WP-2007-007

Technology portfolio analysis for residential lighting

P. Balachandra and B. Sudhakara Reddy

Indira Gandhi Institute of Development Research, Mumbai
May 2007

Technology portfolio analysis for residential lighting

P. Balachandra
Department of Management Studies
Indian Institute of Science,
Bangalore-560012, INDIA

B. Sudhakara Reddy
Indira Gandhi Institute of Development Research (IGIDR)
General Arun Kumar Vaidya Marg
Goregaon (E), Mumbai- 400065, INDIA
Email (corresponding author): sreddy@igidr.ac.in

Abstract

Electricity consumption in India is increasing rapidly over the years. The increased demand for electricity forces the electricity utilities to increase their generating capacity. The huge investments on generation, transmission and distribution (at the cost of alternative development projects) adversely affect India's scarce capital resources. Also, internal energy resources like coal are utilised with a great risk to the environment. This paper attempts to show analytically the benefits of shift in the focus from supply augmentation to demand management through a case study of replacement of inefficient devices with efficient ones for residential lighting. This is being done by analyzing the economics of various alternatives and developing an optimal portfolio for meeting the lighting requirement of a typical household in Maharashtra State in India. A mixed integer-programming model has been used for developing the optimal portfolio and a comparison of annual returns is made. Finally, the results for the typical household have been extended to the state of Maharashtra and the cost and benefits are estimated. The results show that the optimal lighting portfolio provides a far higher return at a lower risk compared to other investment alternatives like the stock market while providing substantial savings both in terms of energy and peak demand.

Key words: Demand management, electricity consumption, energy resources, mixed integer-programming model, rate of return

JEL Code: Q4

Technology portfolio analysis for residential lighting

P. Balachandra and B. Sudhakara Reddy

1. Introduction

India's demand for electricity has been increasing over the years. The electricity consumption in 1979-80 was 78,123 GWh and increased to 339,598 GWh during 2002-2003, an increase of about 6.6% per annum. The share of Maharashtra, a state in Western India, in the total electricity consumption is the highest in India (17%). As development continues, the future demand and the real cost of producing a kilowatt of electricity will increase significantly. As a result, enormous amounts of scarce capital should be invested on generation, transmission and distribution. Also, financial, environmental and energy resource constraints limit the expansion of the supply capacity resulting in severe shortages. With increasing demands and rising costs of generation, the question is how to reduce demand without compromising on services. Energy efficiency may partly fill this gap. The supply expansion can be deferred, at least partly, if the existing inefficient devices/appliances are replaced with efficient ones. From an individual's point of view, energy efficiency can be viewed as an investment opportunity in which the initial cost is weighed against future returns in the form of subsequent reductions in expected energy costs.

In the residential sector, lighting is one of the most important uses of electrical energy. It represents 10 to 20% of electricity use in most countries and sometimes more in developing countries (Dutt, 1994). The technological advances in lighting technologies have resulted in improvement of lighting energy efficiency by a factor of five without any alteration in light levels. Though the potentials in terms of energy savings and economic returns of these efficient lighting technologies have been recognised, penetration rates into the market are very low

(Gadgil and Jannuzzi, 1994). One of the main reasons for this is the high initial capital costs. For example, in India, the purchase cost of compact fluorescent lamps is almost 15 to 20 times that of incandescent bulbs, and thrice that of fluorescent tubes. Also, the individual adopters tend to use very high discount rates to evaluate energy-efficient technologies (Metcaff, 1994). In India typical middle-income investors use a discount rate as high as 40% to evaluate energy efficient devices (Reddy, 1996).

One possible way of improving the market penetration rates of efficient technologies could be to sell them as "lighting packages" consisting of a "portfolio" of both inefficient and efficient lighting, which may help in diversifying the risk associated with investments in efficient devices. In addition, this can facilitate an effective match between lighting technology and lighting levels required. The concept of portfolio theory deals with the efficient combination of risk assets into a single portfolio in which each asset is characterised by its expected rate of return, its risk, and the risk relative to that of other assets in the portfolio (Levy and Sarnat, 1994). A majority of the work related to the choice of energy efficient technologies (based on their economic performances) is done on the basis of these security analyses wherein only the costs and returns of these technologies are estimated without giving any attention to the risk associated with them (Sutherland, 1986 and Sutherland, 1991). That is, the choice of a technology was entirely based either on least cost or on maximum returns. However, recent literature identifies the need for the inclusion of the risk in the investment analysis of modeling energy technology choices (Sutherland, 1991 and Johnson, 1994). It may be a rational proposition to have a portfolio of existing inefficient and efficient technologies rather than having complete replacement of inefficient technologies with efficient ones. A similar approach was attempted by Sutherland (1986) to compare investments in nuclear and coal-based power plants.

The present paper deals with energy efficiency by looking at the individual as well as societal perspectives. This will be done by attempting to answer the following questions, viz., (i) is it possible to view energy efficient technology as an attractive investment alternative comparable to the common stock option? (ii) Considering the high investment required for the efficient alternatives and the risks involved, is there an optimal mix of energy technologies, which is reasonably efficient and provides high returns at low risks? (iii) If an optimal portfolio can be developed, then what are the benefits that could accrue to the residential sector and the state as whole? Thus, the main objective of this study is to answer these questions by analysing the feasible energy efficient lighting technologies and developing an optimal portfolio of them to meet the lighting requirements of residential consumer. This optimal portfolio is expected to have such alternatives of lighting technologies, which provide maximum returns to the individual consumers under given constraints. Lighting for a typical household in Maharashtra State is considered as an example for this exercise. Finally, the results are extended to the residential sector of the state.

The present study analyses the economic and technical feasibility of all the available lighting alternatives and then attempts to construct an optimal portfolio of these alternatives for meeting the lighting requirement of a typical household. Also, a comparison is attempted between the returns from the efficient technologies and their portfolios and the average returns from the stock market (refer Metcaff (1994) for similar comparison). This is based on the assumption that a rational individual is expected to assess the significance of the level of returns obtained through efficient lighting and for this it is natural for him to compare them with the returns from the best available alternative, which is the stock market. Using this logic, the overall benefits to the individual consumer, the residential sector and society as a whole are estimated.

2. Residential lighting: An overview

The state of Maharashtra has an installed capacity of 15,148 MW (in 2001-2002) and the total generation including purchases from licensees is 64,430 GWh of electricity. The state total electricity consumption during the year 2001-02 is 46,338 GWh. Out of this, the residential consumption is 11,901 GWh accounting for about 25.68% of total consumption. Lighting is an important end use accounting approximately for about 40% of residential consumption. The other major end uses include water-heating, cooking and air conditioning. Lighting devices in a typical household consist of various wattage types of incandescent bulbs (IBs), fluorescent tubes (FTs) and compact fluorescent lamps (CFLs). Table 1 contains the basic information on various lighting technologies.

Table 1: Basic Information on various lighting technologies

Lighting Devices	Rated Wattage (Watts)	Actual Wattage (Watts)	Life (hrs)	Cost∗ (Rs.)	Flux (Lumens)
Incandescent Bulb (IB-40)	40	40	1000	12	425
Incandescent Bulb (IB-60)	60	60	1000	12	720
Incandescent Bulb (IB-100)	100	100	1000	13	1380
Fluorescent Tube (FT-20)	20	28	6000	46	970
Fluorescent Tube (FT-40)	40	52	6000	48	2450
Fluorescent Tube (FT-18)	18	26	6000	46	970
Fluorescent Tube (FT-36)	36	46	6000	47	2450
Fluorescent Tube Choke (FT-Choke)			13000	175	
Compact Fluorescent (CFL-10)	10	12	10000	165	600
Compact Fluorescent (CFL-13)	13	15	10000	170	900
Compact Fluorescent (CFL-18)	18	20	10000	195	1200
Compact Fluorescent (CFL-26)	26	28	10000	250	1800
Discount Rate (%)	12				
Electricity Price (Rs.)	3				

Note: Compact Fluorescent Lamps: GE2 Pin Plug in Double Biax CFL lamps.
∗ Costs are given in Indian Rupees in 2002 prices.

The number of lighting points in a typical household is assumed to be equal to 10 and the average hours of usage per day is estimated to be three hours (Reddy, 1995). These usage hours are arrived at by matching the lighting points with the commonly present rooms in a typical house and the usage pattern (Levy and Sarnat, 1994). The assumed distribution of these devices according to various levels of usages (hours per day) is given in Table 2. Also, the table contains information on the approximate level of lighting (Lumens) required for these usage hours.

