J. Inst. Eng. India Ser. B (December 2019) 100(6):541–550
https://doi.org/10.1007/s40031-019-00419-7

ORIGINAL CONTRIBUTION

A Proposal to Adjust the Time-Keeping Systems for Savings in Cycling Operation and Carbon Emission

Amlan Chakrabarti[1] · **Krishnendu Chakrabarty**[2]

Received: 28 August 2017 / Accepted: 28 June 2019 / Published online: 11 July 2019

Abstract With the spread of the power transmission networks to thousands of kilometres, the integrated power grid in many countries cover multiple hours in terms of solar position. We present a general mathematical model with multiple time-keeping systems for flattening the electrical load curve in a territory having integrated power grid operations. The multiple time-keeping system areas are set up as a function of both electrical power demand and mean geographical position in longitude. Fluctuation in load results in cycling operation of coal/gas power plants and enhanced carbon emission. In this paper, an attempt is made to quantify the savings in cycling of electrical power plant operation and the associated carbon emission with adjustment of time-keeping systems. For the territory of India, the reduction in cycling operation of power plants by 9% of peak demand is demonstrated.

Keywords Carbon emission · Time-keeping systems · Peak demand · Cycling operation · Natural Gas Combined Cycle (NGCC)

Abbreviations

PD1	Peak demand with one time zone (MW)
BD1	Base demand with one time zone (MW)
PD3	Peak demand with three time zones (MW)
BD3	Base demand with three time zones (MW)
PR	Peak reduction (MW)
CR	Reduction in cycling operation (MW)
DD	Differential peak demand (MW)
LCR	Load cycling rate
PRR	Peak reduction rate
CRR	Cycling reduction rate
P_{LOSS}	Additional transmission loss in MW per day for transfer of cycling power among time zones
B	Savings in cycling operations in MW capacity per day
C1	Savings in heating value by reduction in cycling operation for coal units (GJ/day)
D1	Savings in carbon emission by reduction in cycling operation for coal units ($\mathrm{MtCO_2}$/year)
C2	Savings in heating value by reduction in cycling operation for NGCC units (GJ/day)
D2	Savings in carbon emission by reduction in cycling operation for NGCC units ($\mathrm{MtCO_2}$/year)
CM1	Additional capital and maintenance cost for coal units with high ramp rate to meet peak demand (US$)
CM2	Additional capital and maintenance cost for NGCC units with high ramp rate to meet peak demand (US$)
F	Savings in coal per annum (Mt)
G1	Fuel cost of cycling operation per annum for coal units (million US$)
K1	Capital and maintenance cost of cycling operations per annum of coal units (million US$)
H	Savings in natural gas per annum (MMBTU)
G2	Fuel cost of cycling operation per annum for NGCC units (million US$)

✉ Amlan Chakrabarti
amlanc@hotmail.com

Krishnendu Chakrabarty
Chakrabarty40@rediffmail.com

[1] Electrical Engineering, Narula Institute of Technology, 81, Nilgunj Road, Agarpara, Kolkata 700109, India

[2] Government College of Engineering and Ceramic Technology, 73, Abinash Chandra Banerjee Lane, Kolkata 700010, India

K2	Capital and maintenance cost of cycling operations per annum of NGCC units (million US$)
X1	Savings in cost by reduction in cycling operation for coal units (million US$/year)
X2	Savings in cost by reduction in cycling operation for NGCC units (million US$/year)

The history of time-keeping started with Clock Tower in towns and cities [1]. The major change in modern history of time occurred with the need of Railway Companies of USA which found it difficult to operate with so many local times [2]. Presently, times are kept across the world based on the need of both governance and commerce [3].

Several countries across the globe, e.g. USA, UK, European Union, etc., which have substantial distance from the equator in terms of latitude, make daylight energy savings by adjusting their time-keeping systems with the availability of daylight [4]. For some countries near the equator, e.g. India, South Africa, Brazil, Australia etc., the territorial distances in terms of longitude justify multiple time-keeping systems. A few studies have been carried out in Australia, India and South Africa to quantify the savings in electrical power with multiple time-keeping systems [5–10]. If the sun takes more than an hour to move across a territory from east to west, the territory may be divided into more than one time zone. With different time-keeping systems across the territory, the electrical power demand will follow different patterns based on shifted working hours. If the territory division can be optimally done, the maximum electrical power demand in the territory can be reduced and minimum electrical power demand can be increased. This will help in flattening the electrical load curve across the territory. It will result in reduction in cycling operations of electrical power plants and associated carbon emission.

The current work makes use of electric power demand data of India for the year 2015 to demonstrate modest reductions in peak demand and cycling operations using time adjustments. In cycling operations, the efficiency of a steam power plant is lower with higher heat rate and the plant produces higher marginal carbon emission [11, 12]. The available research data are used to compute the savings in heating value and carbon emission in India for the year 2015. Based on data on estimated growth of electrical power demand in India up to the year 2050, the cumulative savings in carbon emission and cost are presented in this work.

There are three important assumptions for the current work.

1. With identical hours of operation, the electrical load pattern shall be similar in different load areas.
2. Cycling operation of thermal power plants are implemented using load following operation only.
3. Estimation of cycling penalty is based on 40% minimum loading of coal plants and 60% minimum loading of NGCC plants with normal ramp. Penalty figures are unpredictable for lower minimum loading.

As most of the referred work quantifies heating value in BTU, the savings in heating value have been worked out in BTU. Subsequently, this has been converted to joules and Gigajoules (1 BTU = 1055 J).

