Friday 2-5
Lab 3

Establishing a Demand Curve for Plug-Load Electricity Consumption in an MIT Dormitory

Austin Oehlerking

5/20/08
2.671 Measurement and Instrumentation
Prof. Leonard

Abstract

Plug-load electricity consumption was measured for eighteen undergraduate dorm rooms in German House, an MIT living group, over the span of four weeks. Each room was monitored for 24 hours using a plug-load meter named the Watt's Up Pro. The devices being used in each room were recorded, and specific usage patterns were identified for particular devices and rooms. The eighteen rooms consumed a total of 28.10 kilowatt-hours, or 1.56 kilowatt-hours per student per 24 hours. The average demand per student was 65.08 watts, and over the course of 24 hours each room was responsible for approximately 0.20 pounds of carbon dioxide emissions. Based upon an analysis of power usage during periods of room inactivity, it was estimated as a lower bound that 14% of the energy that the eighteen rooms used was wasted due to idling computers and speakers.

The individual room demand curves were aggregated to create an overall German House electricity demand curve. Data was also taken for the communal German House lounge over a 24 hour period. Sinusoidal and parabolic curves were fit to the data for the aggregate lounge and no lounge cases. It was determined that the optimal fits occurred in the no lounge case, since the lounge data did little more than add noise to the system. The parabolic fit was slightly better than the sinusoidal fit for the no lounge case in terms of error, but the sinusoidal fit curve made more sense because electricity consumption must be a periodic function that repeats each day. The sinusoidal demand function of German House peaks just after midnight and dips to a minimum during the day when students are gone to class.

Introduction

The popular media today is increasingly championing the importance of energy conservation. Energy is becoming more expensive due to the rising costs of fossil fuels, and the environmental imperative of transforming the world's energy supply to cleaner sources is beginning to register with people of all backgrounds. However, very few individuals actually have any idea how much electricity they consume in a given day or where that electricity goes. For instance, it is very difficult to visualize how much a refrigerator is consuming on average versus a laptop computer. Many household devices draw a significant amount of electricity, even when their owners are not in the house or the devices are not in use. Moreover, it is unclear whether consumption habits among similar groups of individuals (comparable living spaces, socioeconomic backgrounds, etc.) are relatively uniform or if some individuals are major wasters of electricity while others use little electricity.

University dormitories represent an excellent opportunity to study personal electricity consumption of large groups of people. Students share a living space that has a very uniform style, and each student is given approximately the same amount of space to work with. The logistical coordination of metering many different individuals is also simplified by the close proximity of the rooms.

Motivating people to conserve electricity requires an understanding of how the typical individual consumes electricity over the course of a day and of where the so-called "low hanging fruit" of wasted energy may be located. As a first step towards this goal, we measure the electricity consumption of devices in the dormitory rooms of eighteen different students, each for a period of 24 hours. We then compare the relative consumption between the students and rank them in terms of average electricity usage throughout the day. We finally apply several best fit functions to the data in order to estimate the 24-hour demand curve of the dorm.

Background

German House (Das Deutsche Haus) is a small cultural community with 22 student residents. It is located within New House, an MIT dormitory with 286 total residents. German House is located on the 2nd, 3rd, and 4th floors of the 6th wing of New House. Every room within the community is a single, meaning that no resident lives with a roommate. The house does share a common lounge and a kitchen, however.

The overall electricity usage of New House was monitored in weekly intervals during the time of this experiment due to the MIT Dorm Electricity Competition [1]. The data was read using an analog electricity meter located within the building. At least one student led project has attempted to install a real time, floor-level electricity metering system within New House. However, due to the antiquated and ad-hoc nature of the electrical system within the building, no finer granularity could possibly be obtained in the data than building level consumption. Efforts to obtain real-time metering of building-level consumption are still ongoing [2].

In the United States, standard electrical outlets operate at a voltage of 120 volts. New House receives three-phase electricity input at 480 volts and 1,600 Amps/phase. The voltage is stepped down to a single phase 120 volt output for all electrical outlets in rooms and lounges. Kitchen stoves, washers, and dryers are exceptions, utilizing 220 volt connections.

The source of New House's electricity is the 20 megawatt MIT cogeneration plant, which powers most of the campus [3]. The cogeneration plant burns natural gas, which is a cleaner fossil fuel than coal or oil. However, the power is somewhat more expensive than average, and generation costs MIT between 10-15 cents per kilowatt-hour. In total, MIT spends about $1 million per week on its energy needs. It is estimated that the cogeneration plant and other MIT activities generated over 275,000 metric tons of carbon emissions last year [4].

Although MIT does receive on average about 20% of its power from NSTAR off the electricity grid, approximate estimates for carbon dioxide emissions associated with electricity consumption in dorm rooms can be obtained using data for the heat rate and fuel content of the cogeneration plant.

MIT 20 Megawatt Gas Turbine

Heat Rate:	17 BTU/kWh
Natural Gas Fuel:	7.89 lbs CO_2/kBTU [5]

$$\left(\frac{lbs\,CO_2}{kWh}\right)=\left(\frac{7.89\,lbs\,CO_2}{1000\,BTU}\right)\times\left(\frac{16\,BTU}{kWh}\right)=0.1262\ \frac{lbs\,CO_2}{kWh}$$

Joule's law provides a simple relationship between current, voltage, and power (Equation 1). Using a fixed value for the voltage of 120 V, conversions can easily be made between current and power for a given data set.

$$P = I \times V \qquad \text{(Equation 1)}$$

We assume that aggregate personal electricity usage will resemble a periodic function, repeating once every 24 hours. This would presumably reflect the average schedule followed by MIT students. We would expect for room device usage to drop off during the day when students are in class and then pick up again in the evening hours when students are in their dorms studying.

Although a Fourier Transform analysis is impossible in a case for which the data set comprises less than one period of the resulting function, a sinusoidal fit curve can be obtained even from a single 24-hour period of analysis. Our generic sine function is represented in Equation 2.

$$D(t) = A\sin(B * t + C) + D \quad (0 \le t \le 24) \qquad \text{(Equation 2)}$$

$$B = \omega = \frac{2\pi}{T} = \frac{2\pi}{24} = 0.2618, \qquad \text{(Equation 3)}$$

where D(t) is the instantaneous plug-load electricity demand in watts, t is the time of day in hours, A is the amplitude, B is the angular frequency, C is the phase, and D is the vertical offset. In Equation 3, the angular frequency is given in terms of the period, T. Since we desire the period to be fixed at 24 hours, the value for the angular frequency, B, becomes a constant.

Best fit values for the parameters A, C, and D can be obtained manually or by using automated solving algorithms. The final fit function, therefore, will resemble Equation 4.

$$D(t) = A\sin(0.2618 * t + C) + D \quad (0 \le t \le 24) \qquad \text{(Equation 4)}$$

As a means of comparison, a parabolic fit to the 24-hour data may also be appropriate. Although such a function may not make sense in terms of the periodic nature of electricity consumption, it may provide clues as to potential improvements on the sinusoidal fit curve. For instance, a piece-wise linear and parabolic function may fit the data significantly better than an ordinary sine function. When students leave their rooms during the day for class, it seems likely that the aggregate demand curve would be relatively linear and constant. Conversely, the demand curve would be expected to increase and decrease in a non-linear fashion as students returned home and went to sleep in staggered intervals. We could, of course, obtain a much better fit curve with the use of a Fourier Transform, but as was mentioned, this method is not available to us with the given data set.

