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Parameters optimization and simulation of highway tunnel offset-of-vault lamp distribution lighting with LED

Optimizing lamp installation parameters (LIPs) can save energy of tunnel lighting system, but a few studies are available in this respect. The parameters optimization model (POM) of offset-of-vault lamp distribution (OLD) lighting system for tunnel interior zone was established to acquire the most energy-saving LIPs. Yanlieshan tunnel was taken as an example for the optimization, the optimial LIPs of the OLD lighting system of the tunnel interior zone were obtained by the POM. A comparison between the optimization results and that of Yanlieshan tunnel's actual lighting system was performed, which showed that the optimized OLD lighting system with LED lamps installed according to the optimized LIPs could save energy remarkably even under full-capacity lighting condition. Illuminance and illuminance uniformity of the tunnel road surface still met lighting demands even the LED lamps' luminance decreased by 30%. An OLD lighting simulation experiment with the optimized OLD LIPs for Yanlieshan tunnel was accomplished in the software Dialux, the simulation results basically agreed with the optimization calculated results from the POM, which proved the correctness of the OLD POM.

Keywords: Tunnel lighting, parameters optimization, offset-of-vault lamp distribution,, energy-saving.

1.0 Introduction

By the end of 2016, total length of all highway tunnels in China reached 14039.7km, the total length of long and extra-long tunnels was 9668.2km [1]. Lighting facilities should be installed in the tunnels longer than 100m in China [2]. Power consumption of lighting system in highway tunnels was high and the cost was huge [3]. The power consumption statistics of highway tunnels in Chongqing showed that the electricity cost per kilometer in tunnel was more than 4×10^5 yuan in one year [4], on the basis of this criterion, the total electricity cost of all highway tunnels in China was more than 5.61 billion yuan in 2016. Energy-saving of tunnel lighting has become an economic problem that must be paid attention to in China. How to reduce power consumption has become an urgent problem. Optimizing light intensity distribution [5], using energy-saving lamps [6], optimizing lamp installation parameters (LIPs) and intelligently controlling lighting system are able to save energy of tunnel lighting. In recent years, most energy-saving studies on tunnel lighting were mainly focused on intelligent control of lamps, but a few studies are available on the optimization of LIPs.

Pachamanov and Pachamanova [7] established an optimization model of tunnel lighting and obtained the optimal LIPs with fixing lamp power. Ren and Han[8] performed energy-saving experiments of the lamp installation height and elevation angle with LED lamps and obtained the optimal lamp-distribution-style (LDS). Ji [9] performed simulations with LED lamps and high pressure sodium (HPS) lamps about the influences of LDS and LIPs on lamp utilization factor, average illuminance and overall illuminance uniformity of tunnel road surface. But Ren and Ji did not establish the parameters optimization model (POM) [8-9]. Li et al.[10] established an intelligent optimization model of tunnel lighting based on genetic algorithms to optimize the illuminance distribution of every lamp, with minimum energy consumption of the lighting system as objective function, and gave simulated optimization results. Yang[11] established a POM for backlighting system of highway tunnel, and compared the optimized results and simulated optimization results. However, few studies were about the installation parameters optimization of offset-of-vault lamp distribution (OLD) lighting of highway tunnel, which is a common LDS.

An OLD lighting POM for tunnel interior zone will be established, with lamp installation height, longitudinal installation spacing, offset-of-vault distance, elevation angle and power as optimization parameters, with minimum total power consumption of the OLD lighting system as objective function. Yanlieshan tunnel of Jiujing highway will be taken as an example for optimization with the OLD lighting POM, and an OLD lighting simulation experiment with the optimized LIPs for Yanlieshan tunnel will be taken in software Dialux to

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verify the correctness of the OLD lighting POM.

2. Parameters optimization model

2.1. Illuminance of road surface

When lamp is installed with elevation angle, ξ, in Y direction (Fig.1), the horizontal illuminance generated by the lamp at point $b(x,y)$ is [11]

$$E_b = \frac{I_c(\gamma,\theta)h}{(x^2+y^2+h^2)^{1.5}} \qquad \text{... (1)}$$

where, E_b is the horizontal illuminance generated by one lamp at the point $b(x,y)$ of the road surface; h is the installation height of the lamp; γ is the intersection angle of light ray Ab and optic axis AO_1 of the lamp; θ is the intersection angle between the plane AOC and the plane AbO_1; $I_c(\gamma,\theta)$ is the luminous intensity of the lamp in the direction of light ray Ab.