Time-Keeping and Rise of Electrical Power Demand in Peak Hour

Let us consider any geographic territory with an integrated power grid. The territory may be divided arbitrarily into two sub-areas along east–west. Let P1 and P2 be the rise in electrical power demands of sub-area1 and sub-area2 during the peak hour. Due to similar pattern of load demand, the peaks occur at the same time, say, $t = T_{\text{peak}}$;

In the peak hour $t = T_{\text{peak}}$, the maximum rise of electrical power demand of the territory with one uniform time-keeping system is given by Eq. (1).

$$P^{\text{MAXPEAK}} = P1 + P2. \tag{1}$$

If the time-keeping systems in sub-area1 and sub-area2 are set 1 h apart, then it is expected that the peak hours of the two sub-areas shall be 1 h apart ($t1 = T1_{\text{peak}}$, $t2 = T2_{\text{peak}}$, $t2 - t1 = 1$ h). The peak rise of electrical power demand of the territory is represented by Eq. (2).

$$P' = P1 \text{ or } P2, \quad \text{whichever is higher}. \tag{2}$$

The minimum value of rise of electrical power demand at peak hour shall be obtained with the equality criteria [13] given in Eq. (3).

$$P^{\text{MINPEAK}} = P1 = P2. \tag{3}$$

Hence, to achieve the minimum rise of electrical power demand (P^{MINPEAK}), a territory may be divided into sub-areas with equal rise in electrical power demand during the peak hour ($P1 = P2$).

Model of Time-Keeping Systems for Minimum Peak Demand

As the longitudinal distance of the extreme points of a geographic territory is constant, the number of solar hours between these two points shall also be a constant (N). Sub-areas between these two points from east to west may be assigned separate time-keeping systems with 1-h time difference between adjacent sub-areas.

$$\begin{aligned}&\text{Maximum number of sub-areas in the territory}\\&=\text{Number of Time-keeping systems with one hour time interval}\\&=N+1.\end{aligned}$$

Let 'A' represent a territory with 'm' physically demarcated unit-areas and 'a_i' represent the 'i'th unit-area between east and west. The relationship between the territory and unit-areas is given in Eq. (4).

$$A = a_1 U\, a_2 U\, a_3 \ldots U a_{m-1} U a_m. \tag{4}$$

Let E_i be the longitude of eastern edge of 'i'th unit-area in degrees. Let W_i be the longitude of Western edge of 'i'th unit-area in degrees. The mean geographical position in longitude of 'i'th unit-area in degrees is given by Eq. (5).

$$M_i = (E_i + W_i)/2. \tag{5}$$

Let us index the unit-areas such that, $M_1 > M_2 > \cdots M_{m-1} > M_m$.

Number of hours between time-keeping systems for the territory is given by Eq. (6).

$$N = (E_1 - W_m)/15. \tag{6}$$

where in terms of solar position, distance in longitude for 1 h is = 15° (360°/24 h).

Let P_j be the rise in electrical power demand in MW (Megawatts) during peak hour for 'j'th unit-area. To achieve minimum peak electrical demand as per Eq. (3), the rise in electrical power demand during peak hour of each sub-area is given by Eq. (7).

$$\begin{aligned}&P^{\text{MINPEAK}} = \Sigma P_j/(N+1),\\&\quad\text{for all '}j\text{' unit-areas within the territory.}\end{aligned} \tag{7}$$

It may not be physically possible to divide a territory according to our choice. However, a territory such as a country is divided into states. The states are further subdivided into districts or counties. A cluster of such unit-areas may form a sub-area of one uniform time-keeping system. The equal rise in power demand among sub-areas during peak hour may be achieved with the constraint equations given in (8), (9) and (10).

$$\begin{aligned}&\text{Sub-area 1 is represented as } A_1(P_j,\, M_j,\, N)\\&= a_1 U a_2 U a_3 \ldots U a_j,\\&\text{where } (P_1 + P_2 + \cdots + P_j) \approx \Sigma P_i/(N+1),\ \text{for all '}i\text{'}\\&\quad\text{such that } M_k < M_j \quad \text{for all } k > j.\end{aligned} \tag{8}$$

$$\begin{aligned}&\text{Sub-area 2 is represented as } A_2(P_{j+x},\, M_{j+x}, N)\\&= a_{j+1} U\, a_{j+2} U\, a_{j+3} \ldots U a_{j+x},\\&\text{where } (P_{j+1} + P_{j+2} + \cdots + P_{j+x}) \approx \Sigma P_i/(N+1),\\&\quad\text{for all '}i\text{' such that } M_k < M_{j+x} \quad \text{for all } k > (j+x).\end{aligned} \tag{9}$$

$$\begin{aligned}&\text{Sub-area } (N+1) \text{ is represented as } A_{N+1}(P_m,\, M_m,\, N)\\&= a_{m-n+1} U\, a_{m-n+2} U \cdots\, U\, a_m,\\&\text{where } (P_{m-n+1} + P_{m-n+2} + \cdots + P_m) \approx \Sigma P_i/(N+1),\\&\quad\text{for all '}i\text{' such that } M_k > M_{m-n+1}\\&\quad\text{for all } k < (m-n+1).\end{aligned} \tag{10}$$

In Eqs. (8), (9) and (10), each sub-area with a separate time-keeping system is represented by a mathematical function of electrical power demand and mean geographical position in longitude. As time adjustments are related to governance, it is necessary that each sub-area consists of distinct unit-areas of governance.

Framework of Time-Keeping Systems for Indian Power Grid

Time-Keeping Systems with Equal Rise in Peak Demand

Across India, there is an interconnected power grid connecting all states and union territories except Lakshadweep and Andaman and Nicobar Islands. The daily peak demand for the entire nation in 2017 and 2018 was 160 GW and 175 GW with a base demand of 141 GW and 149 GW, respectively. The configuration of three time-keeping systems for Indian states based on the hourly demand data of different dates spread over the year 2015 [13, 14] and longitude positions is presented in Fig. 1.