The parabolic fit can be obtained using the method of least squares, minimizing the error for the parameters in Equation 5.

$$D(t) = At^2 + Bt + C \quad (0 \le t \le 24) \ , \qquad \text{(Equation 5)}$$

where D(t) is the instantaneous electricity demand in watts, t is the time of day in hours, and A, B, and C are the fit parameters.

Experimental Procedure

Data collection was carried out using a plug-load electricity meter named the Watt's Up Pro. Two meters were made available on loan by the 2.671 lab. In order to establish the 24-hour demand curve for each room, meters were installed in rooms for at least one day each. The data was logged in the internal memory of the meter, and it was downloaded by a USB connection after data collection was finished.

Figure 1: Watt's Up Pro electricity meter

In order to collect data in a given room, all devices utilizing electrical outlets were rerouted through the Watt's Up Pro meter using extension cords and stacked power strips. Each room in German House has its own circuit breaker that can be reset if consumption within the room exceeds two kilowatts. The Watt's Up Pro is rated for a max current of 15 Amps, which is equivalent to 1.8 kilowatts at the standard outlet voltage of 120 volts. However, the meter was observed successfully measuring power outputs upwards of 3.5 kilowatts during simultaneous testing with two microwaves and a toaster oven. It seems safe to exceed the power rating of the Watt's Up Pro for brief periods of time. Since the room-level circuit breakers are tripped at two kilowatts (roughly 16.7 Amps), the rating of the Watt's Up Pro was never exceeded by much during room level testing. Only room number five managed to trip its circuit breaker during testing, and in this case the Watt's Up Pro meter continued to collect data as normal.

Eighteen rooms were studied, and all data collection took place between April 9 and May 6 (Table 1). Data was only collected on weekdays under the assumption that lifestyle patterns and electrical device usage would be more consistent across different rooms during the week. All together, the data was collected across the span of 28 days. No major seasonal variations occurred during this time which could have substantially affected the data.

The data was logged in 30 second intervals, resulting in 2,880 samples for each room in the 24-hour periods. In each sample, the instantaneous values for time (seconds), power output (W), and electricity consumption (kWh) were logged. Individual rooms were analyzed and ranked in terms of their average consumption over 24 hours as well as their instantaneous demand and cumulative consumption curves.

In each room, the number and type of devices included in the monitoring were recorded. Overhead room lights were not included in the study because they are wired directly into the building and therefore could not be measured with the Watt's Up Pro. Additionally, the sex (male, female) and class years (freshman, sophomore, junior, senior) were recorded for the occupants of each of the measured rooms.

Aggregate graphs for instantaneous demand and cumulative consumption were constructed for the eighteen rooms. The data for each room was aligned with a standardized 24-hour range and summed across matching times in order to achieve the aggregate demand curve. The same process was used for the aggregate cumulative consumption curve. Although these cannot be considered true instantaneous demand and consumption curves since the data sampling took place over many days, it should be a close approximation of a potential demand curve that could occur on any given day.

Table 1: Data Collection schedule for 18 German Haus rooms, April and May 2008, 'X' indicates the usage of a meter in a room on a particular date, 'X (L)' indicates usage of a meter in the common lounge

	S	**M**	**T**	**W**	**T**	**F**	**S**
				4/9	4/10	4/11	4/12
Meter 1				**X**	**X**		
Meter 2							
	4/13	4/14	4/15	4/16	4/17	4/18	4/19
Meter 1		**X**	**X**	**X**	**X**	**X**	
Meter 2		**X**	**X**		**X**	**X**	
	4/20	4/21	4/22	4/23	4/24	4/25	4/26
Meter 1		**X (L)**	**X**	**X**	**X**	**X**	
Meter 2		**X (L)**	**X (L)**				
	4/27	4/28	4/29	4/30	5/1	5/2	5/3
Meter 1		**X**		**X**			
Meter 2							
	5/4	5/5	5/6	5/7	5/8	5/9	5/10
Meter 1			**X**				
Meter 2							

The logistics of the data collection were limited by several factors. Since only two meters were available, electricity demand across all rooms could not be measured simultaneously. Additionally, the expediency of the sampling was limited by the unpredictable schedules of the students involved in the study. In several instances, meters were left for several days in students' rooms because of prolonged absences from the dormitory. As the data set began to expand, it became increasingly difficult to find new individuals within the German House dormitory that were available for metering. Although there are 22 occupied rooms within this community, only 18 could be measured due to these logistical limitations.

Data was also taken for the common lounge and kitchen that serves the entire German House community. Due to the 15 Amp limit on the Watt's Up Pro meter, the metering of the lounge and kitchen had to be split up into three different metering sessions. Also, stoves and ovens could not be monitored because they utilized 220 V connections not compatible with the Watt's Up Pro meter.

Results and Discussion

Average demand across the eighteen measured rooms was 65.08 watts per student. Equivalently, the average room used 1.56 kilowatt-hours of electricity in the 24-hour time span, costing about 19.5 cents and responsible for approximately 0.197 pounds of CO_2 pollution (Table 2). Keeping in mind that these numbers only reflect devices plugged into the outlets in the students' dorm rooms and not their overall consumption patterns throughout the day, the results are quite staggering.

Table 2: Metering results across eighteen rooms, including CO_2 released

Rank	Room #	Average Demand (W)	Total Consumption (kWh)	Min Demand (W)	Peak Demand (W)	Standard Dev (W)	Carbon Dioxide Produced (lbs)
1	Room 5	314.11	7.54	140.80	1874.70	193.41	0.95
2	Room 1	160.31	3.92	22.80	413.20	122.10	0.49
3	Room 18	127.34	3.05	9.10	1685.80	9.10	0.39
4	Room 13	74.03	1.78	14.80	777.80	67.05	0.22
5	Room 3	72.46	1.74	0.60	572.70	96.45	0.22
6	Room 6	70.72	1.70	5.10	1314.70	90.26	0.21
7	Room 10	64.40	1.55	46.30	142.80	30.81	0.20
8	Room 17	60.52	1.45	3.60	248.30	48.76	0.18
9	Room 8	58.76	1.41	37.50	125.70	19.49	0.18
10	Room 7	39.07	0.94	10.80	550.70	46.39	0.12
11	Room 9	33.72	0.81	1.20	731.50	49.54	0.10
12	Room 16	21.00	0.50	1.60	248.20	17.20	0.06
13	Room 4	17.33	0.42	7.80	62.60	10.70	0.05
14	Room 11	15.10	0.36	10.00	115.90	16.63	0.05
15	Room 14	13.24	0.32	4.10	137.10	24.37	0.04
16	Room 15	11.58	0.28	1.20	56.30	14.06	0.04
17	Room 12	11.30	0.27	2.50	69.80	13.30	0.03
18	Room 2	3.61	0.08	1.40	71.10	9.37	0.01
Rooms Total		**1171.52**	**28.10**	**372.80**	**3346.00**	**410.81**	**3.55**
Total Per Room		**65.08**	**1.56**				**0.20**

The analysis of the demand and consumption graphs of individual rooms reveals a great deal of information. The mix of devices utilized in each of the eighteen rooms was very diverse (Table 3). As was to be expected, the rooms with the most devices typically consumed the highest amount of energy as well. The top two consumers each had multiple laptops, a desktop computer, desk lamp(s), refrigerators, computer monitors, surround sound speaker systems, and other devices. The lowest consumers, in contrast, typically only used one laptop, one cell phone charger, and perhaps a lamp. This disparity resulted in a full order of magnitude difference between the average consumption of the top 17% (Rooms 5, 1 and 18) and the bottom 17% (Rooms 15, 12, and 2)

In terms of overall consumption, Room 5, the largest consumer, used nearly twice the amount of electricity as Room 1, the 2nd largest consumer. Room 1, in comparison, used well over twice the average amount of power used by the eighteen rooms.