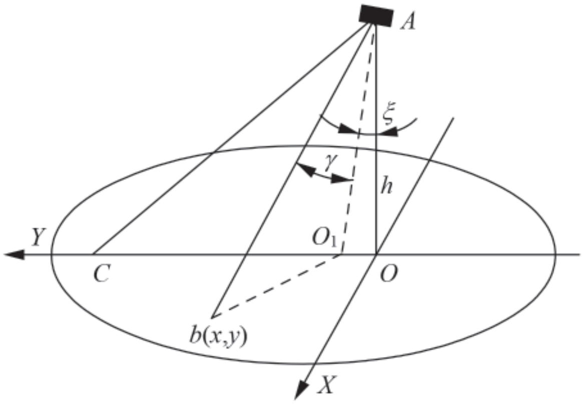

Fig.1: Lighting schematic diagram of one lamp

2.2. Luminous intensity of lamp

If photomatric data of lamp are available, the luminous intensity of the light-direction Ab deviating γ from the optic axis of the lamp is calculated as [11]

$$I_c(\gamma,\theta) = \frac{I_{1000}(\gamma,\theta)\eta\eta_0 M\phi}{1000} \qquad \text{... (2)}$$

where, $I_{1000}(\gamma, \theta)$ is the luminous intensity of the lamp from the photomatric data corresponding to γ and θ; η is light output rate of the lamp; η_0 is utilization factor of the lamp; M is maintenance factor of the lamp; ϕ is the rated luminous flux of the lamp, $\phi=pq$, p is the power of the lamp, q is luminous efficiency of the lamp.

2.3. Offset-of-vault lighting

Offset-of-vault lighting is a common kind of LDS that the lamps are installed with offset from the centerline of vault, which has the advantages of center lamp distribution(CLD) and has not the disadvantage of inconvenient maintainence of CLD[12].

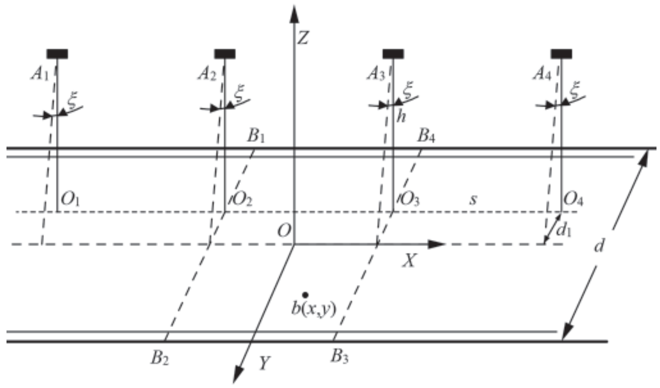

Fig.2: Schematic diagram of tunnel OLD lighting and the Cartesian coordinates system

As shown in Fig.2, A_1~A_4 are adjacent lamps, they have the same type, same power, p, same installation height, h, same longitudinal installation spacing, s, same offset-of-vault distance, d_1, and same elevation angle, ξ. O_1~O_4 are the corresponding points of A_1~A_4 on the road surface, respectively; d is the total width of the tunnel road surface including the width of sidewalks. The region of $B_1B_2B_3B_4$ between the two adjacent lamps A_2 and A_3 was taken as calculation region. A three-dimension Cartesian coordinates system was established with the longitudinal centerline of road surface as the X-axis, the crosswise direction as the Y-axis, the vertical direction as the Z-axis, and the central point, O, of the calculation region $B_1B_2B_3B_4$ as the original point, and is showed in Fig.2.

