Fraunhofer USA Center for Sustainable Energy Systems

Demonstrating a Net-Zero Solar Energy Elevator in a Boston Office Building

Final Report to thyssenkrupp

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Table of Contents

ACKNOWLEDGMENTS **4**
EXECUTIVE SUMMARY **5**
1 INTRODUCTION **6**
1.1 Net Zero Energy 6
1.2 Getting to Net Zero 7
1.3 Organization 7
2 APPROACH **8**
2.1 Building Description 8
2.2 Elevator System 8
2.3 Solar Photovoltaic System 8
2.3.1 Simulated Solar Production 9
2.4 Monitoring Equipment 10
3 RESULTS **11**
3.1 Elevator Activity 11
3.2 Elevator Energy Consumption 12
3.3 Solar PV System Energy Production 14
3.4 Net Zero Energy Analysis 15
4 CONCLUSIONS **17**
5 REFERENCES **18**
6 APPENDIX **19**
6.1 Elevator Specifications 19
6.2 Elevator Power Draw 20
6.3 Solar Panel Specifications 23

List of Figures

Figure 1. Solar PV array on the elevator room. Rendering and installation. 5
Figure 2. Elevator trips by day of week (LEFT) and by hour on weekdays (RIGHT). 11
Figure 3. Elevator trips per day. 11
Figure 4. Daily elevator energy use. Light values are in the bottom 40% (below 13 kWh). 12
Figure 5. Daily elevator energy use. 12
Figure 6. Hourly elevator power draw. 12
Figure 7. Average elevator energy use by component. 13
Figure 8. Daily solar power production with smoothing filter (LEFT) and cumulative production (RIGHT). 14
Figure 9. Solar production on a sunny and cloudy winter day. 14
Figure 10. Cumulative annual elevator consumption, solar production, and net energy. 16
Figure 11. Same as Figure 10, with twice the elevator activity (high usage). 16
Figure 12. Typical drive circuit power draw pattern with the TAC504 controller. At scale (LEFT), zoomed (RIGHT). 20
Figure 13. Typical drive circuit power draw pattern with the TAC32T controller. At scale (LEFT), zoomed (RIGHT) 20
Figure 14. Typical workweek elevator power draw. 21
Figure 15. Typical workday elevator power draw. 21
Figure 16. Daily elevator energy use vs. number of trips by elevator configuration. 22
Figure 17. Solar PV design specifications. 23

List of Tables

Table 1. Simulated solar production for two unshaded south-facing PV systems in various cities. 9
Table 2. Elevator activity categories. Source: VDI (2009). 11
Table 3. Elevator standby power draw component summary. 13
Table 4. Average elevator energy use breakdown. 13
Table 5. Net-zero energy balance. Shaded cells indicate an energy surplus. 15
Table 6. Elevator specifications. 19
Table 7. Elevator power draw by mode. 22
Table 8. Solar photovoltaic system specifications 23

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Finally, we would like to recognize the Boston Landmark Commission for unanimously deciding to approve this unconventional solar photovoltaic system in Boston's historic Fort Point Channel district.

EXECUTIVE SUMMARY

A net-zero energy elevator system produces at least as much energy in a year as it consumes. Using a 3.75 kW rooftop solar photovoltaic array that fits within the elevator footprint, we demonstrated a net-zero energy elevator concept in a Boston, MA office building.

The thyssenkrupp Synergy elevator used in this demonstration includes several energy-efficient features including a regenerative drive, efficient LED cab lighting, and a deep-sleep controller. With these features enabled, and with a low-to-medium activity profile, the elevator used about **2.9 MWh per year** (8 kWh/day). The solar PV array produced **4.2 MWh** in one year (average of 11 kWh/day), leading to an annual energy surplus of 45% (**+1.3 MWh** or 3.6 kWh/day). Under a hypothetical high-usage scenario, where the elevator usage is doubled on business days, we project that net-zero energy would still be possible with the same size solar array.

To validate the net-zero energy concept, we measured elevator power draw in an office building for several years under different hardware configurations and compared this with one year of energy generated by the solar array. Upgrading the elevator controller to enable deep-sleep mode reduced standby power draw by over 75% from about 400 W to 100 W. Similarly, installing an auto-power-down feature on the cab circuit to turn off the lights and fan during periods of inactivity reduced cab standby power by 90% from about 90 W to 9 W.

This demonstration confirms that the energy consumed by an efficient elevator in a mid-rise building with a moderate to high usage profile could be offset by a rooftop solar array to achieve net-zero energy operation.

Elevators consume about 80% of all U.S. vertical transport energy in the commercial buildings sector, approximately 5 billion kWh of electricity per year. Eliminating elevator energy use through a net-zero approach could reduce electric bills by up to $500 million per year.