Rooms 5, 1, and 18 can be designated as the upper consumption tier, each consuming a significantly higher-than-average amount of power during the course of the day. Rooms 13, 3, 6, 10, 17, and 8 formed a second tier, each consuming roughly 5-6% of the overall energy used among the eighteen rooms. Consumption then dropped steadily for the lowest consumption tier, comprised of rooms 7, 9, 16, 4, 11, 14, 15, 12, and 2 (Figure 2, Figure 3).

Table 3: Devices used in rooms compared to average demand and total consumption.

	Room 5	Room 1	Room 18	Room 13	Room 3	Room 6	Room 10	Room 17	Room 8	Room 7	Room 9	Room 16	Room 4	Room 11	Room 14	Room 15	Room 12	Room 2
Sex (M, F)	M	M	F	M	F	M	M	F	M	M	F	F	M	M	M	F	M	F
Year (1, 2, 3, 4)	3	4	4	3	3	4	1	1	1	3	1	2	4	1	1	4	4	2
Room Statistics																		
Average Demand (W)	314.11	160.31	127.34	74.03	72.46	70.72	64.40	60.52	58.76	39.07	33.72	21.00	17.33	15.10	13.24	11.58	11.30	3.61
Power Consumed (kWh)	7.54	3.92	3.05	1.78	1.74	1.70	1.55	1.45	1.41	0.94	0.81	0.50	0.42	0.36	0.32	0.28	0.27	0.08
Devices																		
Laptop 1	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Laptop 2	X	X																
Desktop Computer	X	X	X															
Cell Phone Charger	X	X	X		X			X		X			X	X	X	X		X
Desk Lamp	X	X	X		X	X	X	X	X	X	X		X	X	X		X	
Refrigerator	X	X		X	X	X	X	X	X	X	X							
Monitor	X	X	X															
Speakers	X	X	X							X			X	X				
TV		X																
Microwave						X					X	X						
Alarm Clock						X	X		X	X				X	X			
Water Heater	X		X															
Coffee Grinder	X			X														
Printer			X											X				
Keyboard (Instrument)													X	X				

Comparing the individual room consumption graphs also provides a wealth of information (Figures 4-7). Many of the rooms consume a significant amount of power even when it is clear that the rooms are not being used. Refrigerators are a key indicator of which rooms will consume the most power. Ten of the top eleven consumers used refrigerators, while none of the bottom seven had one. The demand curve of a refrigerator is easily apparent in any graph due to its periodic on-off cycle.

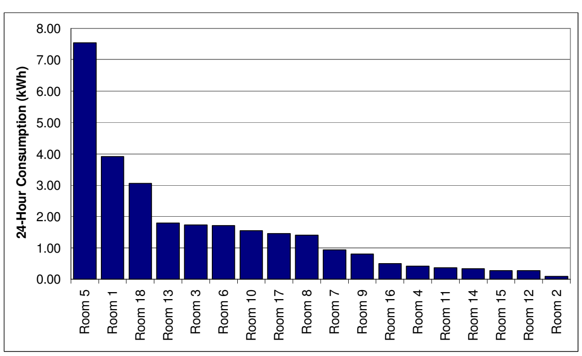

Figure 2: Relative consumption (kWh) of Rooms 1-18

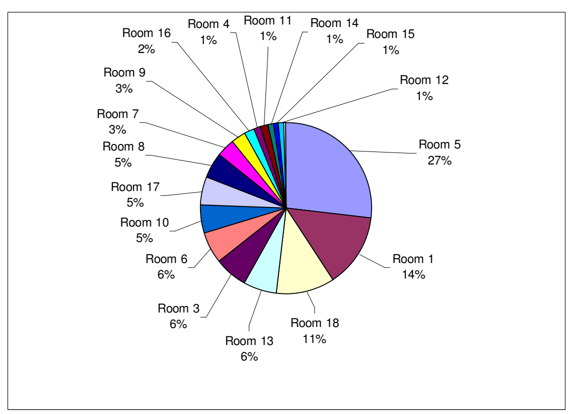

Figure 3: Relative consumption (%) of rooms 1-18

Many of the rooms displayed similar usage patterns, revealing a significant amount of useful information. Four rooms that are representative of the overall sample population are analyzed in detail here.

Room 1

Room 1 (Table 4, Figure 4) was the second highest consumer of all eighteen rooms, using 3.92 kWh of energy in 24 hours. The devices used in the room included two laptops, a desktop computer, an LCD monitor, a 5.1 surround sound audio system, a cell phone charger, a desk lamp, a refrigerator, and a television. Based upon an analysis of Figure 4, three primary consumption patterns can be identified in the room (Table 4). The first pattern seems to occur when most of the devices are activated and there is a high level of activity in the room, including computer, television, and audio use. The base load for this pattern is 225 watts, with fluctuations as high as 413 watts when the refrigerator was actively cooling.

The second pattern likely occurred during sleep of the resident based upon its time span (6:00 AM – 10:30 AM). The variations are much less drastic than in Pattern 1, although some CPU activity can be inferred by the small power fluctuations. The resident apparently awoke at around 10:30 AM, activating several devices at that time. The resident left shortly thereafter, resulting in a 3rd consumption pattern. Very little CPU activity is observed, and the periodic on-off cycle of the refrigerator can be seen very clearly. The total period of this refrigerator is two hours, which is the longest cycle time for any of the refrigerators measured.

The base load for the unoccupied room was approximately 25 W. Since this load is smaller than the base load while the resident was asleep, it can be inferred that at least one device was shut down or disconnected when the resident left the room. For instance, the resident may have disconnected a laptop and brought it to class while leaving at least one of the other computers in sleep mode. The base loads of Patterns 2 and 3, when the resident was sleeping and when the room was not occupied, resulted in 0.568 kWh of wasted energy that could have been saved if all of the devices had been completely shut off while not in use (not including the refrigerator).

Table 4: Electricity usage patterns in room 1. See Figure 4 as a reference.