The overall horizontal illuminance at the point $b(x,y)$ is calculated as

$$E_b = \sum_{i=1}^{4} E_{bi} \qquad \text{... (3)}$$

where, E_{b1}~E_{b4} are the horizontal illuminance at the point $b(x,y)$ generated by the four lamps A_1~A_4, respectively, calculated as

$$E_{b1} = \frac{I_c(\gamma_1,\theta_1)h}{\cos\xi[(1.5s+x)^2+(d_1+y)^2+h^2]} \cdot \frac{\sin\gamma_1}{[(1.5s+x)^2+(d_1+y-h\tan\xi)^2]^{0.5}} \qquad \text{... (4)}$$

$$E_{b2} = \frac{I_c(\gamma_2,\theta_2)h}{\cos\xi[(0.5s+x)^2+(d_1+y)^2+h^2]} \cdot \frac{\sin\gamma_2}{[(0.5s+x)^2+(d_1+y-h\tan\xi)^2]^{0.5}} \qquad \text{... (5)}$$

$$E_{b3} = \frac{I_c(\gamma_3,\theta_3)h}{\cos\xi[(0.5s-x)^2+(d_1+y)^2+h^2]} \cdot \frac{\sin\gamma_3}{[(0.5s-x)^2+(d_1+y-h\tan\xi)^2]^{0.5}} \qquad \text{... (6)}$$

$$E_{b4} = \frac{I_c(\gamma_4,\theta_4)h}{\cos\xi[(1.5s-x)^2+(d_1+y)^2+h^2]} \cdot \frac{\sin\gamma_4}{[(1.5s-x)^2+(d_1+y-h\tan\xi)^2]^{0.5}} \qquad \text{... (7)}$$

where, γ_1-γ_4 are the intersection angles between light from lamps A_1-A_4 to the point b and the optic axis of corresponding lamp A_1-A_4, respectively, calculated as

$$\gamma_1 = \arccos\frac{h\cos\xi + (d_1 + y)\sin\xi}{[(1.5s + x)^2 + (d_1 + y)^2 + h^2]^{0.5}} \quad ... (8)$$

$$\gamma_2 = \arccos\frac{h\cos\xi + (d_1 + y)\sin\xi}{[(s/2 + x)^2 + (d_1 + y)^2 + h^2]^{0.5}} \quad ... (9)$$

$$\gamma_3 = \arccos\frac{h\cos\xi + (d_1 + y)\sin\xi}{[(s/2 - x)^2 + (d_1 + y)^2 + h^2]^{0.5}} \quad ... (10)$$

$$\gamma_4 = \arccos\frac{h\cos\xi + (d_1 + y)\sin\xi}{[(1.5s - x)^2 + (d_1 + y)^2 + h^2]^{0.5}} \quad ... (11)$$

θ_1-θ_4 are the intersection angles between the cross-section C0-C180 of each lamp and the plane composed by the light from corresponding lamp to the point *b* and the optic axis of corresponding lamp, respectively, calculated as

$$\sin\theta_1 = \frac{1.5s + x}{\sin\gamma_1 \cdot [(1.5s + x)^2 + (d_1 + y)^2 + h^2]^{0.5}} \quad ... (12)$$

$$\sin\theta_2 = \frac{s/2 + x}{\sin\gamma_2 \cdot [(s/2 + x)^2 + (d_1 + y)^2 + h^2]^{0.5}} \quad ... (13)$$

$$\sin\theta_3 = \frac{s/2 - x}{\sin\gamma_3 \cdot [(s/2 - x)^2 + (d_1 + y)^2 + h^2]^{0.5}} \quad ... (14)$$

$$\sin\theta_4 = \frac{1.5s - x}{\sin\gamma_4 \cdot [(1.5s - x)^2 + (d_1 + y)^2 + h^2]^{0.5}} \quad ... (15)$$

2.4. Optimization model

The design performance indexes of lighting system for tunnel interior zone based on Ref. [2] are provided as follows.

(1) Strobe frequency, *f*, should meet the requirement of $f < 2.5$Hz or $f > 15$Hz. $f = v/s$, where, *v* is the traffic speed, *f* is set as $f < 2.5$Hz for the tunnel interior zone in this work.

(2) The luminance of road surface for the tunnel interior zone should not be less than specified minimum value under the condition of set driving speed and traffic volume.

(3) The overall and longitudinal luminance uniformity of the tunnel road surface should not be less than the values given in specification.

In addition, at least 0.4m spacing should be reserved between the lamp and the tunnel wall to install the luminaire.