Table 2: Lighting devices/level requirements in a typical household

Lighting Locations	Usage (Hours per day)	Required Lighting Level (Lumens)	Number of Devices Required
1	0.5	425	One IB-40 or CFL-10 or equivalent
2	1	425	One IB-40 or CFL-10 or equivalent
3	1.5	720	One IB-60 or FT-20 or CFL-13 or equivalent
4	2	720	One IB-60 or FT-20 or CFL-13 or equivalent
5	3	1800	One IB-40 and IB-100 or two CFL-13 or equivalent
6	4	2400	Two IB-100 or one FT-40 or two CFL-18 or equivalent
7	5	2400	Two IB-100 or one FT-40 or two CFL-18 or equivalent
8	6	1200	One IB-100 or one CFL-18 or equivalent

The lighting requirements and the available technologies are matched to obtain the feasible replacements of IBs with efficient devices (Table 3). As can be seen from the table, the shifts suggested do not exactly equal in terms of lighting levels (lumens). This is because, the shift has been allowed even if the lighting service is higher than the standard one.

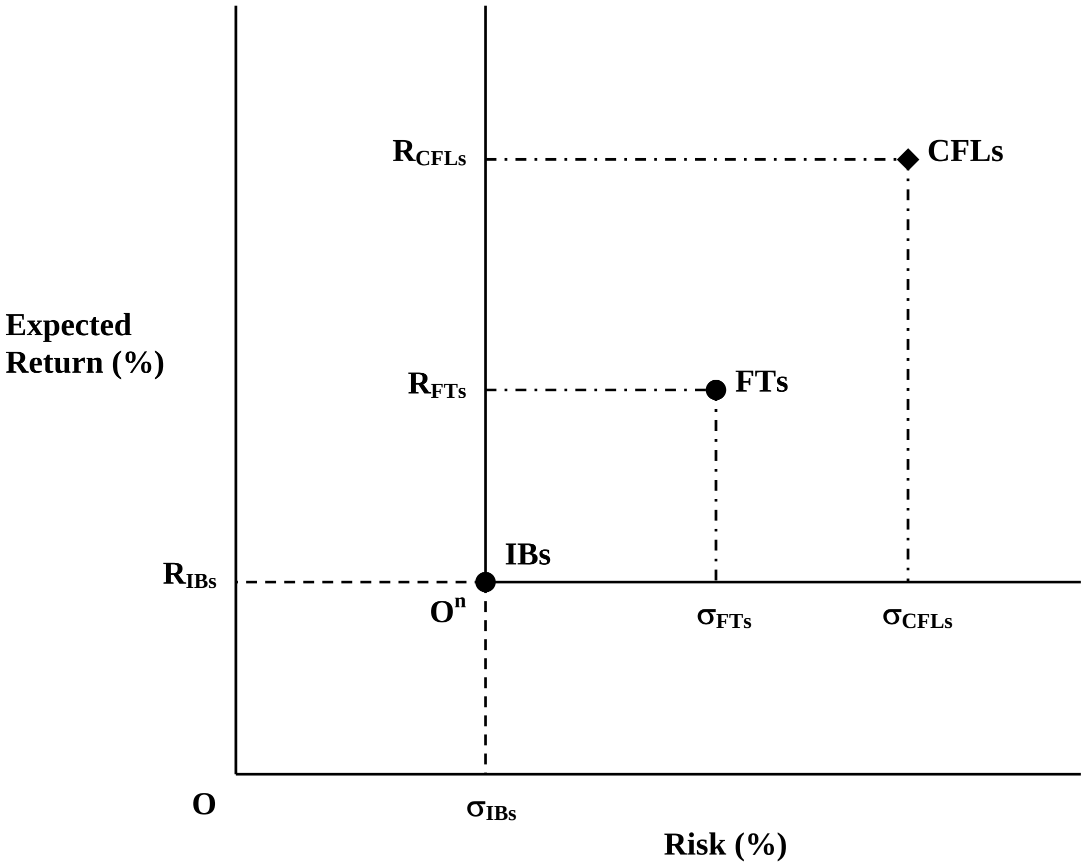
Table 3: Feasible lighting alternatives

Standard Devices	Efficient Devices
Incandescent Bulb (IB-40)	Fluorescent Tube (FT-20)
	Fluorescent Tube (FT-18)
	Compact Fluorescent Lamp (CFL-10)
Incandescent Bulb (IB-60)	Fluorescent Tube (FT-20)
	Fluorescent Tube (FT-18)
	Compact Fluorescent Lamp (CFL-10)
	Compact Fluorescent Lamp (CFL-13)
Incandescent Bulb (IB-100)	Fluorescent Tube (FT-40)
	Fluorescent Tube (FT-36)
	Compact Fluorescent Lamp (CFL-18)
	Compact Fluorescent Lamp (CFL-26)

3. Efficient lighting technologies and the rate of return

The lighting technologies, unlike the common stock options, do not provide direct returns in monetary terms but provide the service, i.e., *light output from the lamps.* These are indirect returns in the form of cost savings in relation to inefficient devices. The lighting technologies considered for the present portfolio posses approximately the same amount of light output and the differences are only in energy input and the cost of these devices. That is, the return based on the light output is the same for all the types of lighting technologies that are studied here. Therefore, the monetary returns are the costs saved on account of reduced energy input required for obtaining the same level of energy service/lighting when compared to the existing inefficient lighting device. Since these returns are in relation to the inefficient devices, we term them as relative returns.

In the present study, the relative returns have been calculated for the feasible efficient replacements by keeping the returns from IB as constant at zero. This concept of relative returns and the risk involved are shown graphically in Figure 1. According to the figure the origin O has been moved to new origin O^n to exclude the return and risk from the light output of IBs. Thus, return R_{IBs} and risk σ_{IBs} for IBs are equal to zero. The values for R_{FTs} and σ_{FTs} for FTs and R_{CFLs} and σ_{CFLs} for CFLs are obtained in relation to IBs.



Note: R = Returns; O = Origin, O^n = New Origin; σ = Risk

Figure 1: Relative return and Risk

4. Expected rates of return on investment

The relative returns from assets of lighting technologies do not remain constant since the purchase price of the devices and electricity tariff change over the years. The returns also can vary with these parameters. Therefore, it is not proper to use just the estimated returns or rates of return for any given year to arrive at some conclusions. For making any reasonable choice of portfolio, it is required to estimate the expected returns from various devices considering variations in the returns across the years. For this, the most commonly used technique is to use the average of returns over the years. In the present analysis, only the variations likely to be caused due to changes in purchase price of lighting devices and the electricity are included.

Since it is very difficult to obtain the cost of lighting devices for different years, the wholesale price index is used as a proxy for changes in device costs while electricity price index is used to estimate the annual electricity prices. The following formulae have been used to obtain these estimates by using the purchase cost of lighting devices and the electricity price in 2001 as reference data. The purchase cost of device is given by

$$C_{it} = C_i * (P.I_t/P.I) \qquad (1)$$

Similarly for electricity price,

$$p_t = p * (E.P_t/E.P) \qquad (2)$$

With above assumptions, the annual rates of return for feasible alternatives of IB replacements have been estimated as follows.

4.1 Annual cost of using the lighting device

To estimate the annual cost, the discounted cash flow (DCF) technique is used. The factors that are considered include the cost of the devices, their life, electricity price, electricity consumption and the discount rate using the following equation:

$$A_{it} = [C_{it}/PV(1, d, n)] + E_{it} * p_t \qquad (3)$$

$$PV(1, d, n) = \sum_{n=1}^{N} 1/(1+d)^n \qquad (4)$$

The annual costs of the devices have been estimated by using the basic data given in Table 1. In addition, the data on the wholesale price indices and electricity price indices from 1971-72 to 2001-02 are used for estimating the year-wise cost of devices and electricity prices. The electricity consumption is estimated assuming five hours of daily usage.

4.2 Estimation of annual rate of return on investment

As mentioned earlier, the returns are relative returns, which are the differential costs (cost saved) between the original IBs and the replaced FTs and CFLs. Thus, the relative annual return for a given type of replaced FT is the difference between its annual cost of utilisation and that of original IB. The annual rate of return is the percentage return over the total cost incurred in utilising the original device.