The estimated reduction in daily peak demand and cycling operation for Indian power grid has been worked out for the year 2015 with the three time-keeping systems.

The variation in actual demand data with single uniform time-keeping system and projected demand data with three time-keeping systems is presented in Table 1 and Fig. 2.

The rate of reduction in terms of peak demand for the year 2015 is calculated based on the data set in the daily operation reports of January to December 2015 [14] and calculations based on Eqs. (11)–(14).

$$\text{Differential Peak Demand (MW)},\quad \mathbf{DD} = \mathbf{PD1 - BD1}. \tag{11}$$

$$\text{Load Cycling Rate (\%)},\quad \text{LCR} = [\mathbf{DD} * \mathbf{100/PD1}]. \tag{12}$$

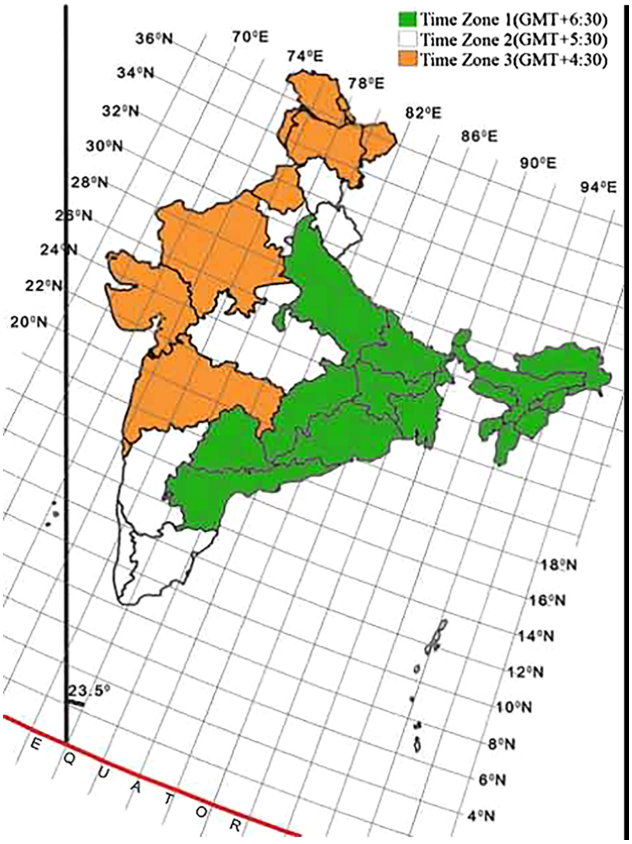

Fig. 1 Geographical configuration of proposed three time-keeping systems with equal power demand in Indian power grid

$$\text{Rate of Reduction of Peak Demand } (\%) \text{ PRR} = [\mathbf{PR} * \mathbf{100/PD1}]. \tag{13}$$

$$\text{Rate of Reduction in Cycling Operation } (\%) \text{ CRR} = [\mathbf{CR} * \mathbf{100/PD1}]. \tag{14}$$

The reduction in peak demand and rate of reduction in cycling operation for the year 2015 is estimated as 6% and 9%, respectively, and demonstrated in Table 1.

Availability of Hourly Demand Data of Indian Power Grid

The peak hour and off-peak hour power demand values of each state in the Indian power grid for a 24-h period are obtained from the daily operation reports [14]. For many states, power demand data for all the hours are available. For some states, the power demand data for intermediate hours are not available. In such cases, linear extrapolation has been used to estimate the hourly power demand data at the intermediate hours [13]. All hourly data and linear extrapolations used in this paper are available in [15].

Estimation of Rate of Reduction in Cycling Operation

The variation in CRR against variation in peak demand and load cycling is presented in Fig. 3.

Table 1 Cycling operation reduction in Indian power grid—computed data set January to December 2015

Date	12/1/2015	12/2/2015	12/3/2015	10/4/2015	12/5/2015	12/6/2015	10/7/2015	12/8/2015	12/9/2015	12/10/2015	12/11/2015	11/12/2015
Peak demand with one time-keeping zone (MW), **PD1**	138,994	138,363	135,191	138,667	144,189	143,122	144,148	143,345	152,512	148,892	130,847	140,058
Base demand with one time-keeping zone (MW), **BD1**	99,988	106,243	107,343	115,929	121,868	122,685	120,869	123,462	131,652	125,310	99.496	106,136
Projected peak demand with three time-keeping zones (MW), **PD3**	132,116	127,489	124,932	127,725	135,752	137,288	135,419	134,424	142,603	138,110	118,102	133,212
Projected base demand with three time-keeping zones (MW), **BD3**	104,391	109,234	115,251	117,812	125,549	129,102	124,278	126,763	135,473	130,546	102,895	108,056
Peak reduction (MW), **PR = PD1 − PD3**	6878	10,874	10,259	10,942	8437	5834	8729	8921	9909	10,782	12,745	6846
Reduction in cycling operation (MW), **CR = PD1 − BD1 − (PD3 − BD3)**	11,281	13,865	18,207	12,825	12,118	12,251	12,138	12,222	13,730	16,018	16,144	8766
CRR (%)	8.12	10.02	13.47	9.25	8.40	8.56	8.42	8.53	9.00	10.76	12.34	6.26

