Watt fluorescent tube Price £1.97	27.0	2000

Year	Event	Efficacy lm/W	Life-time hours
1949	Fluorescent lamp - 80 Watt	43.0	4000
1950	80 Watt fluorescent tube Price 95p Living costs 135% (1940 = 100)	38.0	3000
1954	Mercury lamp with quartz	41.0	
1959	First halogen lamp - tungsten	30	2000
1959	Fluorescent lamp - 80 Watt	57	5000
1960	80 Watt fluorescent tube Price 76p Living costs 200% (1940 = 100)	54.0	5000
1968	261.5 million fluorescent lamps in the US		
1969	Productivity: 3750 bulbs per hour (5 man-hours)		
1969	Fluorescent lamp - 80 Watt	61	7500
1970	85 Watt fluorescent tube Price 70p Living costs 305% (1940 = 100)	74.0	7500
1975	Reached level		
	Halogen bulb	32	
	Mercury high pressure lamp	50...60	
	Sodium high pressure lamp	90...130	
	Fluorescent lamp	70...100	
	Halogen metal vapour lamp	70...110	
	Prospective empirical limits:		
	Bulb	40	
	Fluorescent lamp	120	
	High pressure lamp	150	

APPENDIX B: Output of lamps in the US
1898-1970

Year	Large incandescent Mil	Fluorescent, hot cathode Mil	Coefficient of lmh **	Share of fluorescent light in lmh %
	1	2	3	4
1970	1582	267	39.9	87.1
1969	1476	261	38.7	87.3
1968	1467	258	37.6	86.9
1967	1391	224	36.4	85.4
1966	1394	256	35.2	86.6
1965	1320	225	34.0	85.3
1964	1264	198	32.9	83.7
1963	1254	179	31.7	81.9
1962	1238	164	30.5	80.2
1961	1155	142	29.3	78.3
1960	1142	140	28.2	77.6
1959	1212	131	27.0	74.5
1958	1052	113	25.8	73.5
1957	1112	119	24.6	72.5
1956	1132	126	23.4	72.3
1955	1057	104	28.2	68.7
1954	960	93	21.1	67.1
1953	1028	92	19.9	64.0
1952	864	65	18.7	58.5
1951	1070	111	17.6	64.6
1950	1200	98	16.4	57.3
1949	975	71	15.2	52.5
1948	1030	94	14.0	56.1
1947	999	89	12.9	53.5
1946	774	52	11.7	44.0
1945	787	37	10.5	33.0

Year	Large incan-descent Mil	Fluores-scent, hot cathode Mil	Coefficient of lmh **	Share of fluorescent light in lmh %
	1	2	3	4
1939	517			
1937	501			
1935	388			
1933	306			
1931	320			
1929	352			
1927	335			
1925	267			
1923	233			
1921	155			
1919	225*			
1914	89*			
1909	67*			
1905	113*			
1899	25*			
1891	7.5***			

*Not strictly comparable with later years because of changes in classification.
**Estimated relationship between lmh of fluorescent lamps and lmh of incandescent lamps.
***Bright 1949, p.4.

Source: Historical Statistics of the US, p.696-697. (Column 1 & 2)

APPENDIX C: The production of bulbs and discharge lamps in the GDR since 1950.

Year	t	Production of multi-purpose lamps mil pieces	G lm	Production of discharge lamps mil M	G lm	Total production of light sources G lm	Share of discharge lamps
		(1)	(2)	(3)	(4)	(5)	(6)
1950	1	27	18.9	2.6	1.53	20.43	7.5
1951	2	35	24.5	4.5	2.65	27.15	9.8
1952	3	44	30.5	3.7	2.18	32.68	6.7
1953	4	18	12.9	2.8	1.65	14.55	11.3
1954	5	31	21.7	4.8	2.83	24.53	11.5
1955	6	44	30.5	7.5	4.41	34.91	12.6
1956	7	55	38.6	10.5	6.18	44.78	13.8
1957	8	62	43.3	13.7	8.06	51.36	15.7
1958	9	65	45.8	17.8	10.48	56.28	18.6
1959	10	68	47.3	20.4	12.01	59.31	20.2
1960	11	60	42.0	22.9	13.48	55.48	24.3
1961	12	58	40.3	23.4	13.77	54.07	25.5
1962	13	65	45.6	32.3	19.01	64.61	29.4
1963	14	70	49.1	41.2	24.25	73.35	33.1
1964	15	75	52.6	44.9	26.43	79.03	33.4
1965	16	83	58.1	55.0	32.37	90.47	35.8
1966	17	89	62.3	69.0	40.61	102.91	39.5
1967	18	92	64.4	74.2	43.68	108.08	40.4
1968	19	100	70.0	84.9	49.97	119.97	41.7
1969	20	111	77.7	83.5	49.15	126.85	38.7
1970	21	111	77.7	114.1	67.16	144.86	46.4
1971	22	100	77.0	137.7	81.05	151.05	53.7
1972	23	98	68.6	155.6	91.59	160.19	57.4
1973	24	93	65.1	158.9	93.53	158.63	59.0
1974	25	82	57.4	177.1	104.24	161.64	64.5
1975	26	73	51.1	183.1	107.78	158.88	67.8
1976	27	76	53.2	189.3	111.42	164.62	67.7

REFERENCES

Bright, A.J. 1949. The Electric Lamp Industry: Technological Change and Economic Development from 1800 to 1947. New York: Macmillan.

Carnes, R.B. 1978. Productivity and Technology in the Electric Lamp Industry, Mon. Labor Review 101(8):15.

Ekonomika; organisacija promyslemogo proizoodstva 6/75

Ehenbaas, W. 1972. Light Sources. Philips Technical Library. Macmillan.

Gross, A.T. 1933. Die Glühlampe als Wegbereiterin der Elektrizitätswirtschaft. Technik-Geschichte, Beiträge zur Geschichte der Technik und Industrie. 22. Berlin.

Haustein, H.-D. 1964. Die Messung und ökonomische Analyse des technischen Niveaus unter besonderer Berücksichtigung der Anforderungen der Perspektivplanung (Investigated mainly in the electronic and lighting industry) Habilitation. Hochschule für Ökonomie. Berlin.

Historical Statistics of the US Colonial Times to 1970. Part 2. 1975. Washington, D.C.

Krenezky, J. 1917. Die Geschichte der elektrischen Glühlampe. Wien, Selbstverlag.

Kuczynski, J. 1967. Die Geschichte der Lage der Arbeiter unter dem Kapitalismus. Volv.37. Berlin: Akademie Verlag

Lamps and Lighting. 1972. Henderson and Marsden eds. Edward Arnold.

Liewald, H. 1977. Die analytisch-prognostische und langfristig-Konzeptionelle Arbeit fur Forschung und Entwicklung als Bedingung für die planmässige Erhöhung des wissenschaftlich-technischen Niveaus der Produktion-dargestellt am Beispiel der Lichtquellen-Industrie der DDR. Dissertation A. Humboldt-Universität. Berlin.

Lighting. Encyclopaedia Britannica. Volume 14. 1973.

Statistisches Jahrbuch der DDR 1655-1979.

Technisch-wissenschaftliche Abhandlungen aus dem Osram-Konzern. 1936. Berlin: Julius Springer.

Uvazatele Hospodarskeho Vyvoje v Zahranici. 1976. Prague.

Willoughby, A.H. 1969. The Evolution of Electric Lamps. Lighting Research and Technology. 1(2):77.