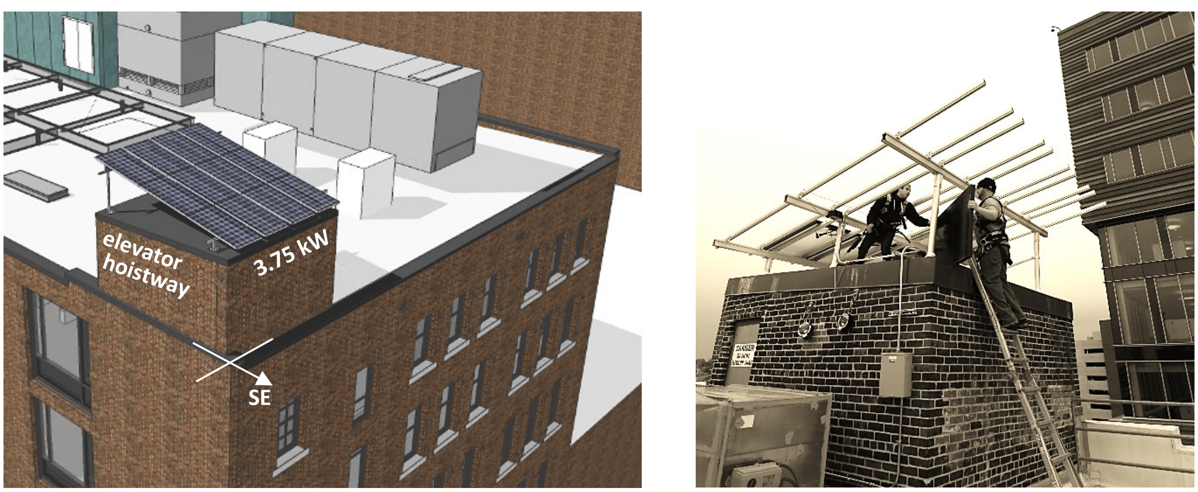


Figure 1. Solar PV array on the elevator room. Rendering and installation.

1 INTRODUCTION

This project demonstrates a net-zero energy elevator and solar photovoltaic (PV) system concept. Using a combination of energy efficient elevator design features supplemented by a rooftop PV array that fits within the footprint of the elevator, the system is designed to produce enough energy during a year to completely offset the energy consumed by the elevator.

This project took place in several phases. Throughout the project we monitored the energy consumption of an energy-efficient, regenerative drive elevator for several years. Next, we installed and monitored a 3.75 kW solar array on the rooftop above the elevator hoistway. Finally, thyssenkrupp upgraded the elevator controller to enable a deep-sleep mode that greatly reduces power draw during periods of inactivity. We then compared annual energy consumption with solar production under different scenarios to evaluate the system's ability to achieve the net-zero energy goal.

The elevator includes state-of-the-art efficiency features, including LED cab lighting and a regenerative drive that recaptures energy when the elevator is in motion. It also includes features that result in very low standby power (about 100 W total for the controller, drive, and cab) using a deep sleep mode and an automatic power down of the cab lighting and fan circuit when the elevator is inactive. Together, these efficient features made it possible to achieve net-zero energy using renewable on-site generation.

1.1 Net Zero Energy

To achieve net zero energy, the combined elevator and PV system must produce at least as much energy as it consumes over the span of a year.

$$\text{Net-zero IF...} \sum_{year} E_{net} \leq 0$$

$$E_{net} = E_{elevator} - E_{gen}$$

The elevator consists of two primary circuits. One powers the cab (lighting, fan), and the second powers the drive (elevator controller and motors).

$$E_{elevator} = E_{cab} + E_{drive}$$

To achieve net zero, the generation source must satisfy:

$$E_{gen} \geq E_{cab} + E_{drive}$$

The drive circuit in this elevator was capable of energy regeneration. This means that when the weight descending exceeds the weight ascending, the drive generates power as it recaptures the excess potential and kinetic energy. When the drive circuit generates power, the elevator behaves as an energy source. The drive circuit can be decomposed into positive and negative values, independently representing energy consumption and regeneration:

$$E_{drive} = E_{drive,+} - E_{regen}$$

Thus, net-zero energy operation can be expressed as:

$$E_{gen} \geq E_{cab} + E_{drive,+} - E_{regen}$$

1.2 Getting to Net Zero

Elevators consume about 80% of all U.S. vertical transport energy[1] (Kwatra et al. 2013), about 5 billion kWh of electricity per year (Sachs et al. 2015). Eliminating this energy use entirely[2] through a net-zero approach could reduce electric bills by approximately $500 million per year.

Individual elevators consume on average about **7.6 MWh** (20 kWh/day),[3] while efficient models use about 25% less, or 5.7 MWh (15 kWh/day). Actual consumption depends on many factors including "speed, payload, frequency of use, motor efficiency, friction losses, regenerative drives, and lighting and fan systems" (Kwatra et al. 2013).

The elevator in this study initially used about 5.4 MWh (15 kWh/day) without deep sleep or automatic power down (APD) of the cab circuit. After upgrading the controller to allow deep sleep mode and after enabling APD, its projected annual usage was reduced by over 50% to **2.5 MWh** (6.8 kWh/day) for the same duty cycle.

A 3.75 kW solar array designed to produce **3.8 MWh** (10 kWh/day) in Boston, MA was deployed on Fraunhofer CSE's headquarters.

The total system was expected to yield an annual energy surplus of about **1.3 MWh** (+45%) or a net-positive system. This energy surplus could provide a buffer in case the elevator usage increases over time, for instance, as building usage or occupancy increases.

1.3 Organization

The remainder of this report provides details about the demonstration.

The APPROACH section describes the building and elevator systems, and the experimental methods and equipment used in the demonstration.

The RESULTS section shows a detailed history of energy consumption and production.

An APPENDIX provides supplemental technical data about the elevator and solar PV system.