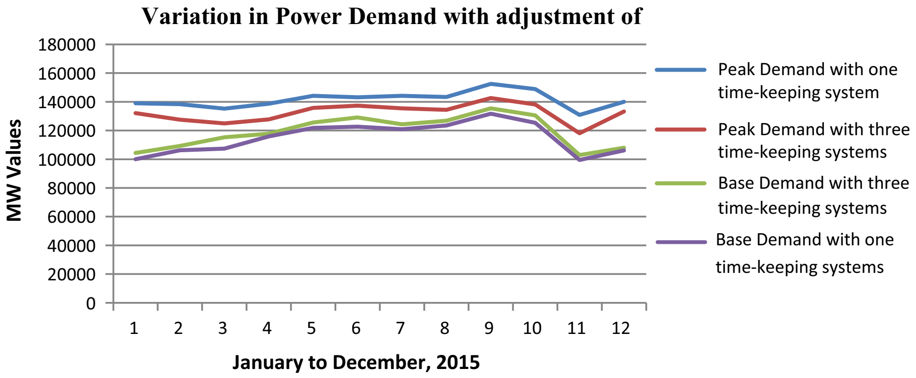

Fig. 2 Variation in power demand with three time-keeping systems for Indian power grid during January to December, 2015

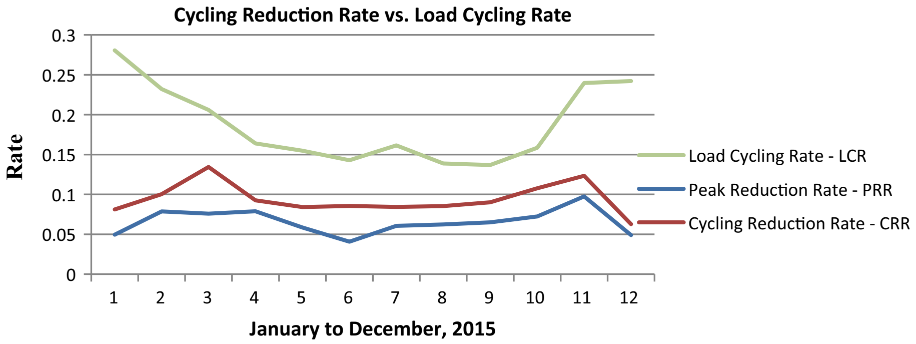

Fig. 3 Cycling reduction rate for Indian power grid—January to December 2015

It is observed from the demand data of developed countries that with development and growth, the differential between peak demand and base demand increases to 40% [16]. It is estimated that India will enter the league of developed countries around the year 2030 [17]. Penetration of renewable energy power plants shall induce additional cycling operations with deep load following [18].

For estimation of savings in carbon emission and expenditure for India up to the year 2050, the rate of reduction with three time-keeping systems has been restricted at 6% in peak demand and 9% in cycling operation.

Savings in Cycling Operations

Efficiencies of Steam Power Plants with Cycling Operations

The costs and damages in cycling operations to serve peak demand have been quantified in the reports of National Energy Technology Laboratory, USA [19], National Renewable Energy Laboratory, USA [20] and the TME working paper of University of Leuven, Belgium [21]. The research on estimation of cycling costs based on 20 years of operational data has been summarized for all kinds of cycling operations, i.e. cold start, warm start and load following operations [22]. An analysis of the historical cycling data shows that 99% of the cycling operations are load following operations and the rest are mostly warm start operations [23]. An analysis of load following operations for coal plants in Ireland shows that efficiency of the power plant may come down by 11% and carbon emission may increase by 65% [24]. The cycling operation also leads to accelerated component failures and creep–fatigue [25].

The drop in efficiency due to partial load operation and load following of steam power plants can be certainly estimated from characteristic equations of individual plants. The steam power plant technologies under consideration are:

Natural Gas Single-Cycle or Open-Cycle Combustion Turbine technology—NGSC
Natural Gas Combined Cycle technology—NGCC
Sub-critical Coal with Rankine Cycle technology
Super-critical Coal with Rankine Cycle technology
Integrated Gasification Combined Cycle technology using Coal—IGCC

The heat rate penalties for the above steam power plant technologies are summarized in Table 2 [19].

The decrease in efficiency due to cycling operation results in carbon emission at a higher rate [26].

Table 2 Heat rate penalties for partial loading with available steam power plant technologies

Steam power plant technologies	NGSC	NGCC	NGCC	Sub-critical coal	Super-critical coal	IGCC
Minimum partial load (%)	50	40	60	50	40	60
Heat rate penalty at minimum partial load (BTU/kwh)	1277	1889	765	464	489	1877

Requirement of Centrally Coordinated Cycling Operation and Additional Transmission Loss

If the requirement of rise in power demand in a sub-area is addressed locally, different sets of power plants will be used for rise in power demand in different areas. Hence, without central pool of cycling power plants, there will be no savings in cycling operation. To coordinate cycling operations with central pool of power plants, the additional transmission loss must be taken into consideration. The percentage power loss in a transmission line depends on conductor resistance (r), the positive sequence reactance (x) and the phase angle (δ). It is given by Eq. (15).

$$P_{\text{LOSS}}(\%) = 100 * \sin\delta * (r/x) \tag{15}$$

A large number of super thermal power plants are located in central India. These plants are suitable for both base load and cycling operations. Based on the hourly data of 2015 in Table 3, the average cycling power required to be transferred from these central pool of power plants to the adjacent sub-area is presented in Eq. (16).

$$\text{CP} = 4385\,\text{MW} \tag{16}$$

The percentage power loss for 1200 kV power line is taken as 0.584% from Eq. (15). The power loss per day for transfer to two adjacent sub-areas from the central sub-area at 1200 kV for 2 h is estimated in Eq. (17).

$$\begin{aligned} P_{\text{LOSS}} &= 2 * \text{CP} * 0.00584 \\ &= 2 * 4385 * 0.00584 = 51\,\text{MWh} \end{aligned} \tag{17}$$

The additional power loss and related penalties for central coordination of cycling operation for average peak demand in 2015 are included in Table 3.

