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Thermal Comfort and Productivity in Offices under Mandatory Electricity Savings after Great East Japan Earthquake

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Abstract
The great east Japan earthquake of March 11, 2011, wreaked enormous damage, forcing the Japanese government to mandate a 15% peak power reduction to address shortages in summer. Office workers were forced to be patient. The present paper reports the results of field studies conducted in Tokyo office buildings during summer to understand the relationship between indoor environment, productivity, and energy conservation measures under the mandated limits. Occupants generally expressed discomfort regarding the high temperature, but widely accepted the decrease in illumination from 750 to 300–500 lux. Increased awareness regarding power savings was found, with more than 90% of people accepting the poor indoor environment in light of the shortages that year. Clothing and raising set point temperature recommendations made by the Super Cool Biz campaign were followed in most offices. However, self-estimated productivity was 6.6% lower than last summer. Thus, strategies for electricity savings that do not affect productivity are necessary.

Keywords
Indoor Environment, Energy Saving, Electricity, Earthquake, Productivity

Introduction
The great east Japan earthquake of March 11, 2011, wreaked wide-spread damage. It was the most powerful to ever hit Japan, with a magnitude of 9.0 on the Richter scale and a maximum intensity of 7 on the Japan Meteorological Agency (JMA) seismic scale. Even in Tokyo, a JMA seismic intensity level of 5-upper was observed. The hypocenter area extended 500 km from north to south and 200 km east to west. The earthquake produced a tsunami over 10 m high on the east coast. Direct earthquake damage was not as high because of the strict quake-resistance criteria instituted after the Great Hanshin Earthquake of 1995. However, the tsunami caused considerable damage to nuclear and thermal power stations. The tsunami washed out all facilities, houses, and buildings. The economic impact has been estimated at 210–330 billion US dollars.

On December 22, 2011, the Japanese government reported that the number of dead was 15,843, 3469 persons were missing, and over 430,000 people were evacuated. During the first week after the earthquake, supplies of food, water, and medicine were handed out because of the fuel shortage and cold weather. The earthquake happened on a Friday afternoon and stopped all modes of transportations in Tokyo. Thus, 100,000–1,000,000 people could not return to their home and were stuck at their work place, downtown regions, train/bus stations, and other public places overnight. I stayed at the Architectural Institute of Japan that night. No wired or wireless phone network was available.

Figure 1 View after Tsunami (courtesy: Junji Katsura)

Japan has 54 nuclear power reactors at 17 sites in total. The tsunami had a serious impact at the Fukushima Daiichi nuclear power station, where it caused critical damage.

Fukushima Daiichi has six reactors (see Table 1), four of which were severely damaged, while the others were stopped safely.

Table 1 Nuclear power stations at Fukushima Daiichi

	Commissioned	Capacity	Manufacturer	Condition
Unit 1	1971	460 MW,	GE	damaged
Unit 2	1974	784 MW	GE	damaged
Unit 3	1978	784 MW	Toshiba	damaged
Unit 4	1978	784 MW	Hitachi	damaged
Unit 5	1978	784 MW	Toshiba	Safely stopped
Unit 6	1979	1100 MW	GE	Safely stopped

On March 11, after the earthquake at 2:46 pm, off-site power was lost at Fukushima. At 3:25 pm, reactors were stopped automatically. However, at 11:35 pm, the cooling system failed because of tsunami damage to the on-site diesel generators. All motor-operated pumps, including the emergency core cooling system (ECCS) became inoperable. Workers then began pouring sea water directly into the nuclear reactor, but this resulted in a hydrogen explosion, which dramatically increased the amount of radioactivity released.