4.3 Estimation of expected annual rate of return on investment

Generally, the expected annual rate of return on any investment is estimated by averaging the annual rates of return of different years. The standard deviation of this series gives the associated risk (Levy and Sarnat, 1994). However, this method cannot be used in cases of FT and CFL since the annual rates of return show an increasing trend. Hence, as a second best approximation, regression analysis has been carried out using time as independent variable and actual rates of return as dependent variable. The regression equations obtained for annual rates of return of FT and CFL are given in Table 4. In the table, R_t is the expected rate of annual returns for any given year `t'. The high R^2 and t-values show that the obtained regression equations and the coefficients are highly significant. Thus, the returns estimated by the regression equations give the expected future returns from investing in assets of lighting technologies. The risks associated with these investments, which include the fluctuations in the energy carrier prices and the device costs, are given by the standard error of their estimates. Other uncertainties such as life of the device, discount rates are not considered in this model but they have been analysed as part of sensitivity analysis.

To compare the investments in lighting technologies, we have used the stock market option. The Reserve Bank of India (RBI) share price index has been used for estimating the average annual rates of return from the stock market. The return is the percentage change in share price index from year to year (1971-72 to 2001-02). However, in the case of annual rates of return from the stock market no clear trend could be observed from the data. Therefore, the average of the annual rates of return is used as the best approximation for the future expected returns.

Table 4: Long term expected annual returns of various alternatives of IB replacements

Feasible Alternatives	Regression Equation	Expected Annual Returns for 2001-02 (%)	Risk∗ (%)
IB-40 → FT-20	$R_t = -0.222 + 0.479 * t$ $R^2 = 0.841$, t-value = 12.168	14.14	1.865
IB-40 → FT-18	$R_t = 3.849 + 0.493 * t$ $R^2 = 0.841$, t-value = 12.168	18.65	1.922
IB-40 → CFL-10	$R_t = 42.331 + 0.470 * t$ $R^2 = 0.841$, t-value = 12.168	55.48	1.707
IB-60 -→ FT-20	$R_t = 28.847 + 0.401 * t$ $R^2 = 0.839$, t-value = 12.102	40.88	1.571
IB-60 → FT-18	$R_t = 31.742 + 0.408 * t$ $R^2 = 0.839$, t-value = 12.102	43.99	1.599
IB-60 → CFL-10	$R_t = 59.078 + 0.343 * t$ $R^2 = 0.839$, t-value = 12.102	69.36	1.342
IB-60 → CFL-13	$R_t = 54.022 + 0.344 * t$ $R^2 = 0.839$, t-value = 12.102	64.33	1.346
IB-100 → FT-40	$R_t = 33.166 + 0.249 * t$ $R^2 = 0.838$, t-value = 12.048	40.63	0.979
IB-100 → FT-36	$R_t = 38.762 + 0.256 * t$ $R^2 = 0.838$, t-value = 12.048	46.43	1.006
IB-100 → CFL-18	$R_t = 64.320 + 0.263 * t$ $R^2 = 0.838$, t-value = 12.048	72.21	1.035
IB-100 → CFL-26	$R_t = 52.109 + 0.334 * t$ $R^2 = 0.838$, t-value = 12.048	62.12	1.313
Stock Market		13.62	20.89

Note: The estimates are based on a five hours per day usage

∗The Risk accounted here is the possibility of suffering financial loss due to fluctuation in the price of electricity and device costs.

The estimated expected returns and risks (standard deviations) from the feasible alternatives of FTs, CFLs and the stock market respectively for the year 2001-02 (reference year for further analysis) are presented in Table 4. From these estimates, it is clear that replacement of 100 Watt IB with 18 Watt CFL gives the highest return. It may be observed from the table that the expected returns from CFL variants range from 55.48% to 72.21% with associated risks ranging from 1.03% to 1.71% compared to FT variants where the range of expected rates of return is 14.14% - 46.43 % with risk varying from 0.98% to 1.92%. This shows that the rates of return from CFL replacements are significantly higher than FTs at comparable risk levels. Comparatively, the stock market provides an average rate of return of 13.62% with a risk level of 20.89%. One can expect a very high rate of return from both FTs and CFLs compared to that in stock market (i.e., on the basis of average returns) at a relatively very low risk. In other words, the results indicate that investing in efficient lighting retrofits is highly profitable and reliable to an individual compared to investing in the stock market. One draw back with this option is that the investments in lighting technologies are limited by the number of lighting devices required in a given household. However, this kind of limitation is not applicable to the stock market option where an individual can continue to investing in it.

4.4 Annual rates of return for various usage patterns

The annual rates of return are estimated for all the feasible alternatives (at different usage hours) using the same methodology as explained earlier. Table 5 contains the estimated annualised capital as well as electricity costs for various devices at different levels of usage. It may be observed that, on an average, annualised capital costs are the lowest in the case of IB variants compared to FTs and CFLs. CFL variants are the most capital intensive of the three types of competing technologies.

Table 5: Estimated annualised capital and energy costs (Rs.) of lighting devices for different usage hours

	IB-40		IB-60		IB-100		FT-20		FT-36		FT-40		FT-18		CFL-10		CFL-13		CFL-18		CFL-26	
Hours per day	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy	Cap-ital	Energy
0.5	3.1	21.9	3.1	32.9	3.4	54.8	26.7	15.3	26.8	25.2	26.9	28.5	26.7	14.2	19.8	6.6	20.4	8.2	23.4	11.0	30.1	15.3
1.0	5.4	43.8	5.4	65.7	5.8	109.5	27.9	30.7	28.1	50.4	28.2	56.9	27.9	28.5	20.7	13.1	21.4	16.4	24.5	21.9	31.4	30.7
1.5	7.7	65.7	7.7	98.6	8.3	164.3	30.3	46.0	30.5	75.6	30.6	85.4	30.3	42.7	22.7	19.7	23.3	24.6	26.8	32.9	34.3	46.0
2.0	10.0	87.6	10.0	131.4	10.8	219.0	33.3	61.3	33.5	100.7	33.7	113.9	33.3	56.9	25.1	26.3	25.9	32.9	29.7	43.8	38.1	61.3
3.0	14.6	131.4	14.6	197.1	15.9	328.5	40.3	92.0	40.6	151.1	40.8	170.8	40.3	85.4	30.7	39.4	31.6	49.3	36.3	65.7	46.5	92.0
4.0	19.3	175.2	19.3	262.8	20.9	438.0	47.9	122.6	48.2	201.5	48.5	227.8	47.9	113.9	36.7	52.6	37.8	65.7	43.3	87.6	55.6	122.6
5.0	23.9	219.0	23.9	328.5	25.9	547.5	55.7	153.3	56.0	251.9	56.4	284.7	55.7	142.4	42.8	65.7	44.1	82.1	50.6	109.5	64.9	153.3
6.0	28.6	262.8	28.6	394.2	30.9	657.0	63.6	184.0	64.0	302.2	64.5	341.6	63.6	170.8	49.0	78.8	50.5	98.6	57.9	131.4	74.3	184.0

Note: Costs are in Indian Rupees (02 prices).

The annual cost of utilising these lighting devices is given in Table 6. According to the table, the annual energy costs are the lowest in the case of CFL variants compared to those of FTs and IBs. In terms of total annual costs, CFL-10, CFL-13 and CFL-18 fare better than the variants of FTs and IBs. Only CFL-26 is more expensive compared to IB-40, FT-18 and FT-20. However, it is important to note that all these lighting alternatives provide different levels of light outputs.

Table 6: Annual cost of utilisation of lighting devices for different usage hours (Rs.)

Hours per day	IB-40	IB-60	IB-100	FT-20	FT-36	FT-40	FT-18	CFL-10	CFL-13	CFL-18	CFL-26
0.5	25.0	36.0	58.1	42.0	52.0	55.4	40.9	26.4	28.7	34.4	45.4
1	49.2	71.1	115.3	58.6	78.4	85.1	56.4	33.9	37.8	46.4	62.1
1.5	73.4	106.3	172.6	76.3	106.0	116.0	73.0	42.4	48.0	59.6	80.3
2	97.6	141.4	229.8	94.6	134.3	147.6	90.3	51.4	58.7	73.5	99.4
3	146.0	211.7	344.4	132.3	191.7	211.7	125.7	70.1	80.9	102.0	138.5
4	194.5	282.1	458.9	170.5	249.7	276.3	161.8	89.2	103.5	130.9	178.2
5	242.9	352.4	573.4	209.0	307.9	341.1	198.0	108.5	126.2	160.1	218.2
6	291.4	422.8	687.9	247.5	366.2	406.1	234.4	127.9	149.0	189.3	258.2

Note: Costs are in Indian Rupees (in 2005 prices).