[1] Escalators account for the remainder.
[2] Based on the average U.S. commercial electric rate of $0.104/kWh (DOE/EIA for 2016).
[3] 1 MWh = 1,000 kWh.

2 APPROACH

This section describes the building, elevator, PV system, and monitoring equipment.

2.1 Building Description

To demonstrate a net-zero elevator concept, thyssenkrupp installed a state-of-the-art, energy efficient elevator at the Fraunhofer Center for Sustainable Energy Systems headquarters in Boston, MA. The historic six-story building, located in Boston's Fort Point Innovation District, is a mix of office and laboratory space. The elevator is part of the Fraunhofer CSE Building Technology Showcase (BTS), a living laboratory used to demonstrate innovative building energy technologies.[4]

The building's 50,000 square feet spans a basement and six floors. Floors four and five were unfinished and unoccupied during the demonstration, and on a typical day, about 50 people occupied the building during business hours.

2.2 Elevator System

The elevator used in this demonstration is a thyssenkrupp Synergy series traction machine-room-less (MRL) building-supported system. The Synergy product line serves low- to mid-rise buildings with travel distance up to 300 ft, capacity of up to 5,000 lbs, and speeds up to 500 feet per minute (fpm). In the demonstration building travel distance from the basement to the sixth floor covered 68 feet, the capacity was 4,000 lbs, and the speed was 200 fpm.

The Synergy elevator includes a regenerative drive system that recaptures kinetic energy while the cab is in motion. The cab includes energy-efficient LED lighting and a system for automatically powering down the cab fan and lighting circuits when the elevator is inactive.

Two elevator controllers were used in this demonstration. The initial controller, the TAC50-04, was upgraded and replaced in July 2016 with the newer, more efficient TAC32T. According to thyssenkrupp, the "TAC32T controller for traction elevators offers increased reliability, safety and efficiency." Notably, it is designed to reduce standby power, and includes a low-power deep-sleep mode that was not available in the TAC50-04. We measured energy consumption with each controller to characterize the relative energy efficiency gains from deep-sleep mode.

Detailed elevator specifications and typical power measurements by mode are provided in the Appendix.

2.3 Solar Photovoltaic System

We installed a 3.75 kW array of solar photovoltaic modules on the rooftop above the elevator. The system occupied approximately 200 ft^2 and fit within the footprint the elevator shaft and equipment closet. The solar array consists of 15 high-efficiency (20%) SunPower X20-250-BLK alternating current photovoltaic (ACPV) modules. Microinverters on each panel help to minimize efficiency losses from partial shading.

Although the elevator room is a challenging and unconventional place to install a solar PV system; it serves our demonstration purpose of showing that an elevator can be truly energy self-sufficient. In practice, the PV system for a net-zero elevator could be situated anywhere convenient with good solar exposure and does not need to be strictly limited to the size of the elevator footprint.

Since solar power is intermittent, the elevator was not powered directly by the PV system. Instead, power from the PV system was fed into and used by the building, while the elevator was powered directly by the electric grid. This is typical of net-zero projects, where the grid is used as a storage mechanism (net-metering). The use of battery or other storage systems could enable a truly independent elevator concept.

[4] See: http://www.cse.fraunhofer.org/5cc.

We selected high efficiency solar modules to maximize the solar electric production within the constrained footprint to improve the chances of achieving the net-zero energy goal. Several design alternatives were considered, including supplemental PV modules mounted on the vertical walls of the elevator shaft. These were ultimately rejected due to practical challenges with permitting and installation.

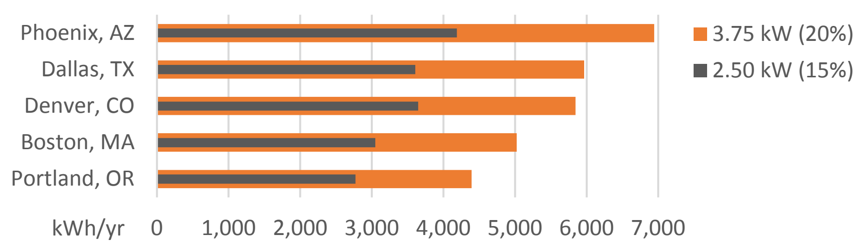
2.3.1 Simulated Solar Production

Annual electricity production simulated[5] for the as-designed solar PV array in Boston, MA was **3.8 MWh.** This estimate was based on the system's actual orientation with a 10-degree tilt angle and azimuth 120 degrees from North (facing South-East), and includes the effects of unavoidable afternoon shading from a neighboring 11-story building, seen at the right of Figure 1. The tilt angle was chosen based on wind load considerations (higher angles require more structural support), and the system orientation was coincident with the southern-most edge of the building.

Annual production without shading and with direct southern orientation was simulated at **5.0 MWh**, or about 30% higher. Illustrative scenarios for conventional and high-efficiency PV systems are shown in Table 1 for several cities. We considered two PV systems, one smaller typical-efficiency system (2.5 kW, 180 ft^2, and 15% efficiency) and a larger high-efficiency system (3.75 kW, 200 ft^2, and 20% efficiency). Simulated production ranged from about **2.8 to 7.0 MWh**. The footprint and PV system capacity required to achieve net-zero depends on the actual site conditions and elevator usage profiles.

Table 1. Simulated solar production for two unshaded south-facing PV systems in various cities.