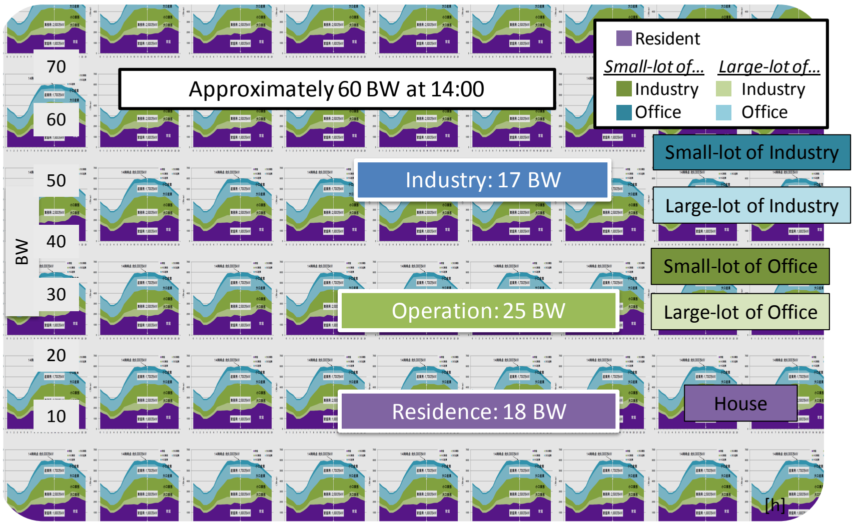
Power Shortage in Tokyo Area

Before the earthquake TEPCO (Tokyo Electric Power Company) had a power generation capacity of 63BW, with 14% hydro, 59% thermal, 27% nuclear, and less than 1% renewable energy. After March 11, the capacity reduced to 38 BW. TEPCO and the Ministry of Economy, Trade, and Industry estimated that they could recover up to 54 BW of capacity by the summer. However, peak power during summer of 2010 was about 60 BW. Thus, in May, the government announced an expected shortage of about 10% in the Tokyo area during peak days in summer.

A reduction of 6 BW is not very easy to achieve. For perspective, one new nuclear power station in Japan can generate around 1100 MW, which is 1.1 BW, and is equivalent to the energy produced by 1,283,333 houses with a 4-kW photovoltaic (PV) system each. Note that nuclear power stations may operate at up to 70%

efficiency, whereas PV systems only achieve 15%. It is not easy task to install a 4-kW PV system on over one million homes immediately. Thus, measures to reduce energy use are required.

As a result, rolling blackouts were carried out during March, which caused serious economic damages for industry. Figure 2 shows breakout of electricity consumption on the peak day of June 23, 2010. We see that the peak is not sharp, but seems to form a plateau extending from 8 am to 9 pm. In May, the government mandated a 15% peak power reduction for large consumers (more than 500 kW of power contracts). They also asked small commercial and residential consumers to achieve the 15% reduction. The Japanese word for electricity savings, *setsuden*, became very popular in Japan after 2011. Office workers were forced to be patient at work given the situation.



*1) including 10% loss of electric power transmission
*2) "14 o'clock" means the average between 14 and 15 o'clock

Figure 2 Breakup of energy consumption on June 23, 2010 (peak day)

Survey in Offices

The field studies were conducted in six office buildings in Tokyo during summer season to investigate the effect of setsuden.

Table 2 Outline of Six Buildings

Name	KH	KB	KI	KS	S	T
						
Completion	2007	2007	1989	1988	1993	1984
	14F+2BF	15F+2BF	9F+1BF	10F+1BF	18F+2BF	40F+3BF
Area/Floor	910m^2	2,722m^2	5,080m^2	1,350m^2	3,202m^2	14,741m^2
Floor Area	15,163m^2	33,517m^2	29,468m^2	11,187m^2	43,320m^2	162,612m^2

The indoor environment, productivity, and energy conservation steps were recorded. More than 500 filled questionnaires were collected. These six building achieved a more than 15% reduction during summer. We focused on the occupants' degree of satisfaction regarding the visual environment, thermal environment, and air quality. In some buildings, we even changed environmental conditions, including lighting, heating, and ventilation. Occupants rated satisfaction level by voting using the following scale: -2 - dissatisfied, -1 - slightly dissatisfied, 0 - neutral, +1 - slightly satisfied, +2 - satisfied.

Lighting – Visual Environment
The relationship between visual satisfaction and the illumination intensity at the desk level is shown in Figure 3. Until March 11, over 750 lux was very common in offices. The range of measured illuminance was 200–650 lux. We found a very weak correlation between the dissatisfaction and the illumination intensity. In Japan, the design value for illuminance is 750 lux. We are discussing to decrease design illumination level at the moment.

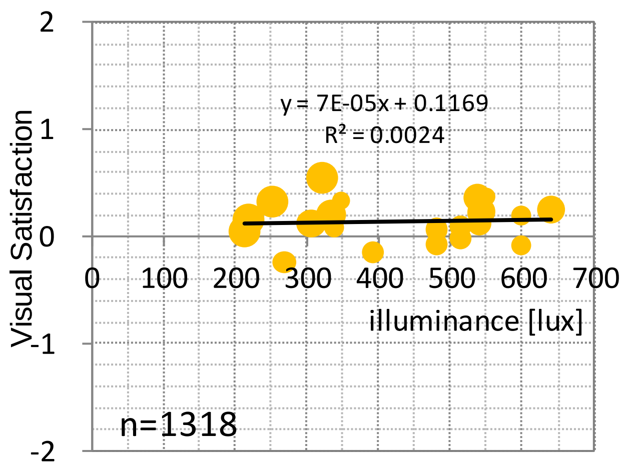


Figure 3 Relationship between illumination intensity on desk and level of satisfaction

Thermal comfort
As shown in Figure 4, a strong correlation was found between dissatisfaction and room temperature. Dissatisfaction was about 25% at 25°C, which increased to 60% at 28°C and higher at higher temperatures. Especially over 27°C thermal satisfaction was decreased steeply. Estimated mean of clo-value was 0.5 clo.