Based on the estimated transmission losses for Indian power grid for the year 2015 with a transmission backbone at 1200 kV level, the additional heating value is approximately 0.2% of the savings from reduction in cycling operation. Also, savings are achieved towards non-fuel expenditure.

Savings in Capital & Maintenance Cost for super-critical coal plants in India in 2015(@ US$ 1.96/MW capacity for 30% ramp operation) [22, 23, 27, 28] are given by Eqs. (18) and (19),

$$\begin{aligned} \text{CM1}(\text{US\$}) &= \text{PD1} * \text{US\$1.96 par MW Capacity} \\ &= 152,512 * 1.96 = 298,924. \end{aligned} \tag{18}$$

Savings in Capital and Maintenance Cost for NGCC plants in India in 2015 (@ US$ 0.64/MW capacity for 20% ramp operation) [22, 23, 27, 28] are given by Eq. (19),

$$\begin{aligned} \text{CM2}(\text{US\$}) &= \text{PD1} * \text{US\$0.64 per MW Capacity} \\ &= 152,512 * 0.64 = 97,608. \end{aligned} \tag{19}$$

Estimation of Growth in Peak Demand in Indian Power Grid

Assessment of the growth of electrical power demand in India is available in research work carried out by government reports, peer reviewed journals, reports of international agencies and international conferences [17, 29–37]. The published research work of a project taken up by The Grantham Institute of Climate Change, The Imperial College, London [29–31], is close to the projections of Central Electricity Authority, Government of India [32, 33].

The SPSS PASW Statistics 18 with exponential growth model is used to estimate curve Eq. (20) for electricity generation from 2005 to 2050.

$$Y = 2.291 * e^{0.05241 * t} \tag{20}$$

where Y = electrical energy generation in exajoules (EJ) and t = 0–45 for the years from 2005 to 2050.

In the annual report of the planning commission, 2014 [32], the minimum rate of growth is observed in the year 2012–2013 with a peak demand of 135, 453 MW. This value is fitted with the estimated curve Eq. (20) to obtain the exponential growth Eq. (21) for peak demand.

$$Z = 93,855 * e^{0.05241 * t} \tag{21}$$

where Z = peak demand in MW; t = 0–45 for the years from 2005 to 2050;

Based on Eq. (21), the estimated peak demand is calculated for the years from 2020 to 2050.

The peak demand of 185,505 MW projected for 2018 as per the exponential growth model is very close to the peak demand of 180,682 MW anticipated in CEA Load Generation Balance Report 2018–19 [33] and the actual data of 174,682 MW [14].

Table 3 Savings in heating value and fuel cost for Indian power grid—January to December 2015

Date	12/1/ 2015	12/2/ 2015	12/3/ 2015	10/4/ 2015	12/5/ 2015	12/6/ 2015	10/7/ 2015	12/8/ 2015
Differential peak demand (MW), **DD = PD1 − BD1**	39,006	32,120	27,888	22,738	22,321	20,437	23,279	19,883
Differential peak demand (%), **[DD * 100/PD1]**	28.06	23.21	20.63	16.40	15.48	14.28	16.15	13.87
Rate of reduction in peak demand (%), **[PR * 100/PD1]**	4.95	7.86	7.59	7.89	5.85	4.08	6.06	6.22
Requirement of power transfer for central coordination of cycling operation with three time-keeping zones (MW), **[CP = (PD3 − BD3)/3]**	9242	6085	3227	3304	3409	2729	3714	2554
Rate of power transfer for cycling operation (%), **[CP * 100/PD3]**	7.00	4.77	2.58	2.59	2.51	1.99	2.74	1.90
Rate of reduction in cycling operation (%), **[CR * 100/PD1]**	8.12	10.02	13.47	9.25	8.40	8.56	8.42	8.53
Transmission losses for central coordination of cycling operation (3.35%) with three time-keeping zones, $\boldsymbol{P_{\mathrm{LOSS}}}$ **= 2 * CP * 0.00584 (MWh)**	108	71	38	39	40	32	43	30
Savings in cycling operation/day for plant capacity, **B1 = CR/0.6** (40% minimum loading)	18,802	23,108	30,345	21,375	20,197	20,418	20,230	20,370
Additional heating value for transmission losses at 1200 kV, $\boldsymbol{P_{\mathrm{LOSS}}}$ *** 10.41 * 1.055** (GJ/day)	1186	780	417	428	439	352	472	330
Savings in heating value by reduction in cycling operation for coal units, **C1 = B1 * 0.4 * 24 * 0.516 + B1 * 0.57 * 1.055 −** $\boldsymbol{P_{\mathrm{LOSS}}}$ *** 10.41 * 1.055** (GJ/day)	**149,827**	**184,818**	**243,306**	**171,251**	**161,778**	**163,640**	**162,010**	**163,277**
Savings in carbon emission for coal units, **D1 = C1 * 365 * .0946 *** $\boldsymbol{10^{-6}}$ (MtCO2/year)	5.17	6.38	8,40	5.91	5.59	5.65	5.59	5.64
Savings in cycling operation/day for plant capacity, **B2 = CR/0.4** (60% minimum loading)	29,203	34,662	45,518	32,063	30,296	30,627	30,345	30,555
Additional heating value for transmission losses at 1200 kV, $\boldsymbol{P_{\mathrm{LOSS}}}$ *** 8.2 * 1.055** (GJ/day)	934	614	328	337	346	277	372	260
Savings in heating value by reduction in cycling operation for NGCC units, **C2 = B2 * 0.6 * 24 * 0.807 + B2 * 0.08 * 1.055 −** $\boldsymbol{P_{\mathrm{LOSS}}}$ *** 8.2 * 1.055** (GJ/day)	**340,893**	**405,112**	**532,469**	**374,967**	**354,275**	**358,218**	**354,822**	**357,392**
Savings in coal per annum (Mt) @17*10^6 GJ/Mt, ***F*** **= C1 * 365/(17 *** $\boldsymbol{10^6}$**) (million tons)**	**3.22**	**3.97**	**5.22**	**3.68**	**3.47**	**3.51**	**3.48**	**3.51**
Savings from fuel cost of cycling operations for coal plants @ US$ 100/*t*, **G1 = F * 100** (million US$)	**322**	**397**	**522**	**368**	**347**	**351**	**348**	**351**
Savings in natural gas (MMBtu/day) ***H*** **= C2 * 0.94781712031332**	**323,104**	**383,972**	**504,683**	**355,400**	**335,788**	**339,525**	**336,306**	**338,742**
Fuel cost per annum for cycling operation of NGCC units @ US$ 3.4 per MMBtu, **G2 = H * 365 * 3.4 *** $\boldsymbol{10^{-6}}$ (million US$)	**401**	**476.5**	**626.3**	**441**	**416.7**	**421.3**	**417.3**	**420.4**