Pattern	Description	Times	Likely Activity
1	Major oscillations between 225 W - 400 W resulting from refrigerator. Small oscillations indicate CPU acitivity. 225 W base load could indicate television, speaker system, lamp, and/or LCD monitor usage	12:00 AM - 6:00 AM 9:15 PM - 12:00 AM 10:30 AM - 10:45 AM	Awake, In-Room
2	Major oscillations between 65 W - 200 W. Minor oscillations indicate some CPU activity. 65 W base load indicates less activity than Pattern 1. The load could result from the idling computers, sound system, and/or LCD monitor	6:00 AM - 10:30 AM	Asleep, In-Room
3	Major oscillations between 25 W - 160 W. Refrigerator is responsible for only fluctuation in energy consumption. 25 W base load from same idling sources as Pattern 2, although the decrease indicates that one or multiple elements have been turned off completely	10:45 AM - 9:15 PM	Out of Room

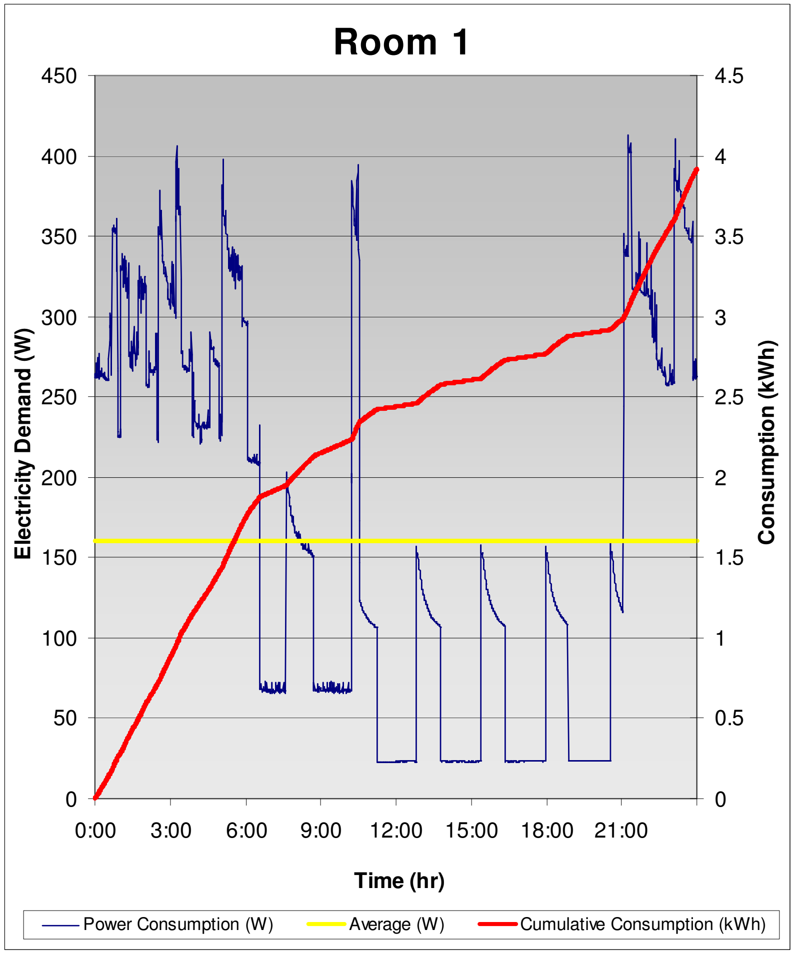

Figure 4: Room 1 demand, consumption, and average demand over 24 hours

Room 4

Room 4 was a bottom tier consumer even though it had an electronic keyboard which could potentially have used quite a bit of power. The consumption graph seems to indicate, though, that the keyboard was never used during the course of the day. Two relatively simple patterns can be deduced from the graph (Table 5, Figure 5). When the room was in use, the laptop and possibly the desk lamp were the exclusive drivers of consumption. Demand fluctuated between 25 watts and 53 watts. While the room was unoccupied or the resident was asleep (2:50 AM – 2:45 PM), demand held steady at 8 watts, probably due to the laptop being in sleep mode. There are no small changes in demand that might indicate a cell phone charger being used during this time, unless the cell phone was left to charge for 12 straight hours. A total of 0.095 kWh was wasted while the room was unoccupied or the resident was asleep.

Table 5: Electricity usage patterns in room 4. See Figure 5 as a reference.

Pattern	Description	Times	Likely Activity
1	Fluctuations in usage between 25 W and 53 W resulting from computer use. Base load of 25 W may indicate the use of the desk lamp, cell phone charger, or speakers	12:00 AM - 2:50 AM 2:45 PM - 12:00 AM	Awake, In-Room
2	Consumption steady at 8 W, most likely from laptop computer in sleep mode	2:50 AM - 2:45 PM	Asleep or Out of Room

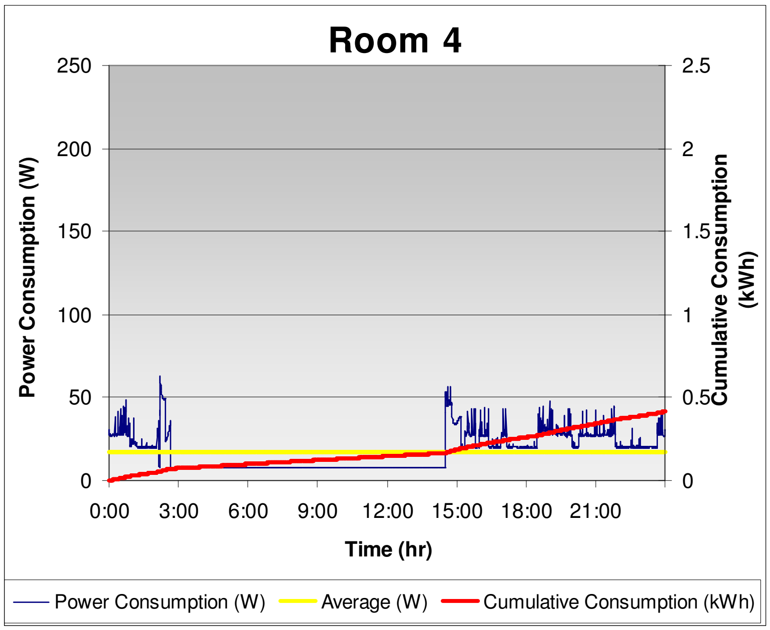

Figure 5: Room 4 demand, consumption, and average demand over 24 hours

Room 10

The consumption patterns in room 10 were quite unusual. Although the room contained a refrigerator that was included in the metering, the demand curve does not demonstrate the typical on-off cycle of all of the other measured refrigerators. Because of the base load of 49 watts, it is assumed that the refrigerator was on at all times and always drew the same amount of power. During the metering, the refrigerator was observed turning off at least once for a short time, but the power consumption still did not change. It is not clear why the power did not vary in proportion to the state of the compressor, but it is possible that the wasted power resulted from a low quality or inefficient design.

Table 6: Electricity usage patterns in room 10. See Figure 6 as a reference.

Pattern	Description	Times	Likely Activity
1	Steady consumption at about 140 watts. Small oscillations indicate computer use. Laptop, desk lamp, and refrigerator all active. Note that this refrigerator does not exhibit typical periodic behavior. It is always on.	1:00 AM - 3:00 AM	Awake, In Room
		7:50 AM - 10:00 AM	
2	Flat consumption at 49 watts indicates no room activity except for the refrigerator.	12:00 AM - 1:00 AM	Asleep or Out of Room
		3:00 AM - 7:50 AM	
		10:00 AM - 6:00 PM	
		8:45 PM - 11:30 PM	
3	Steady at about 75 W. Same shape as Pattern 1 but with a smaller magnitude - the desk lamp is probably turned off.	6:00 PM - 8:45 PM	Awake, In Room
		11:30 PM - 12:00 AM	