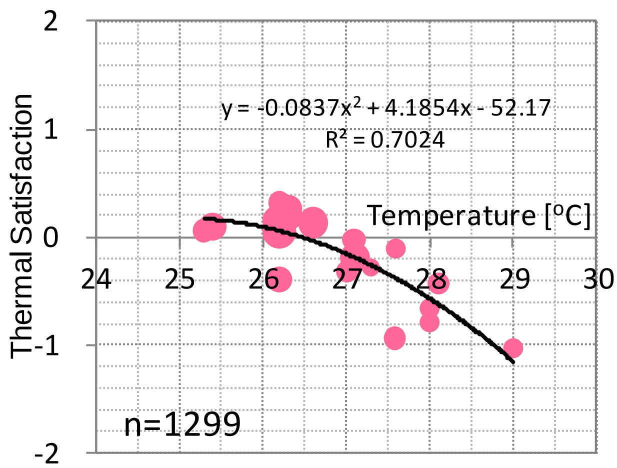


Figure 4 Relationship between room temperature and level of satisfaction

Indoor Air Quality

As shown in Figure 5, there was a strong correlation between satisfaction with indoor air quality and the level of CO_2. For the CO_2 concentration range 600–1200 ppm, we found a gradual increase in dissatisfaction with an increase in concentration. The perception of indoor air quality is also affected by thermal environment. Thus, we divided voting into two categories: Satisfaction levels with CO_2 concentrations less than 1000 ppm are higher than those above 1000 ppm. Furthermore, indoor temperature has a significant influence on perceived air quality.

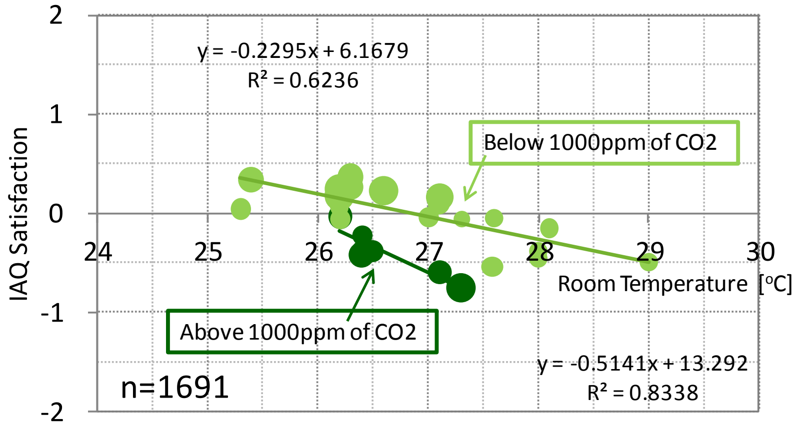


Figure 5 Relationship between CO_2 concentration and level of satisfaction for indoor air quality (IAQ)

Energy Savings and Peak Cut

As shown in the graph in Figure 6, energy consumption is slightly affected by outdoor solar radiation because of day lighting. The mean electricity consumption was 22.6 W/m^2 at 750 lux; it was 16.6 W/m^2 at 500 lux, and 13.2 W/m^2 at 300 lux. In addition, lowering the illumination to 500 lux from 750 lux can be expected to cause a 6.0 W/m^2 reduction in illumination intensity. A reduction from 750 to 300 lux corresponds to a reduction of 9.4 W/m^2. These electricity savings also have an impact on cooling load.