The annual rates of return are estimated for different feasible alternatives of replacements at different usage hours (Table 7). It may be observed that the replacement of 100 Watts IB with 18 Watts CFL gives a maximum return of 72.5% at six hours usage. Among the other alternatives, shift from IB-100 to CFL-18 provides the highest returns for all the usage hours. Based on the rate of return criteria this may seem to be the obvious and only choice in the portfolio of devices. However, from the point of technical feasibility, this may not be the only optimal choice. Because the lighting levels required at various usage hours are different and also the light output levels are different for various lighting alternatives. Discussions on this issue are made in subsequent sections.

Table 7: Annual rates of return for different usage hours for feasible alternatives of IB replacements (%)

Hours per day / Feasible Alternatives	0.5	1	1.5	2	3	4	5	6
IB-40 → FT-20	-67.9	-19.1	-3.9	3.0	9.4	12.3	14.0	15.0
IB-40 → FT-18	-63.5	-14.6	0.6	7.5	13.9	16.8	18.5	19.6
IB-40 → CFL-10	-5.6	31.2	42.3	47.3	52.0	54.1	55.3	56.1
IB-60 → FT-20	-16.8	17.6	28.2	33.1	37.5	39.6	40.7	41.4
IB-60 → FT-18	-13.7	20.7	31.3	36.2	40.6	42.7	43.8	44.6
IB-60 → CFL-10	26.6	52.4	60.1	63.7	66.9	68.4	69.2	69.8
IB-60 → CFL-13	20.3	46.9	54.8	58.5	61.8	63.3	64.2	64.7
IB-100 → FT-40	4.7	26.2	32.8	35.8	38.5	69.9	70.3	41.0
IB-100 → FT-36	10.6	32.0	38.6	41.6	44.3	72.8	73.2	46.8
IB-100 → CFL-18	40.8	59.8	65.5	68.0	70.4	71.5	72.1	72.5
IB-100 → CFL-26	21.9	46.2	53.5	56.8	59.8	70.9	71.5	62.5

5. Optimal portfolio of lighting technologies

The typical household that is considered for this study has a choice of 11 different lighting devices for 10 lighting points. A Mixed Integer Programming (MIP) model is developed to make an optimal selection among the alternatives considering both the economic as well as technical feasibility criteria. Economic feasibility is measured through the returns that could be obtained through an efficient replacement where as the technical feasibility is measured in terms of lighting level demanded and the potential of a given device to provide that level of lighting. In cases where a single device is unable to provide sufficient lighting, a combination of devices is used. A mixed integer programming model is used and the model solution gives the optimal portfolio of lighting technologies.

The objective function for the model is to maximize the annual returns by replacing the standard device with an efficient one.

$$\text{Max } Z = \sum_{i,j=1}^{I,J} \sum_{k=1}^{K} (C_{ik} - C_{jk}) * N_{i\rightarrow j,k} - \sum_{i,j=1}^{I,J} \sum_{k=1}^{K} OC_{i\rightarrow j,k} \quad (5)$$

The constraints are as follows:

i. Number of lighting devices required for a given usage hour

The total number of lighting devices in a given room should be at least equal to the given number, which is being used for a given duration in hours.

$$\sum_{i,j=1}^{I,J} N_{i\rightarrow j,k} \geq N_k \text{ for all } k \tag{6}$$

ii. Total number of lighting devices for a typical house hold

The total number of lighting devices in a given household should not be more than the required number.

$$\sum_{i,j=1}^{I,J} \sum_{k=1}^{K} N_{i\rightarrow j,k} \leq N \tag{7}$$

iii. Demand for the level of lighting

The level of lighting (Flux measured in Lumens) in a given room should be at least equal to the prescribed level.

$$\sum_{i,j=1}^{I,J} L_{i\rightarrow j} * N_{i\rightarrow j,k} \geq L_k \text{ for all } k \tag{8}$$

iv. Opportunity cost of using inappropriate lighting device

The consumer can have a flexibility of choosing a higher wattage lighting device to get more lighting than the prescribed level. However, there are extra costs involved in terms of higher capital and energy costs that need to be incurred to have this facility. The difference in costs between the higher wattage device and the prescribed device is considered here as the opportunity cost.

$$EC_{i\rightarrow j} * N_{i\rightarrow j,k} = OC_{i\rightarrow j} \text{for all i, j and k} \tag{9}$$

v. Non-negativity Constraints

All variables ≥ 0

5.1 Estimation of portfolio returns and risk

The portfolio returns are calculated as follows:

$$R_p = \sum_{i=1}^{m} R_i * P_i \quad (10)$$

The variance associated with the portfolio is calculated as follows:

$$\sigma_p^2 = \sum_{i=1}^{m} \sum_{j=1}^{m} P_i * P_j * \sigma_{i,j} \quad (11)$$

The portfolio risk (standard deviation) is given by the square root of the variance.

5.2 Optimal portfolio of lighting technologies

The solution to the mixed integer programming model is the optimal portfolio containing one 40 Watt IB, two 36 Watt FT, one 10 Watt CFL, four 13 Watt CFLs and one 18 Watt CFL (Table 8).

Table 8: Optimal Portfolio of lighting devices

Lighting Devices	Hours per day	Number Required	Investment (Rs.)	Annual Returns (Rs.)	Estimated Returns (%)	Expected Returns (%)	Risk (%)	Replacement Cycle (Yrs.)
IB-40	0.5	1	12	0.00	0.00	0.00	0.00	5.48
CFL-10	1	1	165	15.33	31.15	31.49	4.41	2.74
CFL-13	1.5	1	170	58.27	54.84	55.10	2.48	10.96
CFL-13	2	1	170	82.68	58.47	58.69	2.04	8.22
CFL-13	3	2	340	328.58	67.00	67.17	1.46	9.13
FT- 36	4	1	222	668.10	72.80	72.86	0.55	4.11
FT- 36	5	1	222	838.93	73.15	73.22	0.50	3.29
CFL-18	6	1	195	498.61	72.48	72.60	0.98	4.57
Total		9	1496	2490.50				

Note: Indian Rupees (in 2002 prices)

The initial investment required to have this portfolio is Rs. 1,496 and the annual returns are Rs. 2,490. This means that the expected rate of return on investment is about 166% with a payback period of 0.6 year. Within the portfolio, FT-36 provides the highest returns at five hours usage. Even though, IB provides no returns, it is included in the portfolio since the replacements are neither technically feasible nor provide positive returns at that usage level. The estimated portfolio return is 62.65%. The long-term expected portfolio return (estimated using the regression equations) is 62.81% with an associated risk level of 0.71%. Compared to this, the long-term investments in stock market provide only 13.62% returns with a very high risk of 20.89% (Table 9).

Table 9: Summary results of portfolio of lighting devices

Return on Investment (%)	166.48
Payback Period (Years)	0.60
Estimated Portfolio Returns (%)	62.65
Expected Portfolio Returns (%)	62.81
Portfolio risk (%)	0.71
Indian Stock Market Returns∗ (%)	13.62
Indian Stock Market Risk (%)	20.89

∗average for the years 1971-72 to 2001-05.