Date	12/9/2015	12/10/2015	12/11/2015	11/12/2015
Differential peak demand (MW), **DD = PD1 − BD1**	20,860	23,582	31,351	33,922
Differential peak demand (%), **[DD * 100/PD1]**	13.68	15.84	23.96	24.22
Rate of reduction in peak demand (%), **[PR * 100/PD1]**	6.50	7.24	9.74	4.89
Requirement of power transfer for central coordination of cycling operation with three time-keeping zones (MW), **[CP = (PD3 − BD3)/3]**	2377	2521	5069	8385
Rate of power transfer for cycling operation (%), **[CP * 100/PD3]**	1.67	1.83	4.29	6.29
Rate of reduction in cycling operation (%), **[CR * 100/PD1]**	9.00	10.76	12.34	6.26
Transmission losses for central coordination of cycling operation (3.35%) with three time-keeping zones, $\boldsymbol{P_{\mathrm{LOSS}}}$ **= 2 * CP * 0.00584** (MWh)	28	30	59	98
Savings in cycling operation/day for plant capacity, **B1 = CR/0.6** (40% minimum loading)	22,883	26,697	26,907	14,610
Additional heating value for transmission losses at 1200 kV, $\boldsymbol{P_{\mathrm{LOSS}}}$ *** 10.41 * 1.055** (GJ/day)	308	330	648	1076

Table 3 continued

Date	12/9/2015	12/10/2015	12/11/2015	11/12/2015
Savings in heating value by reduction in cycling operation for coal units, **C1 = B1 * 0.4 * 24 * 0.516 + B1 * 0.57 * 1.055 −** P_{LOSS} *** 10.41 * 1.055** (GJ/day)	**183,483**	**214,094**	**215,462**	**116,268**
Savings in carbon emission for coal units, **D1 = C1 *365 * .0946 *** 10^{-6} (MtCO2/year)	6.34	7.39	7.44	4.01
Savings in cycling operation/day for plant capacity, **B2 = CR/0.4** (60% minimum loading)	34,325	40,046	40,361	21,915
Additional heating value for transmission losses at 1200 kV, P_{LOSS} *** 8.2 * 1.055** (GJ/day)	243	260	510	848
Savings in heating value by reduction in cycling operation for NGCC units, **C2 = B2 * 0.6 * 24 * 0.807 + B2 *0.08 * 1.055 −** P_{LOSS} *** 8.2 * 1.055** (GJ/day)	**401,538**	**468,486**	**471,924**	**255,671**
Savings in coal per annum (Mt) @17 * 10^6 GJ/Mt, **F = C1 * 365/(17 *** 10^6**) (million tons)**	**3.94**	**4.60**	**4.63**	**2.50**
Savings from fuel cost of cycling operations for coal plants @ US$ 100/*t*, **G1 = F * 100** (million US$)	**394**	**460**	**463**	**250**
Savings in natural gas (MMBtu/day) ***H* = C2 * 0.94781712031332**	**380,585**	**444,039**	**447,298**	**242,329**
Fuel cost per annum for cycling operation of NGCC units @ US$ 3.4 per MMBtu, **G2 = H * 365 * 3.4 *** 10^{-6} (million US$)	**472.3**	**551**	**555**	**301**

Cumulative Savings in Carbon Emission and Expenditure Up to the Year 2050

The estimated savings in carbon emission are presented in Table 4. The cumulative savings in capital expenditure and cost of cycling operation are presented in Table 5 based on published data [38–41].

Conclusion

Calculations for sub-critical coal plants, open-cycle gas turbine plants and IGCC plants have not been included in this work. For these types of plants, the cost of cycling operation is substantially higher. Between the coal plants and NGCC plants, the operation cost of NGCC plants is higher due to fuel cost. Naturally, the NGCC plants are avoided for base load operations and are used in case of higher demand. Hence, the NGCC plants have become the convenient choice for cycling operations. Also, overall carbon emission of coal plants is higher and they are expected to be gradually replaced by IGCC plants with substantially lower carbon emission with the same fuel. With the existing built-up capacity, the coal plants will continue to be an option for cycling for many years. In spite of high penalty for cycling operations of NGCC plants, the life-cycle savings are marginally lower than coal-based plants.