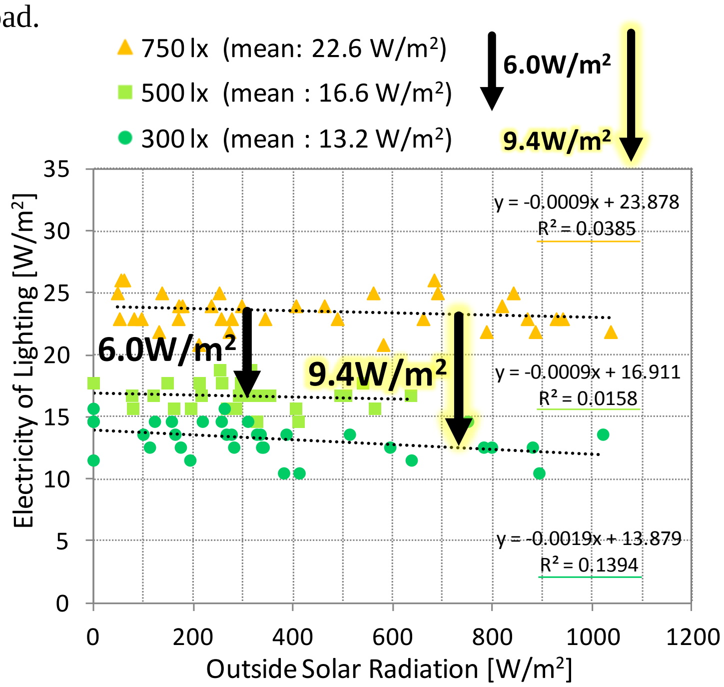


Figure 6 Energy savings and lighting

However, as shown in Figure 7, we cannot expect energy reductions as large as those possible in lighting by changing cooling conditions.

In the Tokyo area, peak demand occurred on August 19, 2011. It was 18% smaller peak than that in 2010.

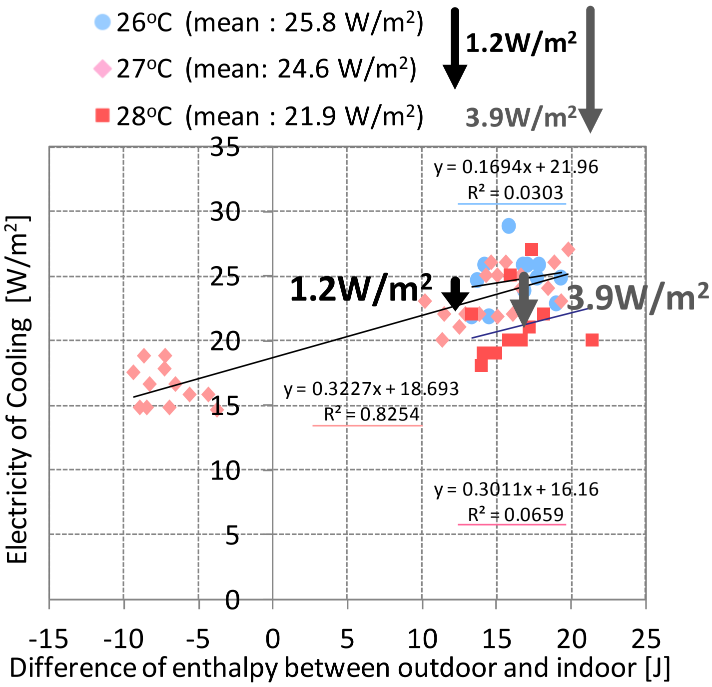


Figure 7 Energy savings by increasing temperature

Office workers' awareness of power savings and productivity

As shown in Figure 8, when asked about changes in attitudes and responses before and after the earthquake, over half admitted to having no prior awareness but heightened awareness after this earthquake. About 70% of people experienced reduced power in their offices. For power saving, "If anything positive" or "positive" and respondents who accounted for about 90%. However, 71% of them expressed some degree of inconvenience because of the measures.

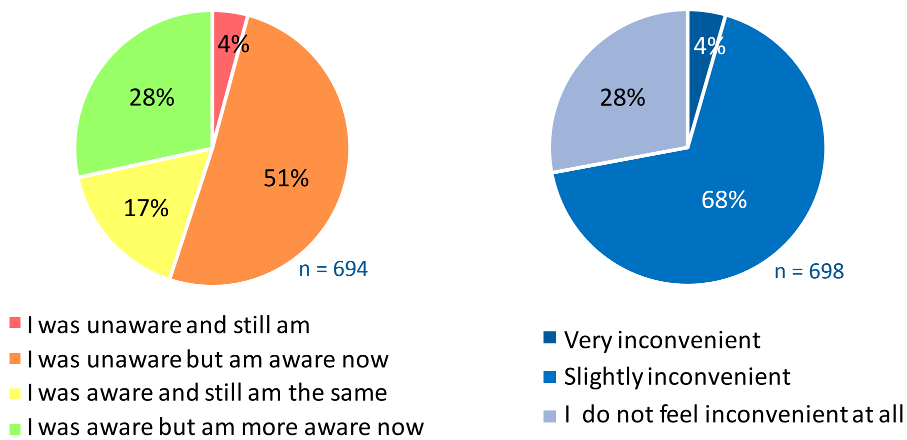


Figure 8 Awareness of energy savings by office workers

We asked respondents to rate the most annoying measure taken to conserve electricity and the number of years they expect these measures to be necessary, as shown in Figure 9.