The OLD lighting POM of tunnel interior zone was established as

$$\min P = n \cdot p = 2Lp/s$$

$$st.\begin{cases} (h-2)\tan(\beta+\xi) \ge 0.5d + d_1 \\ (h-2)\tan(\beta-\xi) \ge 0.5d - d_1 \\ v/2.5 \le s \le 2(h-2)\tan\alpha \\ h_{\min} \le h \le h_{\max} \\ d_1 \ge 0 \\ \xi \ge 0 \\ E_{\min} \ge \max(E_0, U_0 E_{av}) \\ E_{c\min} \ge \max(E_0, U_1 E_{c\max}) \\ d_1^2 + (h-2)^2 \le 25 \end{cases} \quad ... (16)$$

where, h_{min} is the minimum value of the installation height of lamp; h_{max} is the maximum value of the installation height of lamp; *n* is the number of lamps; *P* is the total power of *n* lamps; *L* is the length of the tunnel interior zone; E_0 is the minimum illuminance to meet the traffic requirements for tunnel interior zone; E_{min} is the minimum illuminance of the tunnel road surface; E_{cmin} is the minimum illuminance of the tunnel road surface centerline; E_{cmax} is the maximum illuminance of the tunnel road surface centerline; U_0 is the required overall luminance uniformity of the tunnel road surface; U_1 is the required longitudinal luminance uniformity of the tunnel road surface centerline; E_{av} is the horizontal average illuminance of the road surface.

2.5 Tunnel for optimization

Yanlieshan tunnel of Jiujing highway was taken as example for optimization, which was designed as one-way and double holes and consisted of tunnel #1 and tunnel #2. The tunnel #2 was selected as study object, it is 1819m long and its interior zone is 1383m long. The designed traffic volume is greater than 1200 vehicles per hour, designed driving speed is 80 km/h. The total width of the tunnel road is 10.25m; it has two traffic lanes and each is 3.75m wide; the clear height of the tunnel hole is 7.425m. There is 0.5m wide marginal strip at each roadside in the tunnel, 1m wide maintaining roadway at one roadside and 0.75m wide maintaining roadway at the other roadside for the requirements of traffic safety and maintenance[13]. The cross section of the tunnel hole is circular arch with radius of 5.4m. Cement concrete was paved on the tunnel road surface.

Based on Ref. [2], U_0 is 0.4, U_1 is 0.6, the required luminance value for tunnel interior zone is 3.5 cd/m^2. Cement concrete was paved on the tunnel road surface, the conversion relationship between the average illuminance and average luminance is 10 lx/(cd · m^{-2}), so E_0 is 35 lx. The value range of luminaire installation height in the optimization model is from 5 to 7 m to ensure vehicles to pass through the tunnel safely, so, h_{min} was set 5m and h_{max} was set 7m in the POM.

3. Optimization and analysis

3.1. Adopted LED lamp

NVC LED lamp (NHLED101~103) were adopted in this optimization. For NHLED101~103 lamp series, q=100 lm/W, the light-emitting angle is 120°, η=100%. the light distribution curve (LDC) of the NHLED102120W120deg lamp is showed in Fig.3. It can be observed that the LDC in cross-section C0-C180 is close to the LDC in cross-section C90-C270, so the LDC of the LED lamp was treated as full axial symmetric for simplification. M was set 0.7, η_0 could be 0.8~0.913 [14-15], 0.87 was set to η_0 in this optimization.