LOCATION	PV PRODUCTION (kWh/yr) 15% Eff. 180 ft^2 2.5 kW	20% Eff. 200 ft^2 3.75 kW	AREA-NORMALIZED ($kWh/ft^2 \cdot yr$) 2.5 kW	3.75 kW
Phoenix, AZ	4,186	6,945	23	35
Dallas, TX	3,609	5,964	20	30
Denver, CO	3,647	5,845	20	29
Boston, MA	3,049	5,024	17	25
Portland, OR	2,774	4,395	15	22



[5] Solar simulations were performed using the PVsyst software package using typical meteorological year weather files for selected cities.

2.4 Monitoring Equipment

Elevator power draw, current, and voltage were monitored using current transformers and voltage probes (DENT PowerScout) and logged using automated data acquisition hardware (Obvious Acquisuite).

Before the upgraded controller was installed (April 2014 to July 2016), power was measured at one second intervals to permit separate analysis of energy consumption and regeneration. Unfortunately, when the logger power was reset during the controller upgrade, an automated firmware update was triggered that irreversibly reduced output to one-minute polling. Because the measurements were apparently no longer integrated over time, the post-upgrade metering accuracy was not reliable.

When this monitoring issue was discovered, we installed supplemental data loggers (DENT ElitePro) to restore high-accuracy integrated power measurements at 15-second intervals. These revised measurements began in October 2016.

Subsequently, in February 2017, an additional logger was added to measure power on the elevator cab circuit. Since the cab power usage remains highly stable at prescribed levels (lights on/off, fan off/low), calculating its contribution to the energy balance is straightforward. We also performed spot measurements of various combinations (see Appendix).

The solar PV hardware (SunPower) includes a built-in monitoring system that records production for each solar module and for the entire system at five-minute intervals. In addition, a revenue-grade meter (Locus Energy LGate 120) was installed and reports production at hourly intervals. Data from these sources were used to compare PV production with elevator consumption.

3 RESULTS

3.1 Elevator Activity

Elevator activity can be classified by the number of trips or travel time per day. On most business days, elevator usage in this demonstration was low to medium, see Table 2 (VDI 2009). Activity and usage consistently followed typical office occupancy patterns, shown in Figure 2 and Figure 3. Based on data for 2015, there were at least 16,000 trips with an average of 45 per day (63 on weekdays and 2 on weekends). We estimated the number of trips based on a 1 kW threshold on the drive circuit power-draw. This method counts at most one trip per minute (based on available power data resolution), and could underestimate frequent trips during busy periods.

Table 2. Elevator activity categories and measured activity. Source: VDI (2009).

VDI Elevator Activity Categories				
	Intensity	**Frequency**	**Travel Time (hours/day)**	**Measured Activity (% of days)**
1	very low	very seldom	0.0-0.3	31.5%
2	low	seldom	0.3-1.0	27.8%
3	medium	occasional	1.0-2.0	39.3%
4	high	frequently	2.0-4.5	1.3%
5	very high	very frequently	4.5+	0.0%

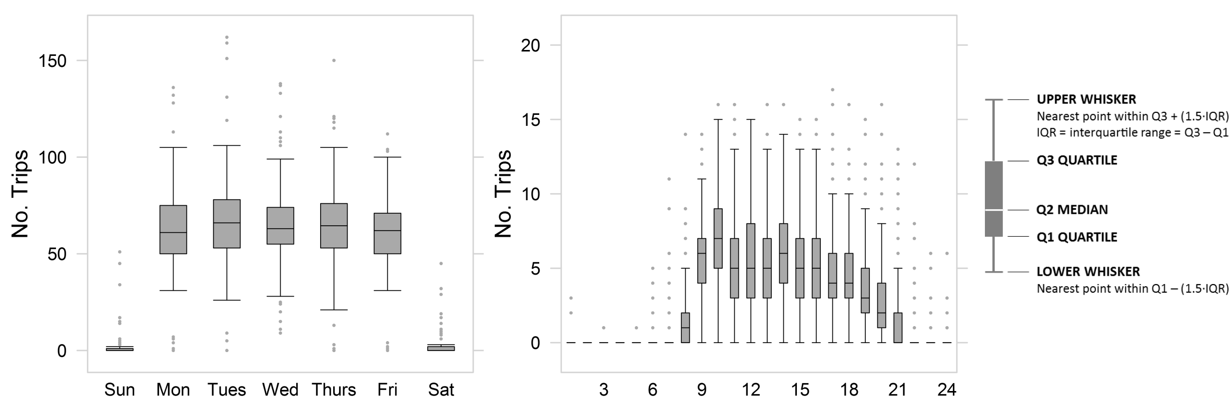


Figure 2. Elevator trips by day of week (LEFT) and by hour on weekdays (RIGHT).