They suffered changing room set point temperature of air-conditioning system, elevator operation, and turning off ceiling light. On the other hand Cool Biz, cutting stand-by electricity, and turning off lighting during lunch and after office hours were fairly accepted. It shows that decreased tolerance for energy saving and comfort through thorough.

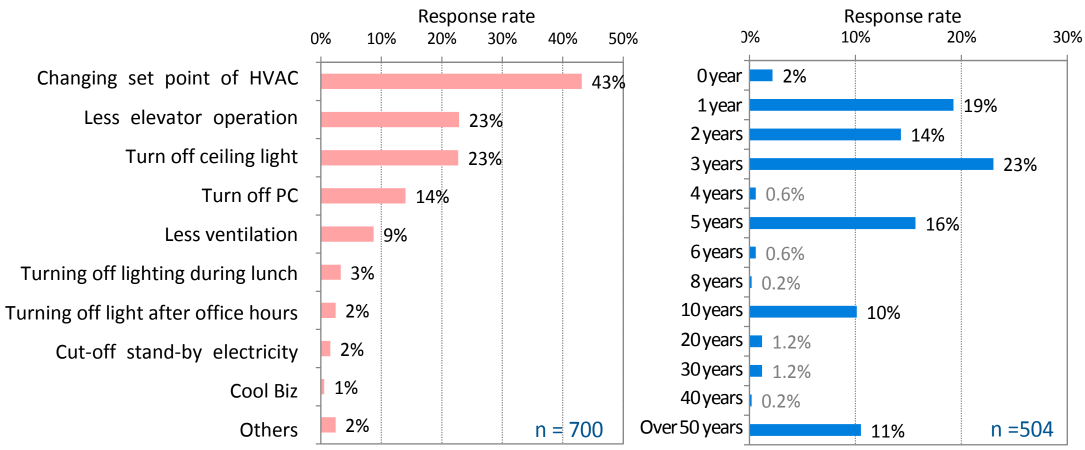


Figure 9 Most annoying means of conserving energy and the expected number of years necessary for setsuden.

We asked respondents, "Compared with last summer. How much do you estimate is your loss or gain in productivity?" Taking the average of the 474 respondents, we found that loss in productivity was 6.6% due to setsuden, as shown in Figure 10. This represents a considerable economic impact. Hence, we have to find good strategies for electricity savings that do not affect productivity. We wonder whether such claim can be purely attributed to environmental conditions and particular thermal comfort. Office workers in Tokyo in the summer of 2011 might have other reasons for reduced productivity. Further investigation is planned during 2012.

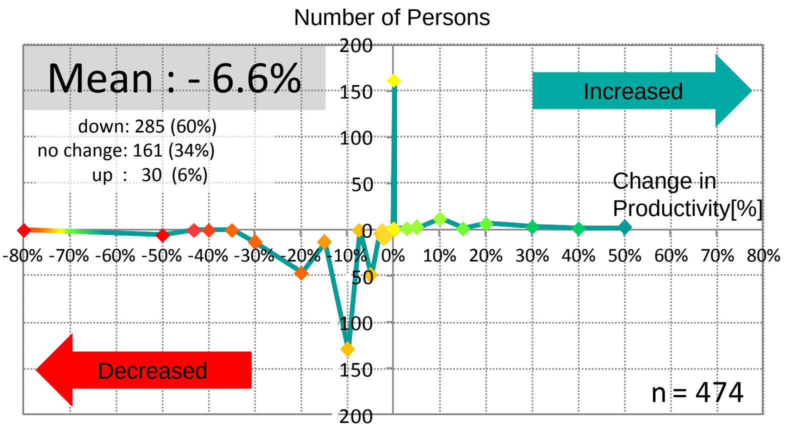


Figure 10 Productivity losses under setsuden

Conclusions

It was found that self-estimated productivity was 6.6% lower than last summer. Hence, we have to find good strategies for electricity savings that do no reducing productivity.

Acknowledgement

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Reference

Ministry of Economy, Trade, and Industry, Japan, http://setsuden.go.jp (in Japanese)