Figure 2 presents a comparison of estimated annual rates of return (actual and expected) from the replaced FT-36 and CFL-18 for five hours usage with those from the stock market for the years 1971-72 to 2001-02. For comparison, the approximate matching in terms of light output is obtained by considering the combination of 60 and 100 Watt IBs to be equal to one 36 Watt FT or two 18 Watt CFLs. From the figure one may observe a clear increasing trend in the cases of returns from FT-36 and CFL-18. Among the two, FT-36 consistently provides a higher rate of return. In comparison, the stock market returns show no particular trend and the

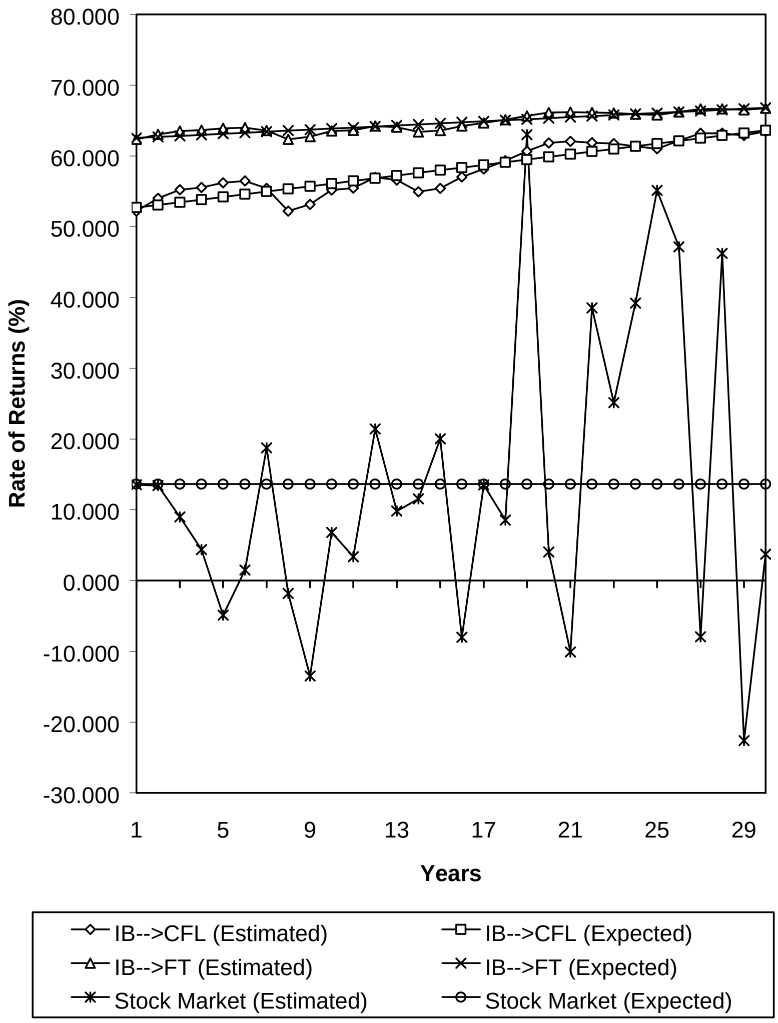


Figure 2. Annual Returns from retrofitted efficient lighting devices and stock market.

fluctuations are very high. This clearly shows that in the long run, investments in efficient lighting alternatives provide safe and high returns compared to the stock market.

6. Perspectives - Optimal And Other Scenarios

6.1 Customer Perspective

Implementation of efficient options reduces the energy bills of the consumer significantly. These savings by customers are determined by using a rate module that computes customers' bills for the standard technology and after the use of efficient technology (Reddy, 1996). The differences between the two are the savings for customers. In order to compare the overall performance of the optimal portfolio of lighting technologies (Optimal Case Scenario - OCS), two scenarios have been developed. The first one (Worst Case Scenario - WCS) considers the portfolio of only IBs to meet the demand for lighting and the second one, being the Medium Case Scenario (MCS) considers a possible mix of IBs and FTs. The results of this analysis are presented in Table 10.

Table 10: Optimal and probable portfolios of lighting in the residential sector of Maharashtra - Scenario results

Worst Case Scenario (WCS)				Medium Case Scenario (MCS)				Optimal Case Scenario (OCS)				Hours per Day
Devices	Capital Cost (Rs.)	Energy Cost (Rs.)	Energy (kWh)	Devices	Capital Cost (Rs.)	Energy Cost (Rs.)	Energy (kWh)	Devices	Capital Cost Rs.)	Energy Cost (Rs.)	Energy (kWh)	
IB-40	12	21.9	7.3	IB-40	12	21.9	7.3	IB-40	12	21.9	7.3	0.5
IB-40	12	43.8	14.6	IB-40	12	43.8	14.6	CFL-10	165	13.1	4.4	1
IB-60	12	98.6	32.9	IB-60	12	98.6	32.9	CFL-13	170	24.6	8.2	1.5
IB-60	12	131.4	43.8	IB-60	12	131.4	43.8	CFL-13	170	32.9	11.0	2
IB-(100+40)	25	459.9	153.3	IB-(100+40)	25	459.9	153.3	CFL-13 (two)	340	98.6	32.9	3
IB-100	26	876.0	292.0	FT-Tube-40	223	227.8	75.9	FT-Tube-36	222	201.5	67.2	4
IB-100	26	1095.0	365.0	FT-Tube-40	223	284.7	94.9	FT-Tube-36	222	251.9	84.0	5
IB-100	13	657.0	219.0	FT-Tube-40	223	341.6	113.9	CFL-18	195	131.4	43.8	6
Total	138	3383.6	1127.9	Total	742	1609.7	536.6	Total	1496	775.8	258.6	

According to the table, in terms of investment (total purchase cost of the devices) by the household, the requirement in WCS is Rs. 138 and for MCS it is Rs. 742 compared to Rs. 1,496 in the Optimal Case Scenario (OCS). However, in terms of annual energy costs, the cheapest alternative is provided by OCS with Rs. 776 compared to Rs. 1,610 for MCS and Rs. 3,384 for WCS. To find out the overall costs and benefits, the results obtained for a typical household is extended to the total residential sector of Maharashtra state (Table 11).

Table 11: Scenario Results for the Residential Sector of Maharashtra State (2001-02)

Domestic Consumers (No.)	9258154
Annual Consumption (GWh)	11901
Domestic Consumers with 10 lighting points (No.)	1851631
WCS - Consumption (GWh)	2088.36
MCS - Consumption (GWh)	993.49
OCS - Consumption (GWh)	478.84
Total Investment for OCS (Rs. Million)	2770.04

Here we have assumed that, out of a total of 9.26 Million domestic consumers, only 20% will have lighting points equal to 10. Thus the estimates made here for the total residential sector are only for these consumers. The annual energy savings that could be achieved by implementing OCS are about 1,609 GWh compared to WCS and about 514 GWh compared to MCS. This results in a cost savings of Rs. 3,129 Million and Rs. 1,029 Millions respectively at an average electricity price of Rs. 3.0/kWh. From the table it may be observed that the payback periods of around 0.8 and 1.36 years are quite attractive for a shift from either WCS or MCS to OCS (Table 12).

Table 12: Savings of OCS compared to WCS and MCS

	WCS	MCS
Energy saved (GWh)	1609.53	514.66
Cost of Energy saved (Rs. Million)	3129.05	1029.31
Additional Investment (Rs. Million)	2514.51	1396.13
Payback Period (Years)	0.78	1.36
Peak Demand Saved (MW)	882	282
Cost of Capacity Avoided (Rs. Million)	35277.27	11280.14

6.2 Power Utility Perspective

The average unit cost of electricity to the utility for sales to the consumer is calculated by dividing the total annual revenue requirement by the total annual generation. If the avoided costs associated with efficient technologies result in a decrease in average costs without increasing costs elsewhere in the system, the modification is desirable. The costs for various lighting technologies are compared with the average cost to the Maharashtra State Electricity Board (MSEB), which is Rs.2.00/kWh for the year 2001-02. Table 13 gives the estimated unit costs of energy saved for various devices in the optimal portfolio compared to the WCS and MCS portfolios. The unit costs vary from a low of Rs. 0.0/kWh (actually negative costs) to Rs. 1.50/kWh while the average being Rs. 0.13/kWh for WCS to OCS and Rs. 0.26/kWh for MCS to OCS shifts. These values indicate that the costs of efficient lighting options are significantly lower than the MSEB's average cost of generation. If the portfolio suggested by the OCS is implemented, the utility saves money on investments required for new capacity additions as well as costs of fuel for power generation. The total cost of energy saved due to OCS portfolio works out to about Rs. 3,129 Million and Rs. 1,029 Million respectively compared to WCS and MCS (at long run marginal cost of Rs. 2.00/kWh and without considering T&D system costs and loss component). Even with the lowest estimate, the peak demand saved works out to about 882 MW compared to WCS and 282 MW compared to MCS. This results in cost of capacity avoided equivalent of Rs. 35,277 Million and Rs. 11,280 Million respectively compared to WCS and MCS. These savings are very significant.