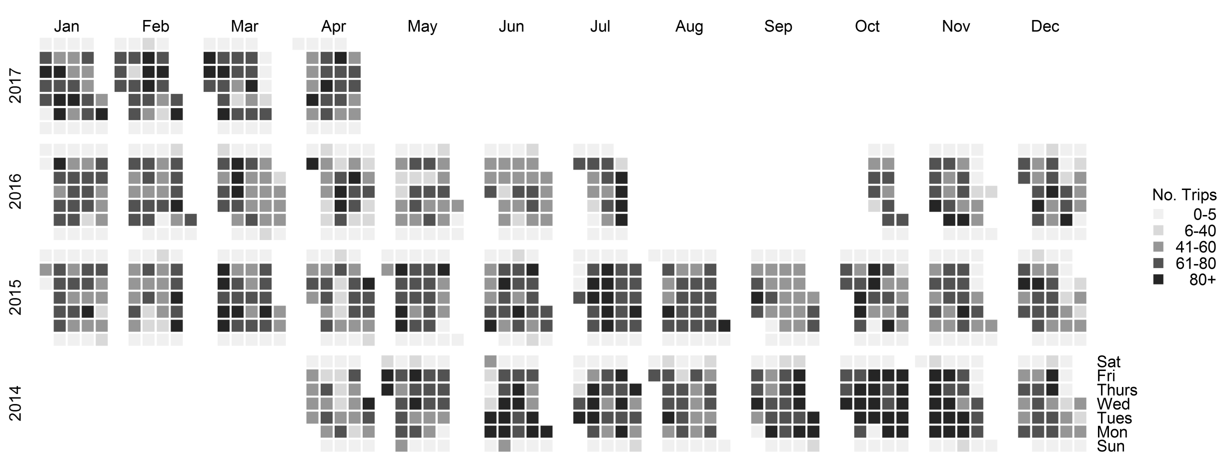


Figure 3. Elevator trips per day.

3.2 Elevator Energy Consumption

The elevator's energy consumption varied primarily based on usage, power draw in standby modes, and the *ability* of the controller to enter lower power modes. Net elevator energy usage, summarized in Figure 4, Figure 5, and Figure 6, represents both drive and cab circuits and includes the savings achieved from the regenerative drive.

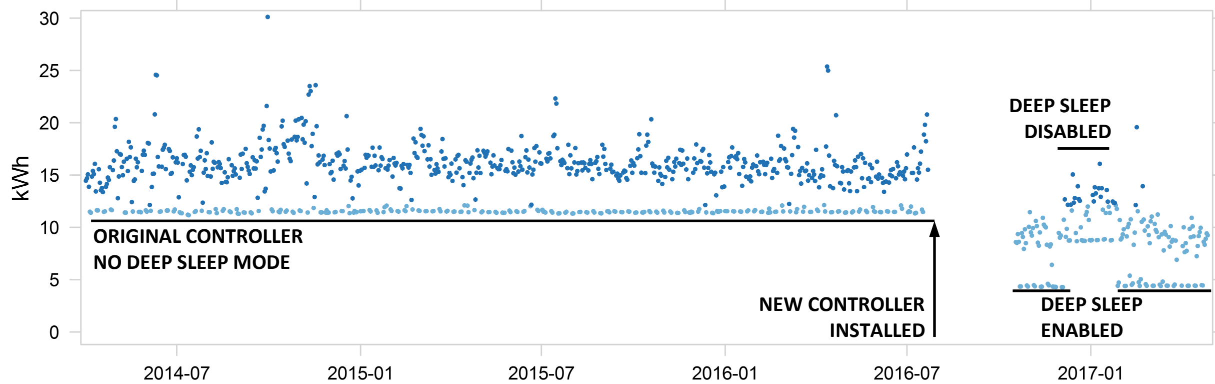


Figure 4. Daily elevator energy use. Light values are in the bottom 40% (below 13 kWh).

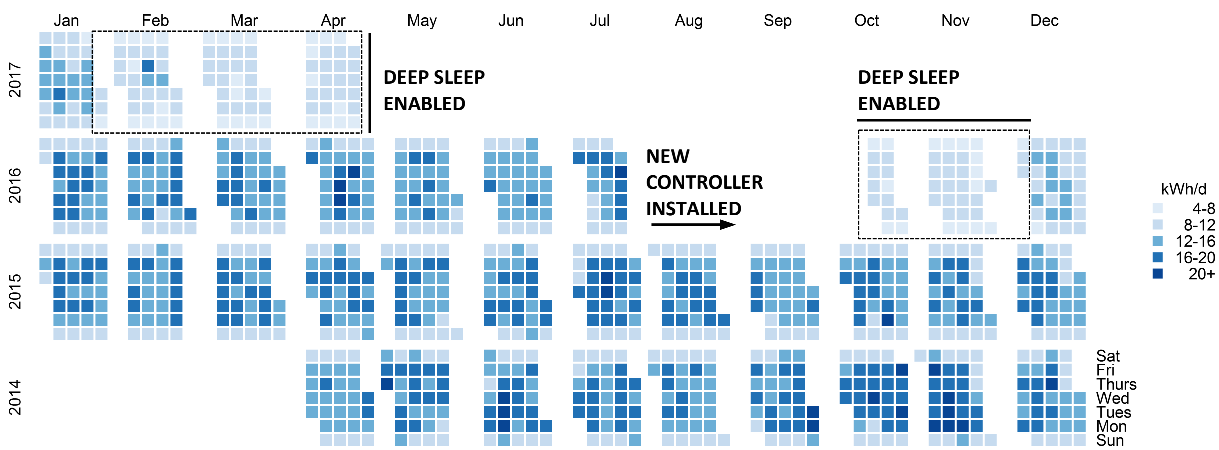


Figure 5. Daily elevator energy use.