As time is in the domain of public interest, all adjustments of time have to be implemented through legislation. The major technical challenge of implementation of time adjustments across India shall be to adjust the transmitter and receiver end-equipments of Standard Time & Frequency Systems under National Physical Laboratory (NPL) [13]. To minimize the cost of these changes, it is possible to restrict the modifications to software and firmware without replacing the hardware.

The load consumption pattern across the geography of a country is not expected to change within a decade. Hence, the Standard Time and Frequency Systems will not need frequent adjustments. Given that several countries are adjusting their time systems every year for daylight savings [4], it is expected that the proposed time adjustments can be implemented across the states of India.

Adjusting the time-keeping systems in other countries should result in similar benefits. With the availability of a precise model, the application can be replicated for any large country where the territory is suitable for more than one time-keeping system.

Table 4 Estimated carbon savings with three time zones

Year	2020	2025	2030	2035	2040	2045	2050
Estimated peak demand with single time-keeping system (MW)	206,005	267,722	347,930	452,167	587,632	763,682	992,474
Estimated reduction in cycling operation (9%) with three time-keeping systems (MW), CR	18,540	24,095	31,314	40,695	52,887	68,731	89,323
Savings in carbon emission for coal units, **$D1 = C1 * 365 * .0946 * 10^{-6}$** (MtCO2/year)	**5.9**	**7.7**	**9.91**	**12.94**	**16.82**	**21.87**	**28.42**
Savings in carbon emission for NGCC units, **$D2 = C2 * 365 * .0561 * 10^{-6}$** (MtCO2/year)	**11.10**	**14.42**	**18.74**	**24.36**	**31.65**	**41.13**	**53.46**
Savings in coal per annum (Mt) @17 * 10^6 GJ/Mt, **$F = C1 * 365/(17 * 10^6)$**	3.67	4.77	6.16	8.05	10.46	13.60	17.67
Fuel cost of cyclic operation per annum for coal units @ US$ 100/*t*, **$G1 = F * 100$** (million US$)	367	477	616	805	1046	1360	1767
Savings in natural gas (MMBtu/day) **$H = C2 * 0.94781712031332$**	513,593	667,483	867,460	1,127,416	1,465,074	1,903,982	2,474,423
Fuel cost per annum for cycling operation of NGCC units @ US$ 3.4 per MMBtu, **$G2 = H * 365 * 3.4 * 10^{-6}$** (million US$)	637	828	1077	1399	1818	2363	3071

Table 5 Cumulative savings in capital expenditure, cycling operation expenditure and social cost of carbon from year 2020 to 2050

Description of savings	With cycling of coal plants	With cycling of NGCC plants
Savings in one-time capital expenditure (billion US$)		
= **$PR(2050) * 3.246 * 10^{-3}$** for advanced coal unit	193	
= **$PR(2050) * 1.023 * 10^{-3}$** for advanced NGCC unit		61
Investment in 1200 kV, 18,000 MW UHVAC transmission lines (cost 220 million EURO [42]) (billion US$)	− 4	− 4
Savings in capital and maintenance (**$\sum CM1$ or $\sum CM2$**) (billion US$)	30	10
Savings in cumulative cost of cycling operation (**$\sum G1$ or $\sum G2$**) (billion US$)	27.2	47.5
Cumulative savings in carbon emission [43] (billion US$)	11	20
Total cumulative savings (billion US$)	**257**	**134**

References

1. D. Howse, *Greenwich Time and the Discovery of the Longitude* (Oxford University Press, Oxford, 1980)
2. M.W. White, The Economics of Time Zones. The Wharton School, University of Pennsylvania (2004)
3. S. Fleming, "Recommendations Suggested", Protocols of the Proceedings of The International Prime Meridien Conference, Washington DC, October 1884, Gibson Brothers, Printers and Bookbinders
4. D. Prerau, *Seize the Daylight: The Curious and Contentious Story of Daylight Saving Time* (Thunder's Mouth Press, New York, 2005)
5. R. Kellogg, H. Wolff, Daylight time and energy: evidence from an australian experiment. CSEM Working Paper 163, UC, Berkeley (2007)
6. D.R. Ahuja, D.P. SenGupta, V.K. Agrawal, Energy savings from advancing the Indian standard time by half an hour. Curr. Sci. **93**(3), 298 (2007)
7. Planning Commission, Integrated Energy Policy, New Delhi (2006)
8. Planning Commission, *Government of India* (Indian Planning Experience, New Delhi, 2001)
9. B. Natarajan, et al., Two Strategies for Electric Load Leveling for India: Phase II—Final Report, Advisory Board on Energy, TERI, New Delhi (1988)
10. Don't tinker with the clock to save energy, The Energy and Resources Institute (TERI), New Delhi, India, Policy Brief (2011)
11. S.A. Lefton, D. Hilleman, August 11, pp. 1–12 (2011). http://www.powermag.com/print/issues/features/Make-Your-Plant-Ready-for-Cycling-Operations
12. EPRI, Palo Alto, CA: 2002. 1004412, Determining the Cost of Cycling and Varied Load Operations: Methodology (2002)
13. A. Chakrabarti, Reducing peak demand by time zone divisions. J. Inst. Eng. India Ser. B (2014). https://doi.org/10.1007/s40031-014-0091-2
14. Power System Operation Corporation Ltd, Daily Operation Reports. http://www.posoco.in
15. https://osf.io/b2vcn/?view_only=131dd9437b6542a9818dccd99cfb265e
16. T. Shear, Peak-to-average electricity demand ratio rising in New England and many other U.S. regions. Independent Statistics and Analysis, February 18 (2014). http://www.eia.gov/todayinenergy/detail.cfm?id=15051
17. S. Zhai, Z. Wang, The prediction of carbon emissions demands in India under the balance economic growth path. Smart Grid