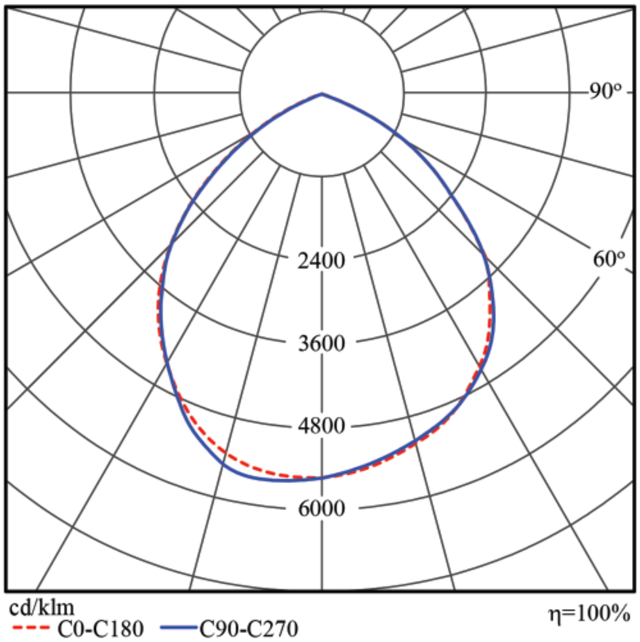

Fig.3: Light distribution curve of LED lamp

3.2. Optimized results and analysis

Optimized LIPs of the OLD lighting with the LED lamps in the tunnel interior zone with different offset-of-vault distance, d_1, were obtained and listed in Table 1. As seen from Table 1, with increasing of d_1 in the range of 0m to 2.5m, the lamp installation height, h, decreases, the elevation angle, ξ, of the LED lamp increases, the power of one LED lamp and total power increases. No optimal solution could be obtained by the POM when d_1 is greater than 2.5m.

Obviously, when ξ=0° and d_1=0m, the LDS is center lamp distribution (CLD), that means that CLD is more energy-saving than OLD.

The optimized parameter values while d_1=1m were adopted as the LIPs, the power of one lamp and total power of the original lighting system with HPS lamps, the transformed lighting system with electromagnetic induction (EI) lamps [16] and the optimized lighting system with LED lamps (with optimized parameter values from Table 1) were listed in Table 2. As seen from Table 2, the original HPS lighting system consumes most electric energy, the transformed EI lighting system can save 20% of electric energy than the HPS lighting system only by replacing the 100W HPS lamps with 80W EI lamps, and the optimized OLD lighting system with 110W LED lamps can save 38% of electric energy than the transformed EI lighting system and can save more 50% of electric energy than the HPS lighting system even the optimized lighting system with LED lamps works at full capacity. The energy-saving effect of the optimized lighting system is remarkable.

Table 2: Total power consumption comparisons of three lighting systems

Lamp	LDS	s [m]	n	p [W]	P [kW]
LED	offset-of-vault	8.89	156	110	17.16
EI	symmetric	8	346	80	27.68
HPS	symmetric	8	346	100	34.60

4.0 Simulation

In order to verify the correctness of the POM, a simulation tunnel model was built in the software Dialux based on the structural parameters of Yanlieshan tunnel, and an OLD lighting system was established in the tunnel model based on the optimized LIPs. NVC NHLED102 120W/120° was adopted in the simulation lighting system. For the adopted LED lamp, p is 120W. For the simulation lighting system, s is 8.89m, h is 6.9m, d_1 is 1m and ξ is 11°. The calculation region was divided by 10 in both X-direction and Y-direction, the simulated illuminance values of the tunnel road surface (11×11 calculation points in all) were obtained by the simulation lighting system and listed in Table 4. Fig.4 showed the lighting effect of the optimized OLD lighting system with LED lamps.

Table 1: Optimized parameter values of OLD lighting with different offset-of-vault distance

d_1 [m]	s [m]	h [m]	ξ [°]	p [W]	n	P [kW]
0.0	8.89	7.00	0	0	107	16.692
0.5	8.89	6.97	5.5	108	156	16.848
1.0	8.89	6.90	11	110	156	17.160
1.5	8.89	6.77	16.5	114	156	17.784
2.0	8.89	6.58	22	119	156	18.564
2.5	8.89	6.33	27	126	156	19.656
>2.5	No optimal solution					

Table 3: Simulated results of the calculation region

E_{min} [lx]	E_{cmin} [lx]	E_{cmax} [lx]	E_{av} [lx]	U_0	U_1
54	99	124	91.05	0.593	0.798