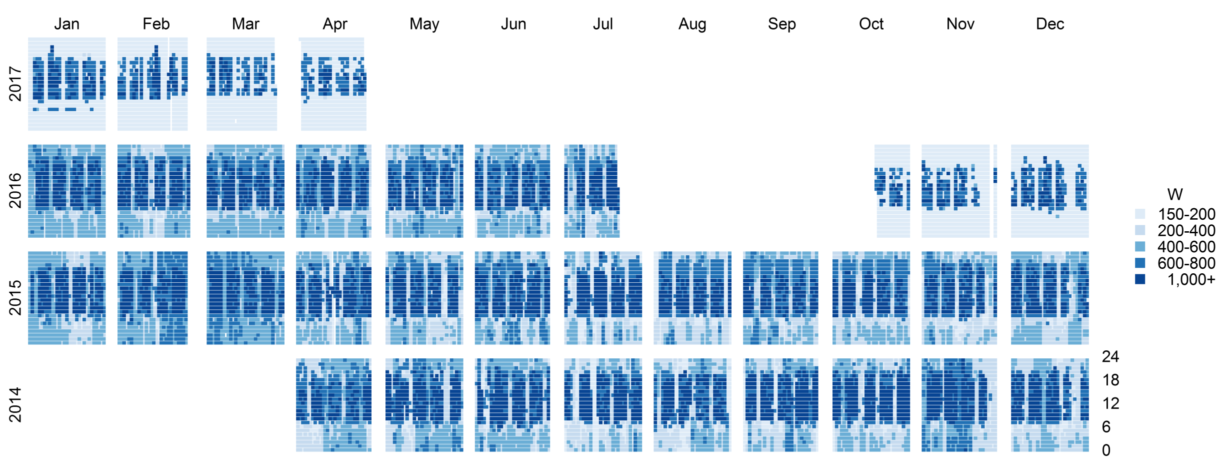


Figure 6. Hourly elevator power draw.

The initial controller lacked a deep-sleep mode and the drive circuit drew about **380 W** continuously in standby mode. After the controller upgrade in July 2016, deep sleep reduced standby power by more than 75% to **90 W**. The deep-sleep mode was enabled, disabled, and re-enabled during the demonstration period as indicated in Figure 4. In practice, the deep-sleep feature should remain enabled continuously.

The cab energy contribution was calculated based on a constant **92 W** load corresponding to a mode where the cab lights and low-speed fan are always on. Cab power draw could be further reduced by up to 90% to reach **9 W** if these circuits are automatically turned off during periods of inactivity. This feature was available but not implemented during the demonstration. Spot measurements were made on the cab circuit to verify power draw under different combinations of fan and light settings (see Appendix) to permit modeling of lower energy scenarios. When both deep sleep and auto-power-down are enabled, total standby power (cab + drive) can approach **100 W**. Average daily energy use by component are shown in Table 4 and Figure 7 for the different elevator configurations.

Table 3. Elevator standby power draw component summary.

CIRCUIT	CONTROLLER	POWER (W)	NOTES
DRIVE	TAC54-01	380	before upgrade – deep sleep mode NOT AVAILABLE
DRIVE	TAC32T	260	after upgrade + deep sleep mode DISABLED
DRIVE	TAC32T	90	after upgrade + deep sleep mode ENABLED
CAB	-	92	fan + lights ALWAYS ON
CAB	-	9	fan + lights AUTO POWER DOWN

Table 4. Average elevator energy use breakdown.
DS = deep sleep. APD = auto-power-down cab.

			AVG. ENERGY (kWh/d)							NET
CONTROLLER	DS	APD	DRIVE	REGEN	CAB	NET	TRIPS	DAYS	TRIPS/DAY	(kWh/trip)
TAC54-01	-	OFF	13	-0.6	2	**15**	38,880	844	46	0.32
TAC32T	OFF	OFF	9	-0.3	2	**11**	2,150	51	42	0.26
TAC32T	ON	OFF	6	-0.4	2	**8**	4,349	98	44	0.18
TAC32T	ON	ON	6	-0.4	0.2	**6**	4,349	98	44	0.14

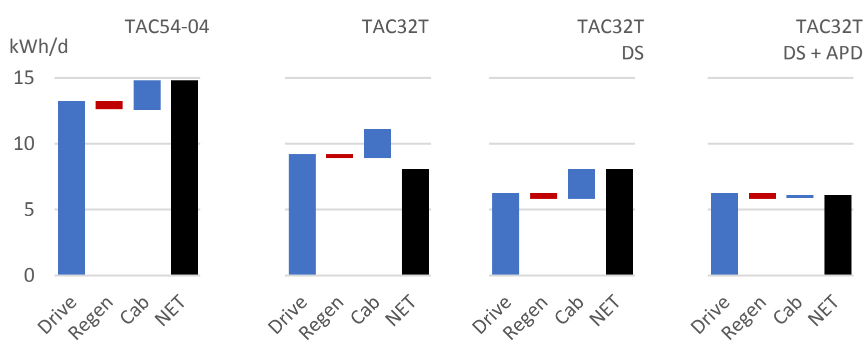


Figure 7. Average elevator energy use by component.
APD = auto-power-down cab enabled.
DS = deep sleep enabled.