Renew. Energy Sci. Res. **3**, 186–193 (2012). https://doi.org/10.4236/sgre.2012.33026

18. N. Troy, E. Denny, M. O'Malley, Base-load cycling on a system with significant wind penetration. IEEE Trans. Power Syst. **25**(2), 1088–1097 (2010). https://doi.org/10.1109/TPWRS.2009.2037326
19. P. Myles, S. Herron, Impact of load following on power plant cost and performance: literature review and industry interviews. National Energy Technology Laboratory, DOE/NETL-2013/1592 (2012)
20. D. Lew, G. Brinkman, et al., The western wind and solar integration study phase 2. National Renewable Energy Laboratory, September, Technical Report NREL/TP-5500-55588 (2013)
21. K. Van den Bergh, E. Delarue, Cycling of conventional power plants: technical limits and actual costs. TME Working Paper—Energy and Environment, University of Leuven—Energy Institute, TME Branch, Belgium, WP EN2015-5 (2015)
22. N. Kumar, P. Besuner, S. Lefton, D. Agan, D. Hilleman, Power plant cycling costs. National Renewable Energy Laboratory, USA, Subcontract Report, NREL/SR-5500-55433 (2012)
23. N. Kumar, S. Paterson, K. Coleman, C. Lee, D. Agan, S. Lefton, Power plant cycling measure—evaluating historical cycling to model future grid operations, EPRI, IEEE 978-1-4799-1303-9/13, copyright, IEEE (2013)
24. R. Turconi, C. O'Dwyer, D. Flynn, T. Astrup, Emissions from cycling of thermal power plants in electricity systems with high penetration of wind power: Life Cycle Assessment for Ireland. Appl. Energy **131**(2014), 1–8 (2014). https://doi.org/10.1016/j.apenergy.2014.06.006
25. E. Denny, M. O'Malley, The impact of carbon prices on generation-cycling costs. Energy Policy **37**(4), 1204–1212 (2009)
26. USEPA, S.D. Piccot, J.A. Buzun, H.C. Frey, Emission and cost estimate for globally significant anthropogenic combustion sources. EPA-600/7-90-100 (1990)
27. P. Keatley, A. Shibli, N.J. Hewitt, Estimating power plant start costs in cycling operation. Appl. Energy **111**(2013), 550–557 (2013). https://doi.org/10.1016/j.apenergy.2013.05.033
28. S.A. Lefton, P.M. Besuner, The cost of cycling coal fired power plants, coal power magazine, pp. 16–20 (2006)
29. A. Gambhir, T. Napp, C. Emmott, L. Vallejo, G. Anandarajah, India's CO_2 emission pathway to 2050, Grantham Institute for Climate Change. An Institute of Imperial College, London, DECC Funded Research Project GA0215/GASRF123, Report No. AV/WS2/D1/R41, Ref. M/DoE/2/9, December 30 (2012)
30. G. Anandarajah, A. Gambhir, India's CO2 emission pathways to 2050: What roles can renewable play? Appl. Energy **131**(2014), 79–86 (2014). https://doi.org/10.1016/j.apenergy.2014.06.026
31. G. Anandarajah, A. Gambhir, T.A. Napp, C.J.M. Emmott, India's CO2 emission pathways to 2050: energy system, economic and fossil fuel impacts with and without carbon permit trading. Energy **77**(2014), 791–801 (2014). https://doi.org/10.1016/j.energy.2014.09.055
32. Power and Energy Division, Planning Commission, Government of India, Annual Report 2014–15 on the Working of State Power Utilities and Electricity Departments (2014)
33. Central Electricity Authority (CEA), Load Generation Balance Report 2018–19, Government of India, Ministry of Power, New Delhi (2018)
34. R. Gupta, S. Sankhe, S. Sarma, *Environmental and Energy Sustainability: An Approach for India* (McKinsey & Company Inc., New York, 2009)
35. The Energy Resources Institute (TERI), National Energy Map for India—Technology Vision 2030. Office of the Principal Scientific Investigator to the Government of India, PSA/2006/3. ISBN 81-7993-099-8
36. BP, Energy Outlook 2035 (2014). http://www.bp.com/energyoutlook, #BPstats
37. IEA, World Energy Outlook (2014). http://www.iea.org/Textbase/npsum/WEO2014SUM.pdf
38. Ernst and Young LLP, EYIN 1404-040, ED0115 copyright 2014, PHD Chamber of Commerce. Natural Gas Pricing in India—Current Policy and Potential Impact
39. US Energy Information Administration (EIA), Updated capital cost estimates for utility-scale electricity generating plants (2013)
40. C. Batlle, P. Rodilla, An enhanced screening curve method for considering thermal cyclic operation costs in generation expansion planning. IEEE Trans. Power Syst. **28**(4), 3683–3691 (2013)
41. D. Schlissel, A. Smith, R. Wilson, *Coal-fired power plant construction costs* (Synapse Energy Economics Inc., Cambridge, 2008)
42. C. Humpert, Long distance transmission systems for the future electricity supply—analysis of possibilities and restrictions. Energy **48**(2012), 278–283 (2012). https://doi.org/10.1016/j.energy.2012.06.018
43. NCEE Working Paper Series, The social cost of carbon made simple. Working Paper #10-07, USEPA (2011)