Table 13: Unit Cost of Energy Saved (Rs/kWh)

Devices	Energy Saved (kWh)		Incremental Cost (Rs.)		Unit Cost of Energy Saved (Rs./kWh)	
	WCS to OCS	MCS to OCS	WCS to OCS	MCS to OCS	WCS to OCS	MCS to OCS
IB-40	0.0	0.0	0	0	---	---
CFL-10	10.2	10.2	15.33	15.33	1.50	1.50
CFL-13	24.6	24.6	15.64	15.64	0.63	0.63
CFL-13	32.9	32.9	15.87	15.87	0.48	0.48
CFL-13 (two)	120.5	120.5	32.77	32.77	0.27	0.27
FT-36	224.8	8.8	6.42	-0.32	0.03	-0.04
FT-36	281.1	11.0	4.22	-0.39	0.02	-0.04
CFL-18	175.2	70.1	26.99	-6.54	0.15	-0.09
Total	869.2	277.9	117.25	72.36	0.13	0.26

The preceding results indicate that investments in efficient lighting technologies would reduce the need to construct new power plants. If these options is integrated into the supply-side process, the investment plans drafted by MSEB to meet anticipated loads will be properly altered.

7. Sensitivity analysis

In the previous analyses, the estimated risks associated with efficient lighting alternatives accounted only the variations in rates of return caused by the fluctuations in the cost of the devices and the price of electricity. In case of physical assets, unlike stocks, there are other parameters, which determine the level of returns. In our analysis, we have used some such parameters with assumed or actual values for estimating the relative annual returns from the usage of FTs and CFLs. Any changes in the values of these parameters will have direct impact on the estimated values of annual returns. For this, a sensitivity analysis is performed to study the impact of changes in these parameters on the annual returns obtainable from the retrofitting suggested by the optimal portfolio. This analysis is limited to assessing the sensitiveness of a given parameter (by making the changes in its value) on the value of rate of return. As mentioned earlier, the matching of devices is made based on the light output and the choices are IB-(60+100) to be replaced either by one FT-36 or two CFL-18. Five hours of usage per day is assumed for this analysis.

7.1 Effect of change in electricity price on annual returns

Figure 3 gives the estimates of annual returns from IB-(60+100) $\rightarrow$ FT-36 and IB-(60+100) $\rightarrow$ CFL-(18*2) replacements for different changes in the electricity prices. It may be observed from the figure that the replacements provide positive returns and increase with the

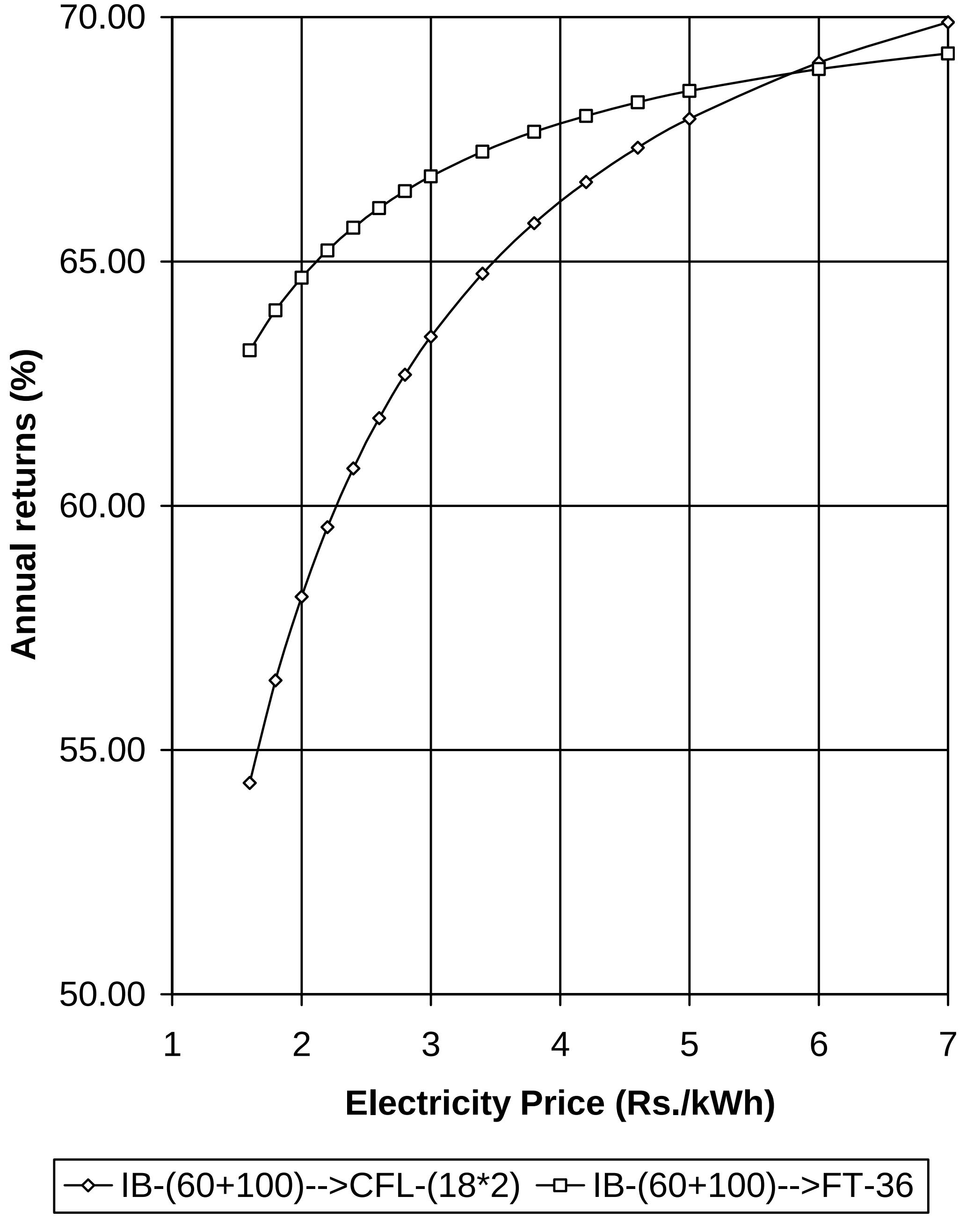


Figure 3. Effect of change in electricity price on annual returns.

increase in energy price while tending towards saturation. Beyond the price of Rs. 6.00/kWh, CFL-18 gives more returns compared to FT-36.