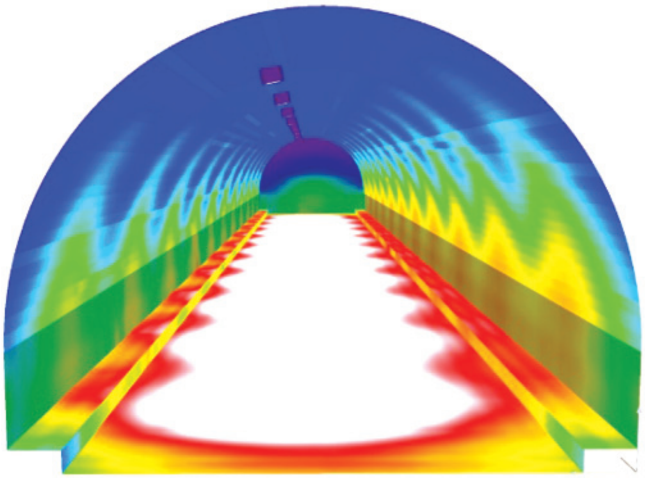

Fig.4: Lighting effect of the optimized OLD lighting system with LED lamps

From Table 4, it can be observed that the tunnel lighting is "over-illumination" when the LED lamps work at full capacity. The optimal OLD lighting system with LED lamps still meets the tunnel lighting demands when the LED lamps' luminance decrease by 30%, the corresponding power of one LED lamp is 77W, which means some measures can be taken to control the 110W LED lamp's output power to 77W until the LED lamp's real luminous efficiency decreases to 70% of its original luminous efficiency. Under this controlled condition, the total power of the optimized OLD lighting system with 110W LED lamps is 12.012kW, which is 43.4% of total power of the transformed EI lighting system (meaning to save 56.6% of energy) or 34.7% of total power of the HPS lighting system (meaning to save 65.3% of energy), the energy-saving effect of the optimized lighting system is more remarkable.

6.0 Conclusions

An OLD lighting POM for tunnel interior zone was established and applied to optimize the lighting system of Yanlieshan tunnel interior zone. The illuminance and illuminance uniformity of the tunnel road surface meet the tunnel lighting requirements

Table 4: Illuminance and illuminance uniformity of the tunnel road surface with the optimized lighting parameter values

	E_{min} [lx]	E_{cmin} [lx]	E_{cmax} [lx]	E_{av} [lx]	U_0	U_1
Optimized values	51.19 (35.83)	88.25(61.78)	107.5(75.25)	78.93(55.25)	0.648	0.822
Simulated values	49.5(34.65)	90.75(63.53)	113.7(79.59)	83.46(58.42)	0.593	0.798
Demands				> 35	>ˇ 0.4	>ˇ 0.6

5.0 Results and discussion

The simulated illuminance data of the tunnel road surface with 110W LED lamps could be obtained by multiplying the data in Table 4 by (110/120). The optimized illuminance and illuminance uniformity and simulated values with the same LIPs were listed in Table 5, the data in round brackets were the estimated values after the LED lamps' luminance decreased by 30%.

As seen from Table 4, if the optimal OLD lighting system was adopted, the optimization calculated illuminance, illuminance uniformity, the simulated illuminance and illuminance uniformity of the tunnel road surface all met tunnel lighting demands before the LED lamps' luminance decreased by 30%. When the LED lamps' luminance decreased by 30%, only the simulated minimum illuminance (at the roadside) was bit less than 35lx, which did not influence the traffic safety, and all other illuminance values met tunnel lighting demands. The optimization calculated values basicly agree with the simulated values, the maximum error between the simulated values and the optimization calculated values is less than 5.5%.

Except the minimum illuminance, other simulated illuminance values are bit greater than optimization calculated values, the causes maybe: (1) some light were reflected to the tunnel road surface by the tunnel walls in simulation, however, light reflection was not considered in the POM. (2) the utilization factor of the lamp changed while LIPs changed, error may be caused while it was treated as a constant.

while the LED lamp's luminance decrease is less than 30% of its original luminance. Compared to the original LDS with HPS lamps and the transformed LDS with EI lamps, the energy-saving effect of the optimized OLD lighting with LED lamps is remarkable, even the optimized OLD lighting system works at full capacity.

The simulation experiment for the optimized OLD lighting LIPs completed in the software Dialux proves the correctness of the OLD lighting POM.

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(Continued from page 166)

States have initiated process for determining the tariff. Ministry of Power has revised the Tariff Policy 2006 vide resolution dated 28.01.2016, under the Indian Electricity Act, 2003, making it mandatory for State DISCOMS to purchase power from waste-to-energy plants [10].

4.0 Conclusion

Considering the present trend of rapid urbanization, lack of source segregation and suitable technology, scientific disposal of waste generated in the country is a major point of concern. However, awareness towards safe disposal of waste, viability of WtE plant and selection of appropriate technology according to waste characteristics is important. At the outset any waste to energy plant shall primarily aim at disposing the waste in a scientific manner. During that process, if any net energy is available, that is to be considered as incentive only rather than generating energy from waste for commercial sale. Further, a technology development that is suitable for Indian conditions needs to be promoted to achieve cost effective solution.

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