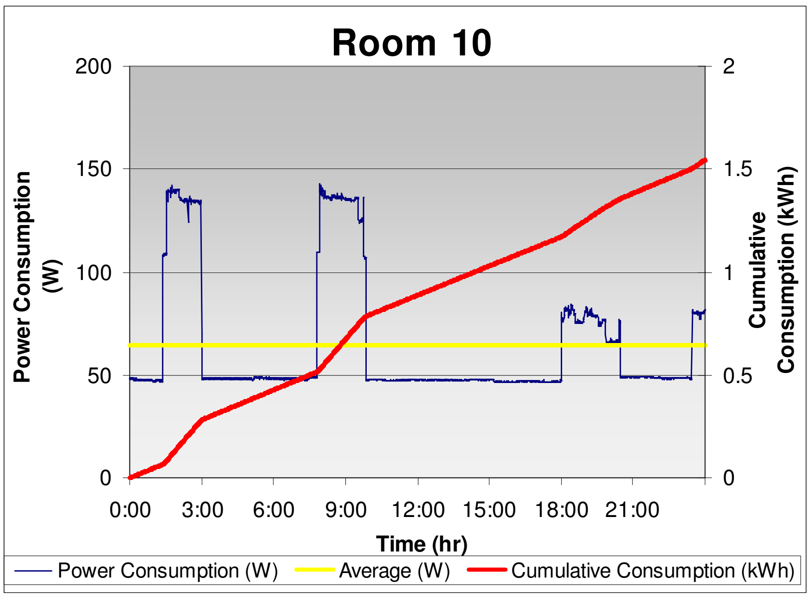

Figure 6: Room 10 demand, consumption, and average demand graphs over 24 hours

Room 17

The consumption pattern in room 17 was dominated by a refrigerator, a laptop computer, and a desk lamp. The refrigerator had a relatively quick cycle, turning on and off once per hour. The laptop was plugged in for most of the day except for about half and hour just before noon. At two points in the day, a desk lamp was turned on for about an hour. Because the laptop may have displayed the same characteristics if it was plugged in while the resident left the room, it is somewhat unclear when the resident was in the room awake, in the room sleeping, and out of the room. The only certainty is that the resident was in the room at each point when the desk lamp was turned on as well as when the laptop was unplugged and then plugged back in.

Table 7: Electricity usage patterns in Room 17. See Figure 7 as a reference.

Pattern	Description	Times	Likely Activity
1	Oscillation between 40 W-175 W due to refrigerator. Minor fluctuations due to laptop computer. Base load of 40 W probably due to computer and cell phone charger	12:00 AM - 2:50 AM 4:30 AM - 11:30 AM 12:15 PM - 9:00 PM	Unclear
2	Same as Pattern 1 with an increase of about 60 W, indicating that the desk lamp was turned on	2:50 AM - 4:30 AM 9:00 PM - 12:00 AM	Awake, In Room
3	Brief drop to zero consumption, meaning the laptop was probably unplugged for a period of time	11:30 AM - 12:15 PM	In Room at First, then Unclear

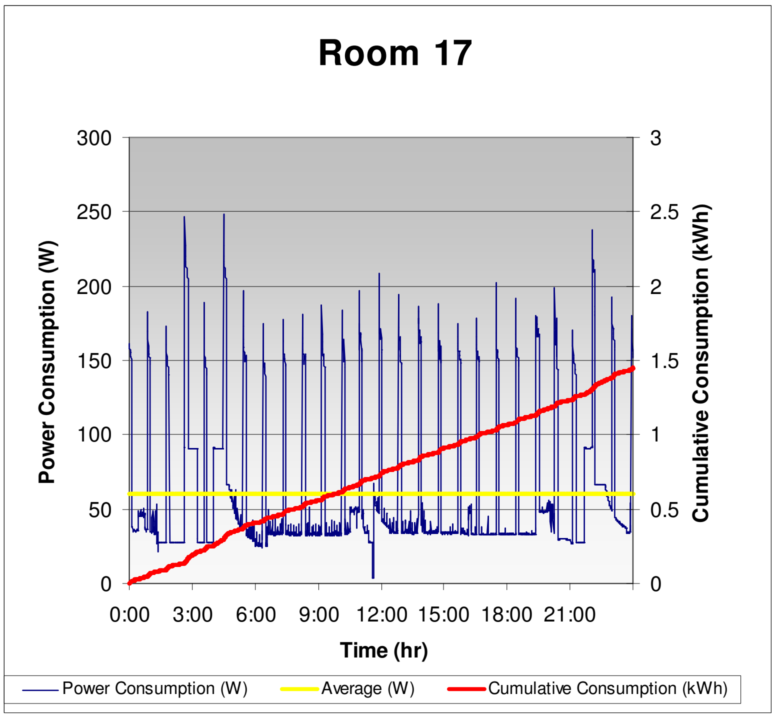

Figure 7: Room 17 demand, consumption, and average demand graphs over 24 hours

By carefully examining the consumption graphs of each of the 18 rooms in the same manner as above, estimates for total wasted power can be obtained. Wasted power in this case is defined as power that could have been saved when residents were either asleep or gone from their rooms, as best as could be determined from the demand graphs. Typically, the periods of inactivity were easy to identify within each graph. From these regions, refrigerators were discounted and the resulting base load consumption was used to determine the total wasted power (Table 8). Overall, the 18 rooms wasted 3.94 kWh of power, or 14% of the 28.1 kWh consumed in total. Almost all of this waste was the result of computers, speakers, and monitors being left on while not in use. There was likely more waste that occurred during the course of the experiment, but the observable portion of this waste from the individual room graphs establishes a lower bound for what was probably wasted.

Table 8: Wasted energy rankings, calculated from base load demand when residents are asleep or gone from room. Refrigerators not included.

	Rank (Wasted Energy)	Rank (Total Consumption)	Rank Change	Time Inactive (hr)	Inactive Base Load (W)	Energy Wasted (kWh)	CO2 released (lbs)
Room 5	1	1	**0**	11	150	1.650	0.208
Room 1	2	2	**0**	15.5	36.7	0.569	0.072
Room 8	3	9	**+6**	15	37.5	0.563	0.071
Room 17	4	8	**+4**	7	40	0.280	0.035
Room 11	5	14	**+9**	22	10	0.220	0.028
Room 7	6	10	**+4**	12	10.8	0.130	0.016
Room 13	7	4	**-3**	8	14.8	0.118	0.015
Room 4	8	13	**+5**	11.92	8	0.095	0.012
Room 6	9	6	**-3**	14.5	5.1	0.074	0.009
Room 14	10	15	**+5**	12	4.1	0.049	0.006
Room 18	11	3	**-8**	8	6	0.048	0.006
Room 12	12	17	**+5**	17	2.5	0.043	0.005
Room 2	13	18	**+5**	23	1.6	0.037	0.005
Room 16	14	12	**-2**	7	4.3	0.030	0.004
Room 9	15	11	**-4**	12	1.2	0.014	0.002
Room 15	16	16	**0**	11	1.2	0.013	0.002
Room 3	17	5	**-12**	17	0.6	0.010	0.001
Room 10	18	7	**-11**	16.5	0	0.000	0.000
					Total	**3.943**	**0.498**

The data from each of the 18 rooms was aggregated to produce demand and consumption graphs for the entire community (Figure 8, Figure 9). The disparity between the consumption of the highest and lowest consumers is especially apparent in the 24 hour consumption graph in Figure 8. The community as a whole consumed 28.1 kilowatt-hours, and a major portion of this is dominated by the biggest consumers.

The cumulative demand curve in Figure 9 is quite extraordinary. Although many of the individual room data sets did not display the expected periodic, sinusoidal demand function, the aggregate demand graph by inspection seems periodic and sinusoidal despite the noise that exists. The large spikes that occur throughout the day are anomalies caused by devices consuming very large amounts of power for short periods of time. Some of these devices that were used in rooms included coffee grinders, personal water heaters and microwaves. Each operates typically for less than two minutes but consumes between 1-2 kilowatts of power. Since the aggregate demand average is only 1,171 watts, these devices can easily skew the aggregate curve. Fortunately, since they only persist for two or three data points each, the data is not corrupted very much.