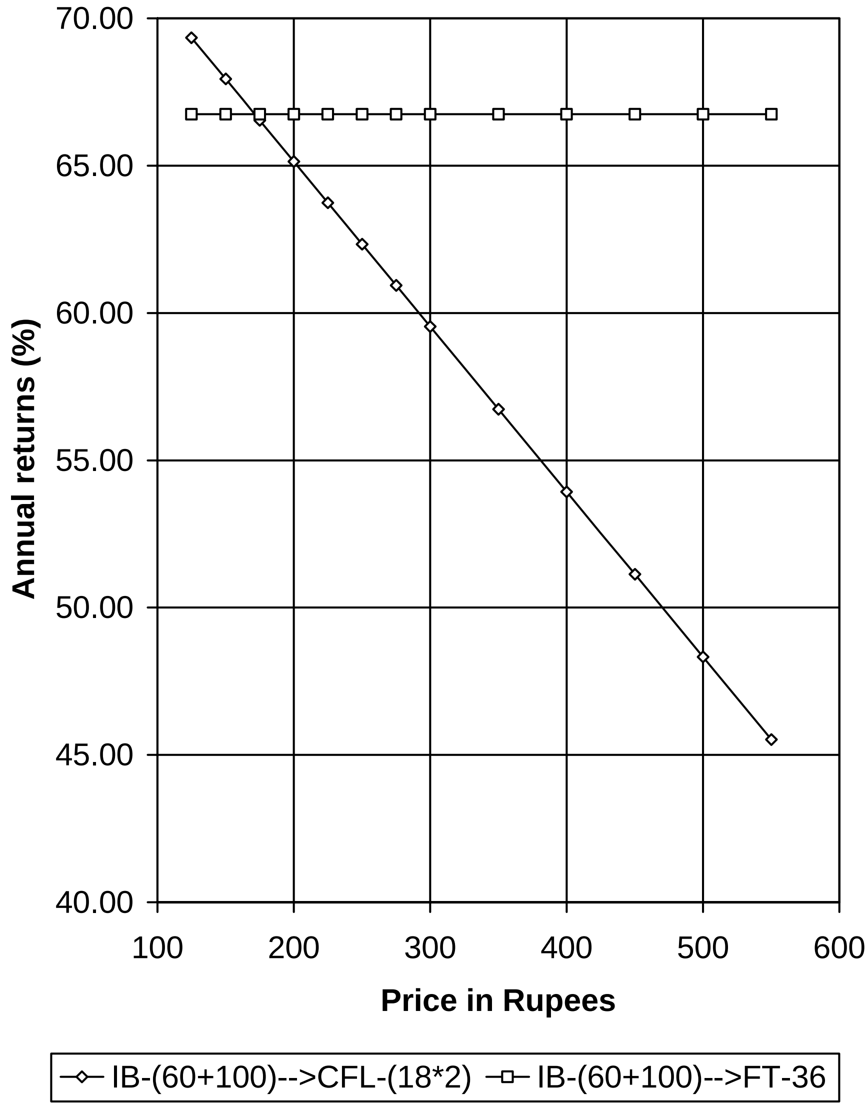


Figure 4: Effect of change in the price of CFL on annual returns

7.2 Effect of change in the cost of CFLs on annual returns

The high cost of CFLs has significant influence on the annual rate of return. The cost of CFLs used to be quite high in India because of high customs duty and low sales volume. However, with the setting up of manufacturing facilities within the country and sales level going up, the prices have declined significantly. Figure 4 clearly shows that, the returns from CFL-18 are more than that from FT-36 if the price of CFL-18 is below Rs. 175 (Rs. 350 for two CFLs).

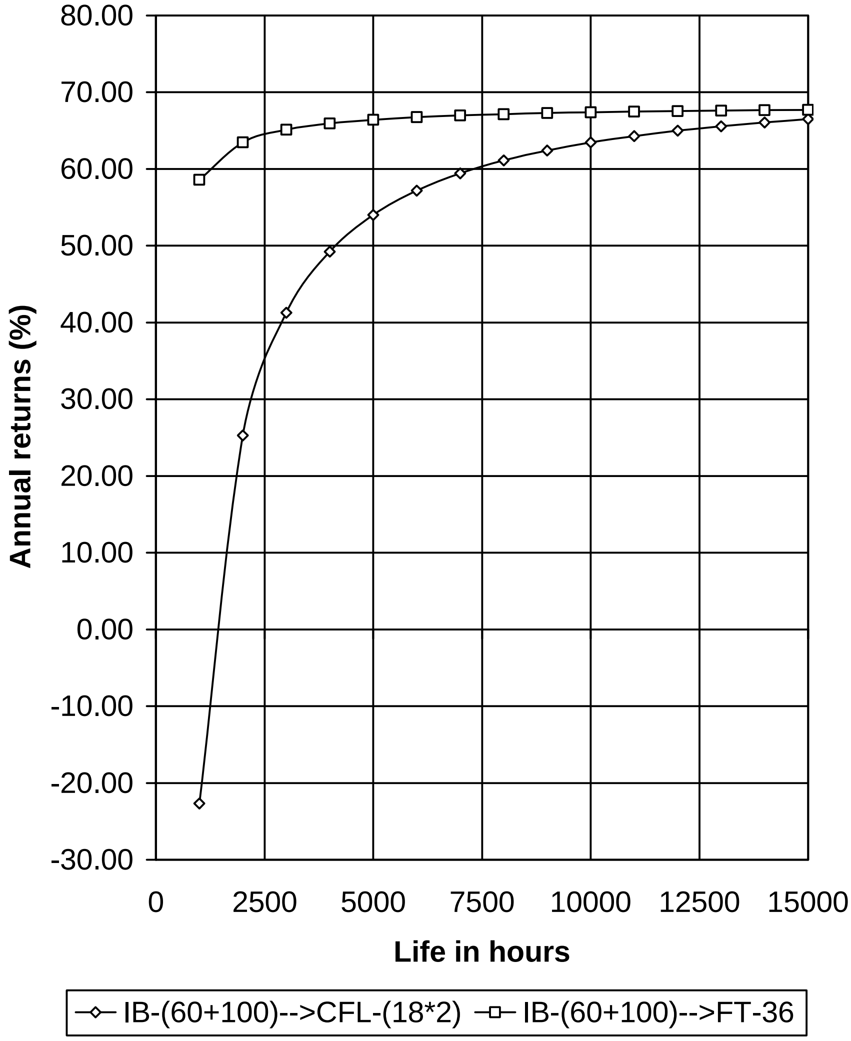


Figure 5. Effect of change in the life of lighting devices on annual returns

7.3 Effect of change in the life of CFLs on annual returns

The CFLs are designed to work in the stable range of voltage. However, in India, the fluctuations vary from 190V - 260V. Despite their design to cope with the fluctuations, the survival of CFLs have not been adequately tested in the field. Lab tests in India have reported that the life of CFL is about 10,000 hours. It may be observed (Figure 5) that shifting of IB-(60+100) to CFL-(18*2) starts providing positive returns once the life exceeds 1,300 hours.

However, in comparison, FT-36 gives higher returns than CFL-18 and they appear to converge as lifespan increases.

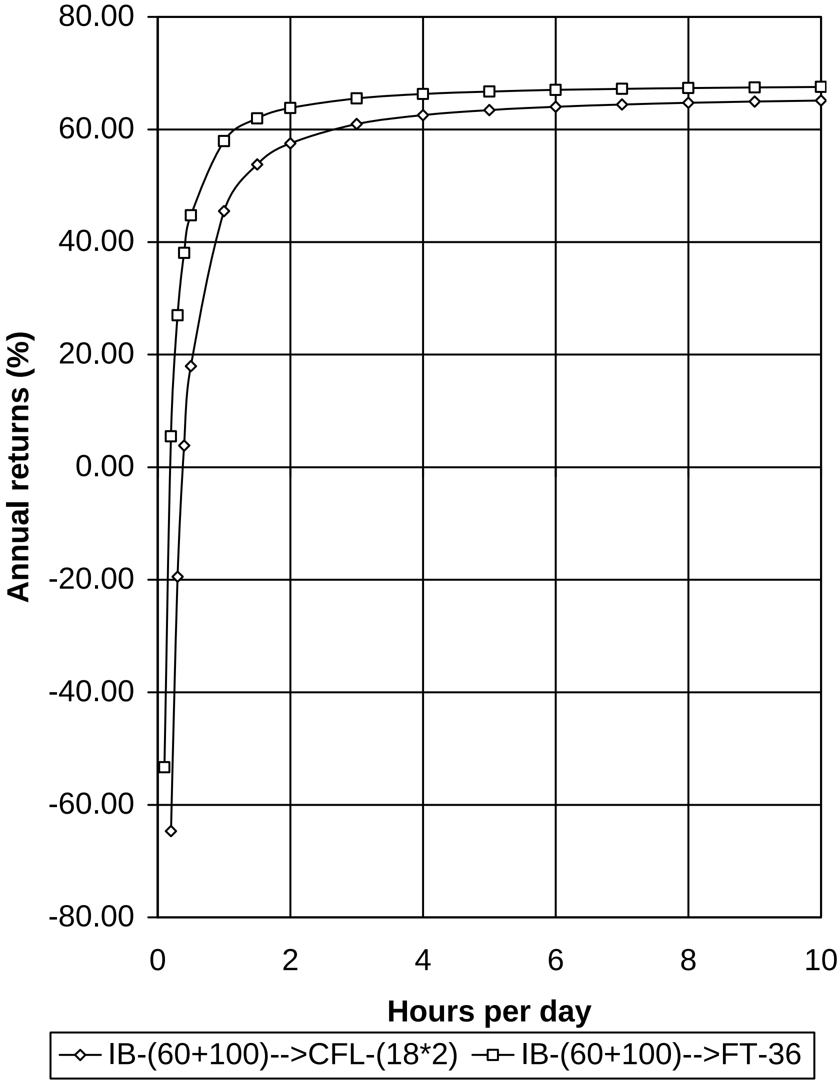


Figure 6. Effect of change in daily hours of usage on annual returns

7.4 Effect of change in daily hours of usage on annual returns

Another important parameter, which affects the annual returns, is the daily hours of usage of lighting devices. From Figure 6, it can be observed that one can expect positive returns