3.3 Solar PV System Energy Production

The annual PV system production from April 2016-2017 was **4.2 MWh** (average of 11.4 kWh/day). This slightly exceeded simulated production and well exceeded the net-zero target of 8 kWh/day. The annual solar yield was about 1.1 kWh per W of installed PV.

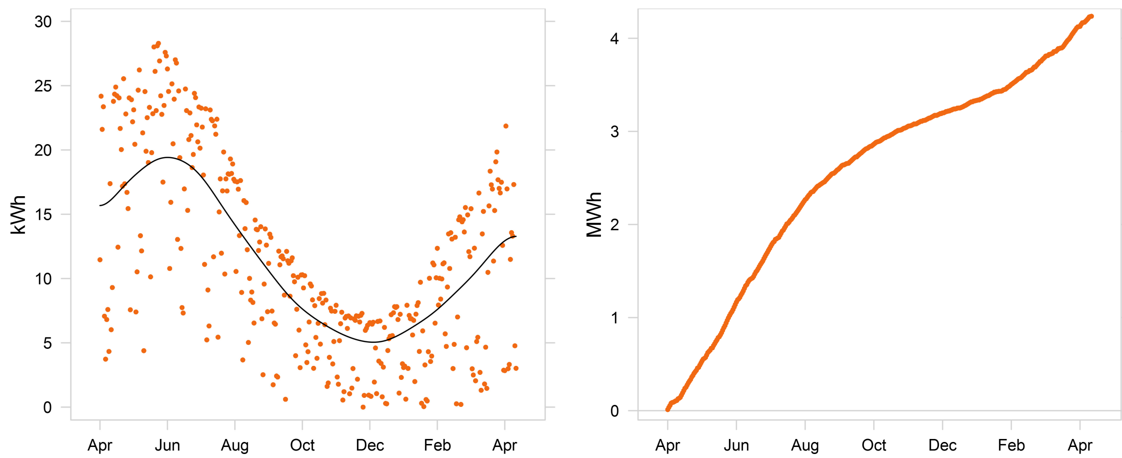


Figure 8. Daily solar power production with smoothing filter (LEFT) and cumulative production (RIGHT).

Detailed solar production for a typical sunny and overcast day, Figure 9, shows how the shading from a neighboring tall building to the west reduced afternoon production. Shading was most prominent on clear sunny days and reduced total production by up to 30%. We estimate that without shading a similar solar array would yield about 5 MWh per year.

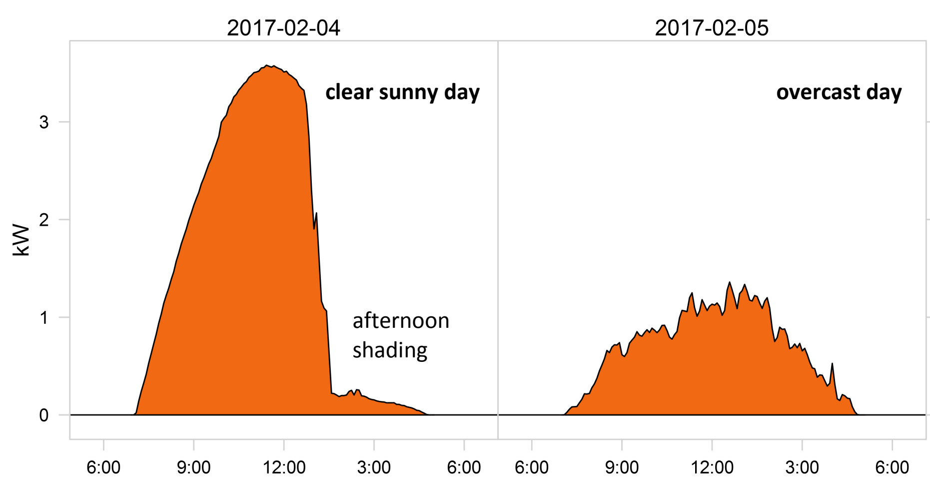


Figure 9. Solar production on a sunny and cloudy winter day.

Daily global horizontal irradiance (GHI) data for the actual year were obtained from nearby public weather stations within 10 miles of the Boston, MA test site (Weather Underground 2017). The average daily GHI was not statistically different from the typical year weather files used in the PV design simulations. The historic average GHI for Boston over 45 years was 3.8 kWh/m^2 (-13%/+5%, NREL 2017).

3.4 Net Zero Energy Analysis

To achieve net-zero energy consumption, the solar PV system must produce enough energy to offset the elevator consumption over the course of a year. This section compares energy generation and consumption under different scenarios.

The elevator underwent several hardware changes and software reconfigurations during the demonstration. To isolate these effects, we performed the net-zero analysis based on the elevator activity observed during the full year April 2015 to April 2016. During this period the original TAC50-04 controller was in place and its settings did not change. The solar energy data correspond to the same period exactly one year later.

We calculated cumulative elevator energy consumption as-measured with the original TAC50-04 controller, and under two modeled scenarios with the new, more efficient TAC32T controller. The modeled scenarios include: (M1) deep sleep enabled with cab lighting and fan always on, and (M2) deep sleep enabled with auto-power-down of the cab lighting and fan.

To model elevator energy consumption, we developed linear regressions relating the number of trips to the daily energy consumption (see Appendix for details). We applied these regressions to the elevator activity observed during the 2015-2016 period. This approach provides a consistent elevator usage profile to allow meaningful comparisons between scenarios.