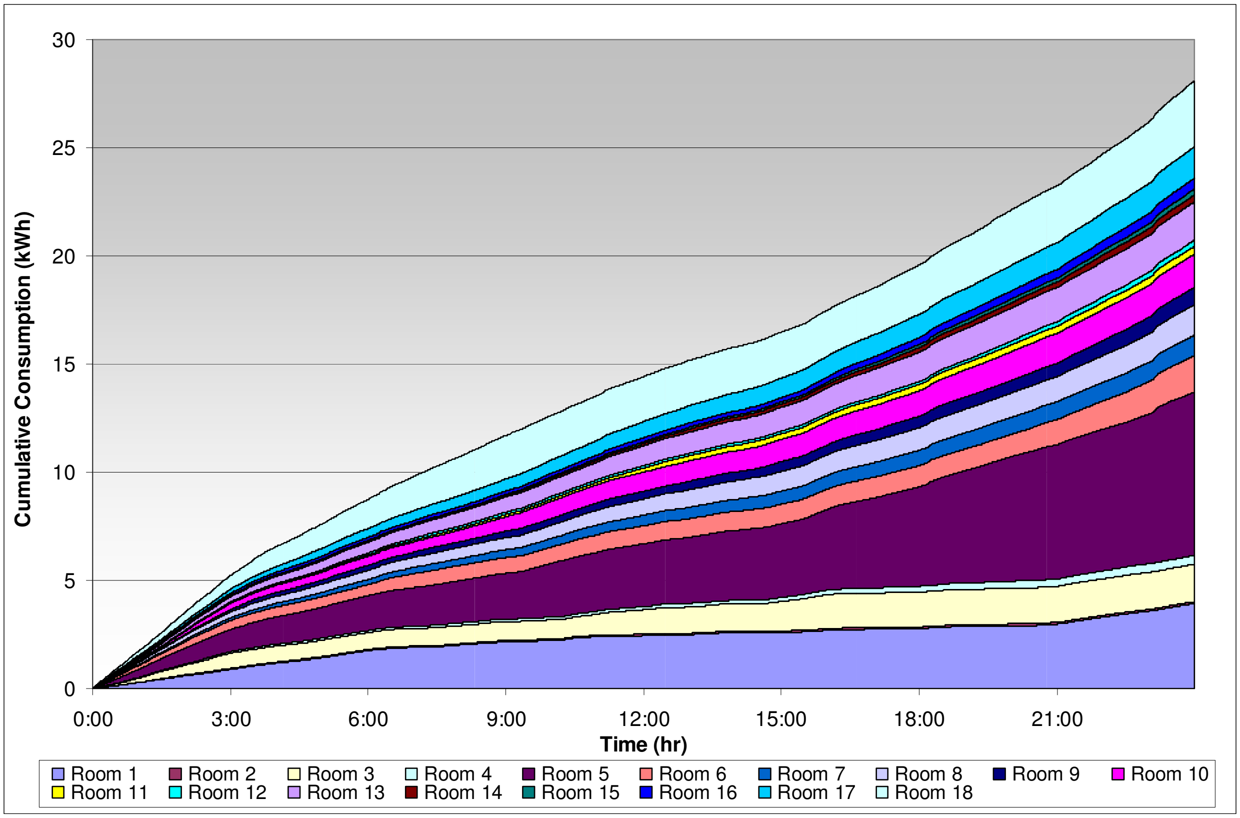

Figure 8: Cumulative 24-hour power consumption, rooms 1-18

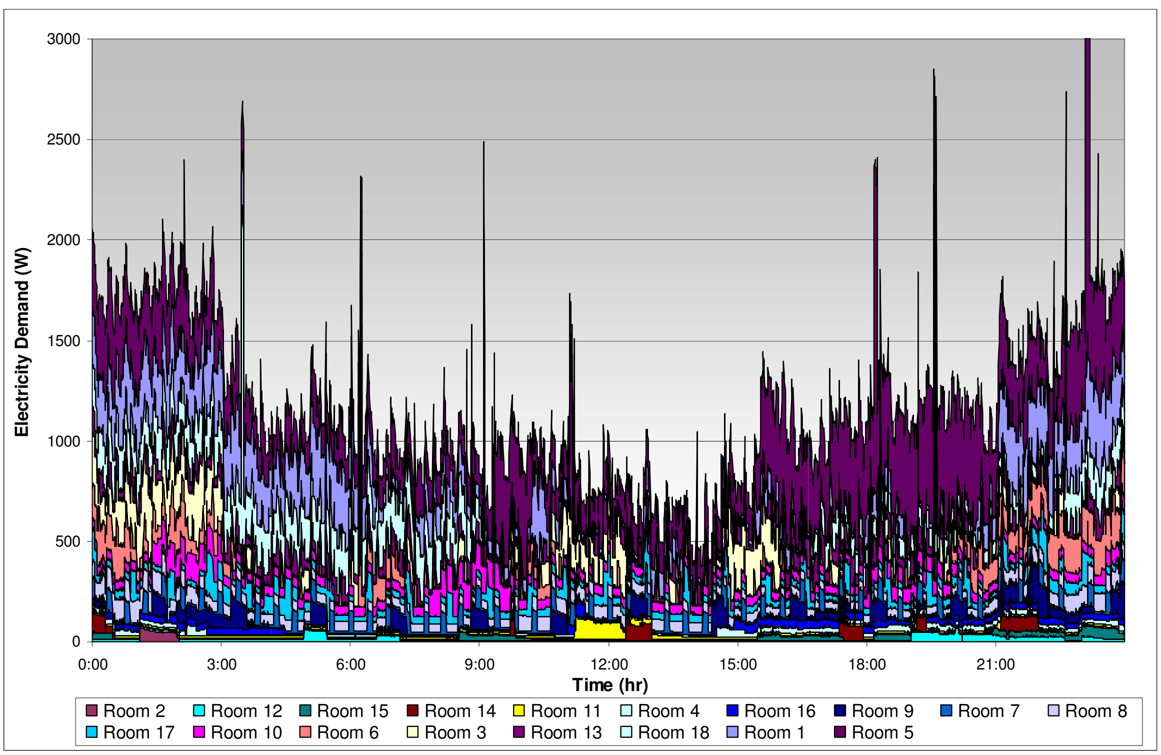

Figure 9: Cumulative 24-hour demand curve, rooms 1-18

Data was also taken for three different lounge meters (Table 9). In total, these meters measured a combination of microwaves, large refrigerators, toasters, and entertainment devices. The stoves and ovens could not be measured due to their 220 V connection.

Since the lounge and kitchen are communal, the aggregate demand and consumption per student in the lounge was calculated (Table 10). When combined with the room data, the lounge consumed 28.0% of the device power used by students.