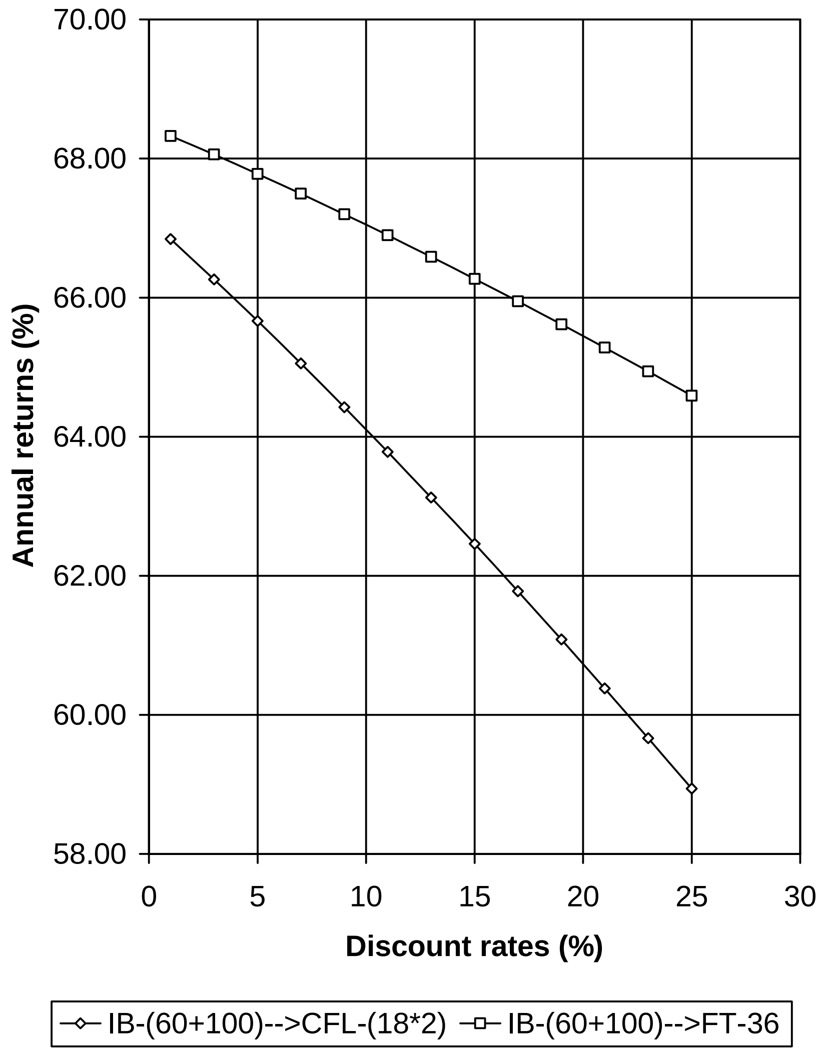


Figure 7. Effect of change in discount rates on annual returns

from FT-36 and CFL-18 if daily usage hours are more than 0.2 and 0.4 respectively. With the present level of device costs and electricity prices, the returns from FT-36 always exceed that of CFL-18.

7.5 Effect of change in discount rates on annual returns

For estimating the relative annual returns we have used a discount rate of 12 per cent. Any change in this value will influence changes in annual returns. This is being reflected in

Figure 7, which clearly shows that there is a strong relationship between annual returns and the discount rates. A decline in annual returns can be observed with the increase in discount rates. A high discount rate indicates that the present value of costs is very high compared to future benefits (or inflows). The decline in returns from IB-(60+100) shift to CFL-18 is more rapid then that from shift of IB-(60+100) to FT-36 since CFL has a high initial cost.

6 Conclusions

This paper attempts to construct an optimal portfolio of lighting technologies for a typical household in the State of Maharashtra, India. Initially, 11 feasible alternatives of FT and CFL for the replacements of inefficient IBs were identified. The relative annual rates of return for these alternatives are estimated from 1971-72 to 2001-02. Using regression models, the long term expected rates of return and the associated risks are estimated which are compared to the average stock market returns and risks. A mixed integer-programming model has been developed to determine an optimal portfolio of the alternatives. A sensitivity analysis is performed to study the effects of changes in various parameters on the rates of return from the efficient alternatives of the portfolio. Finally, a comparison is made of the optimal scenario with two probable scenarios and the results are extended to estimate the cost and benefits that could accrue to the residential sector of Maharashtra state and the society as a whole.

The comparison of three lighting technologies indicates that, though expensive, the CFLs are a quite attractive proposition in terms of returns compared to IBs while the FT variants are quite close to CFLs. The advantages with FTs are that they provide the returns at lower risk levels compared to those of CFLs. With the expected increase in electricity prices and the declining CFL costs makes them highly attractive investment proposals. The results also show that the optimal lighting portfolio provides a far higher return at a lower risk compared to the stock market. The overall results indicate a substantial savings both in terms of energy and peak demand for the state.

Nomenclature

C_{it} = Purchase cost of device *i* in the year *t*

C_i = Cost of device *i* in reference year (i.e., 2001-02)

$P.I_t$ = Wholesale price index value in the year *t*

P.I = Wholesale price index in the reference year (2001-02)

p_t = Electricity price in the year *t*

p = Electricity price in the reference year (i.e., 2001-02)

$E.P_t$ = Electricity price index value in the year *t*

E.P = Electricity price index in the reference year (2001-02)

A_i = Annual cost of utilising the device type *i*

d = Discount Rate in per cent

n = Life of the Device in years

E_i = Electricity consumption per year by the device *i*

PV = Present Value

i = Type of original lighting device, i = 1, 2, …., I

j = Type of replaced lighting device, j = 1, 2, …., J

k = Type of usage hours, k = 1, 2, ….., K

C_{ik} = Annual cost of utilisation of original device `i' for `k'th usage hours

C_{jk} = Annual cost of utilisation of replaced device `j' for `k'th usage hours

$N_{i\rightarrow j,k}$ = Number of replaced lighting devices of type `j' used for `k'th usage hours

$OC_{i\rightarrow j,k}$ = Opportunity cost of not using the appropriate device for `k'th usage hours

N_k = Minimum number of lighting devices for `k'th usage hours

N = Maximum number of lighting devices in a given household

$L_{i \to j}$ = Lighting levels (Flux in Lumens) given by the lighting device

L_k = Minimum lighting level required where the duration of usage type is `k'

$EC_{i \to j}$ = Extra cost needs to be incurred for adopting higher wattage device

$OC_{i \to j}$ = Opportunity cost of using inappropriate device

R_p = Portfolio rate of return

R_i = Expected rate of return on asset *i*

P_i = Proportion of asset *i* in total investment

m = Total number of assets in the portfolio

σ_p^2 = Portfolio variance

P_j = Proportion of asset *j* in total investment

$\sigma_{i,j}$ = Covariance

$\sigma_{i,i}/\sigma_i^2$ = Variance

References

Dutt, G.S. (1994) ‘Illumination and sustainable development: part I’, *Energy for Sustainable Development*, Vol. 1, No. 2, pp.21-33.

Gadgil, A.J. and Jannuzzi, G.D.M. (1994) ‘Conservation potential of compact fluorescent lamps in India and Brazil’, *Energy Policy*, Vol. 19, No. 5, pp.449-463.

Johnson, B.E. (1994) ‘Modeling energy technology choices’, *Energy Policy*, Vol. 22, No. 10, pp.877-883.

Levy, H. and Sarnat, M. (1994) *Capital investment and financial decisions*. London: Prentice Hall.

Metcaff, G.E. (1994) ‘Economics and Rational Conservation Policy’, *Energy Policy*, Vol. 22, No. 10, pp.819-825.

Sutherland, R.J. (1986) ‘A Portfolio Analysis Model of the Demand for Nuclear Power Plants’, *Energy Economics*, Vol. 8, No. 4, pp.218-226.

Sutherland, R.J. (1991) ‘Market barriers to energy-efficiency investments’, *The Energy Journal*, Vol. 12, No. 3, pp.15-34.

Sudhakara Reddy B. (1995) ‘Appliance Electricity Consumption in the Residential Sector: An Economic Approach’, *Energy Sources*, Vol. 17, No. 2, pp.179-193.

Sudhakara, Reddy B. (1996) ‘Consumer Discount Rates and Energy Carrier Choices in Urban Households’, *International Journal of Energy Research*, Vol. 20, No. 4, pp.187-195.

Sudhakara Reddy, B. (1996) ‘Economic evaluation of Demand Side Management Programmes’, *Energy- The International Journal*, Vol. 21, No. 6, pp.473-482.