Table 9: Devices Measured in Common Lounge and Kitchen

Lounge Devices	Total Measured
Microwaves	2
Large Refrigerators	4
Toasters	1
Speaker Systems	1
TV	1
DVD/VCR	1

Table 10: Electricity usage results for three lounge meters

Lounge Meter	Average Demand (W)	Total Consumption (kWh)	Min Demand (W)	Peak Demand (W)	Standard Dev (W)	Carbon Dioxide Produced (lbs)
1	321.98	7.73	6.40	1183.50	185.88	0.98
2	63.95	1.53	6.30	3231.70	310.88	0.19
3	68.25	1.64	0.00	468.11	70.74	0.21
Total	**454.18**	**10.90**	**13.05**	**3031.53**	**358.98**	**1.38**
Total per Student	**25.23**	**0.61**				**0.08**

The demand curve for the lounge was driven primarily by the four large refrigerators being measured as well as the television and speaker system (Figure 10). Demand increases in the middle of the day, probably due to television use. Unfortunately, this occurs during the period of time in which we expect rooms to be consuming the least amount of power. Because the lounge contains several high power devices, such as the microwaves and toaster, there are also very large spikes in the demand periodically throughout the day.

The final objective in the analysis is to find a function for the best fit line of the demand curve. Since demand is periodic and is expected to repeat in approximately the same form each day, we expect a sinusoidal curve to demonstrate the best fit. However, since the data also seems to resemble a parabolic function, we test a parabolic fit even though this function would not make sense for a periodic system.

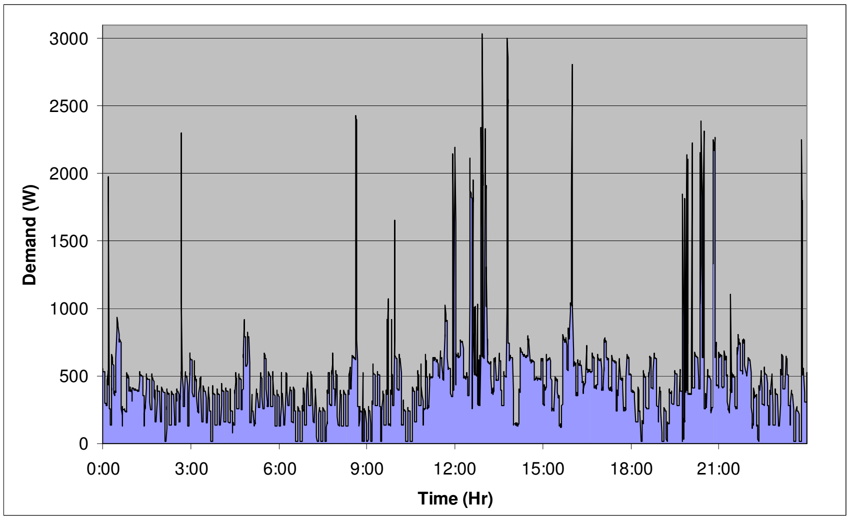

Figure 10: Plug-load electricity demand, German House lounge

The curves were fit for the aggregate demand of the 18 rooms as well as the demand of the 18 rooms plus the lounge (Table 11). As described in the background, the periods of the sinusoidal functions were set to 24 hours while the parameters for amplitude, phase, and offset were optimized using an internal LoggerPro algorithm. The parameters were also optimized by varying the parameters manually, and the same result was obtained.

The parabolic functions were optimized within LoggerPro using a least squares algorithm. Overall, the parabolic fits had lower root mean square errors than the sinusoidal fits. Additionally, the demand curves that included the lounge data had much larger errors than the pure room data. This result was expected since the lounge demand curve essentially just added noise to the system and had no dominant shape that resembled a sinusoidal or parabolic function.

Table 11: Best fit parameters for sinusoidal and parabolic functions, no lounge and lounge scenarios, 95% confidence integrals for fit parameters. See Equations 4 and 5.

		No Lounge	Lounge
Sinusoidal Fit	A	444.6 +/- 13.67	393.7 +/- 22.19
	B	0.2617 (fixed)	0.2617 (fixed)
	C	-19980 +/- .04	36580 +/- 0.05
	D	1172 +/- 9.66	1626 +/- 15.69
	RMSE	**264.5**	**429.6**
Parabolic Fit	A	7.574 +/- .217	6.706 +/- .183
	B	-184.4 +/- 5.39	-155.5 +/- 4.53
	C	1930 +/- 27.42	2204 +/- 23.55
	RMSE	**250.54**	**421.6**

The sinusoidal demand curve peaks just after midnight, demonstrating the unique consumption pattern of MIT students. Whereas normal households would likely peak in their electricity consumptions sometime in the early evening (8-10 PM), MIT students definitely seem to be working later than average into the evening.

The rest of the curve seems to follow the expected shape, dipping to a minimum in the middle of the day when the majority of the students are gone for class. As students return during the mid to late afternoon, the demand curve steadily ramps up again to its peak value.

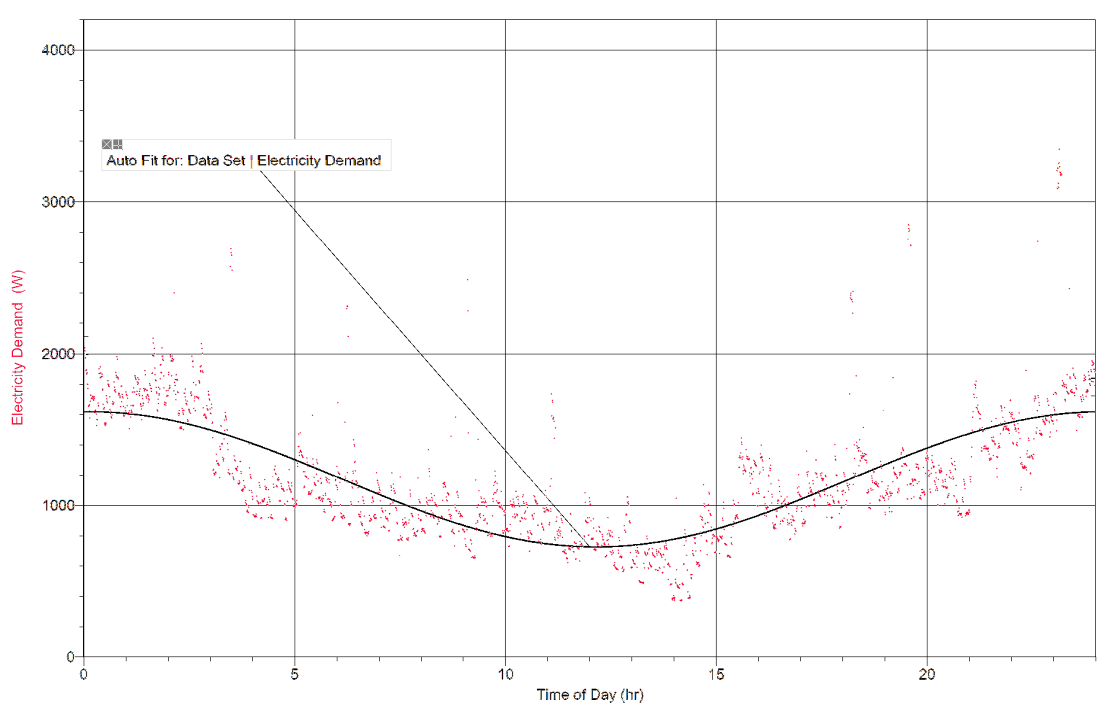

Figure 11: Aggregate German House Demand Curve (No Lounge), Sinusoidal Fit

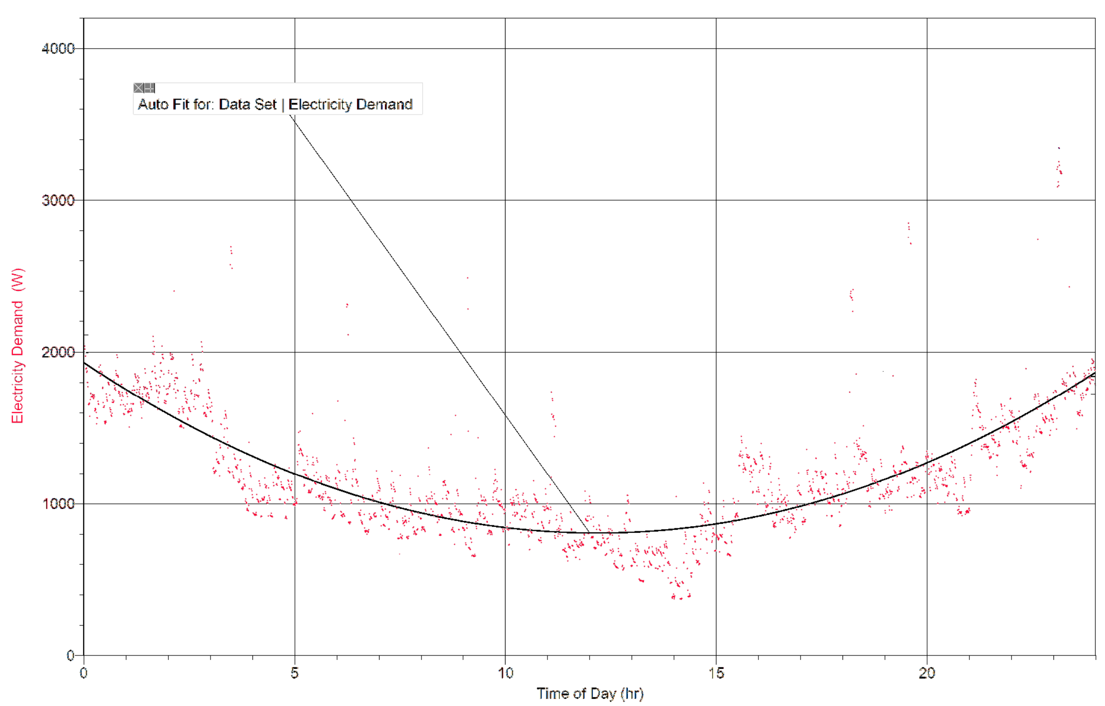

Figure 12: Aggregate German House Demand Curve (No Lounge), Parabolic Fit

Conclusions

A simple analysis of the electricity demand in 18 undergraduate dormitory rooms revealed many insights into individual consumption patterns, opportunities for the elimination of wasted power, and the characteristics of the overall demand. Individually, the rooms displayed a wide variety of demand curves. However, certain patterns were observed repeating across many rooms. Specifically, the periodic nature of the power usage of refrigerators was easily identified. Active computer use could be pinpointed by the small power fluctuations of the CPU.

By determining the base load consumptions of each individual room while the resident was either asleep or gone, it was estimated that the 18 rooms wasted 3.94 kWh over the 24 hour time period, equivalent to 14% of total consumption. So, as a lower bound, 14% of a room's electricity usage by devices could be saved merely by turning off the computers and speakers used in that room during times of inactivity.

Among the takeaways from the aggregate data is the great disparity between the levels of consumption exhibited by the rooms. The highest consumer more than doubled the energy usage of the 2nd highest consumer. Consumption was highly correlated to the numbers of devices used in one's room. Among the worst offenders were refrigerators, which consumed power continuously throughout the day, even when the room was not being used. Devices that utilized large bursts of power, such as microwaves and water heaters, served to add noise to the demand curve. However, these devices did not have a great effect on the overall power consumption since they were typically only used for one or two minutes at a time.

The lounge data was not well correlated to the demand curves for the individual rooms. In the aggregate graphs, the lounge data only added noise to the demand values and increased the error of the fit curves dramatically. Additionally, the parabolic fit had slightly less error than the sinusoidal fit, even though a parabolic demand curve makes less sense because the function must repeat on a daily basis.

The experiment could potentially be improved by metering all rooms on the same day. This would require, however, the acquisition of a sufficient number of meters, which would come at a great capital cost. We do not expect that too much error was incurred, however, by the fact that the data acquisition was spread over the course of a few weeks. No major seasonal variations occurred during this time, and the data was only taken on weekdays. The resultant demand function, rather than being a curve representative of a specific day, was a hypothetical curve that would potentially occur on any given day in German House.

It would be worthwhile in the future to further explore the consumption of specific devices utilized in the German House rooms. Data for individual devices could be compared to the overall demand data for each room, and a so-called figure of merit could be determined for specific device classes. This data would hopefully provide better clues as to the exact breakdown of plug-load consumption in rooms.

There is a significant opportunity in the future to test the effect of interventions on individual consumption patterns. For instance, while metering an individual's consumption, if a specific pattern is observed or if a certain threshold is crossed, a notification could be sent to that individual and his reaction could be observed in the data. Additionally, the building level consumption of New House could be observed, E-Mail notifications could be sent to residents about the dorm's consumption, and the instantaneous consumption effects could be recorded.

Personal electricity metering is a new area of interest that has only become relevant as energy prices have risen in recent years and public concern over global warming has come to a head. With some additional work, data on personal electricity consumption could provide insights that would allow for significant improvements in device usage efficiency. With a little bit of knowledge, individuals could have a much clearer picture of how much power they are using and where that power is going. Ideally, this insight would enable them to save a little money while saving a little bit of the environment as well.

Acknowledgements

I would like to thank all of the German House residents who allowed me to invade their personal living spaces for days at a time. I was amazed at how well this project was received by my fellow students. Most were very eager to see their own consumption graphs and to identify particular device patterns. Specifically, I would like to thank Cecilia Scott, Jodie Fernandes, Erik Stafl, Jason Bryslawskyj, Marcelo Alvisio, Ben Switala, Vladamir Sobes, Susan Virgem, Bruno Alvisio, Joshua Hester, Valery Brobbey, Harsha Wasalathanthrig, Juan, Irida Altman, Isabel Mattos, Ashley Mobbs, and Zheng Gong.

Additionally, I could not have completed this project without the enthusiastic support of the 2.671 course instructors. Professor John Leonard provided invaluable feedback that helped me early on in the data gathering phase. The electricity consumption of eighteen rooms is a lot to measure, so doing it in a consistent manner was essential. Dr. Barbara Hughey helped to guide me through many rough patches, including the process of narrowing down the appropriate data analysis to pursue when I had a gigantic maze of data to navigate. Thanks again!

References

1. MIT Dorm Electricity Competition website. http://energymap.mit.edu/dorm.
2. Database output for real time dorm electricity consumption. Only Macgregor is active as of May 12, 2008. http://www.sharpedgestudios.com/powerdata.php.
3. MIT Facilities website. http://web.mit.edu/facilities/environmental/cogen.html. Accessed 12 May, 2008
4. Cooper, Peter and Lanou, Steve. PowerPoint presentation at MIT Generator Event. Fall 2007. http://sustainability.mit.edu/wiki/images/b/be/MIT_Generator_Event_2007_final.ppt#270,6,Our GHG Challenge. Accessed 12 May, 2008.
5. Power MIT. Real time output of fuel and electricity consumption for MIT. http://cogen.mit.edu/powermit/.