For the modeling analysis, we made the following assumptions:

Cab power remains constant at one of two levels. When auto-power-down (APD) is disabled (as-measured and M1 model), the cab lights are always on and the cab fan speed is always on low speed, drawing 92 W. When APD is enabled (M2 model), we calculated the number of hours per day that the elevator did not take any trips. For these inactive hours, we assumed the lights and fan were both off, drawing only 9 W in standby. For all remaining hours, we assumed the lights and fan were both on drawing 92 W. On average (including weekends), there were 14.5 hours per day without any activity.

Elevator drive circuit power was modeled (M1 and M2) based on the linear regressions for the more efficient TAC32T controller with deep sleep enabled. The linear model was applied to the measured activity (number of trips per day) to calculate energy use.

Table 5. Net-zero energy balance. Shaded cells indicate an energy surplus.

	MEASURED	M1	M2
Deep Sleep Controller	-	ON	ON
Auto-power-down Cab	OFF	OFF	ON
Controller Model	TAC50-04	TAC32T	TAC32T

	325-days			365-day projection		
MWh/yr	**MEASURED**	**M1**	**M2**	**MEASURED**	**M1**	**M2**
Solar Production	3.73	3.73	3.73	4.19	4.19	4.19
Elevator Consumption	4.76	2.57	2.18	5.35	2.89	2.45
NET = SOLAR – ELEVATOR	**1.03**	**-1.16**	**-1.55**	**1.16**	**-1.30**	**-1.74**
% = NET/ELEVATOR	28%	-31%	-42%	28%	-31%	-42%

Cumulative energy consumption, solar production, and net energy use, shown in Figure 10, indicates that net-positive energy can be achieved when deep sleep is enabled. Net-zero occurs when the grey curve is above zero after one year. Enabling auto-power down further increases the net-positive energy surplus. Two separate scenarios in Figure 11 show the estimated consumption if the activity (number of trips) were doubled. In this case, net-zero energy can still be achieved, but the surplus margin is much smaller.

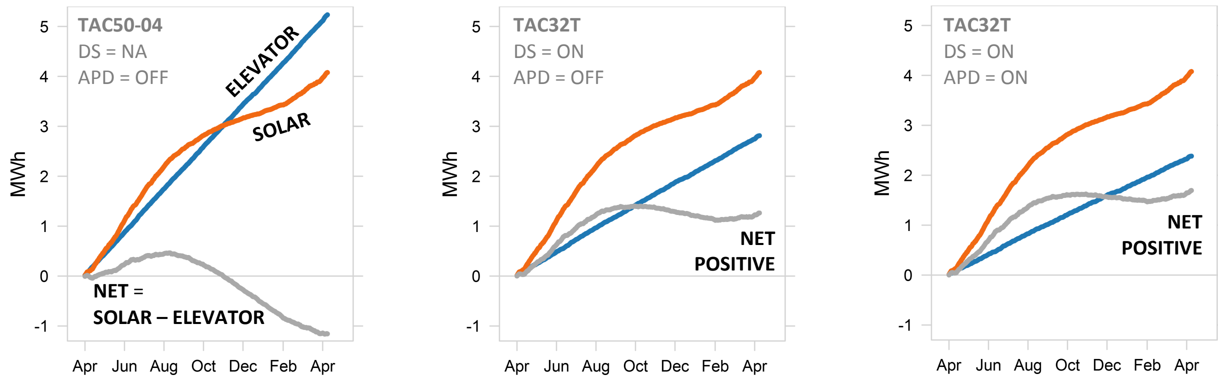


Figure 10. Cumulative annual elevator consumption, solar production, and net energy.
LEFT: as-measured with original controller. MID and RIGHT: as modeled with new controller.
DS = deep sleep mode, APD = auto-power down cab lighting and fan.

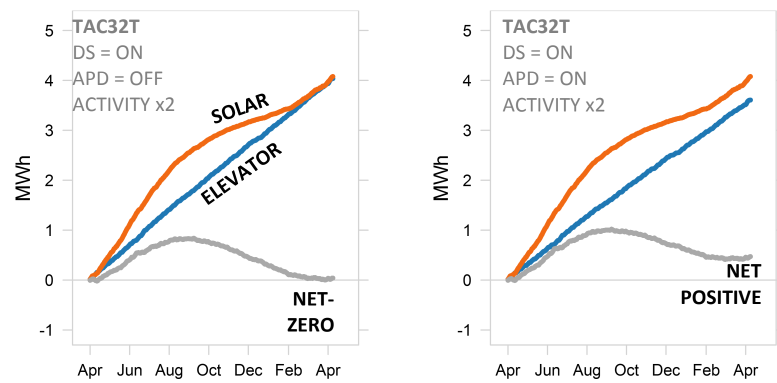


Figure 11. Same as Figure 10, with twice the elevator activity (high usage).

4 CONCLUSIONS

Through a field demonstration, we validated a net-zero elevator concept in a mid-rise Boston, MA office and laboratory building. An energy-efficient elevator with a moderate duty cycle, coupled with a 3.75 kW solar photovoltaic array that fits within the elevator footprint, can produce at least as much energy during a year as it consumes.

Annual elevator energy consumption with deep-sleep mode enabled was about **2.9 MWh** (8 kWh/day). Enabling the automatic-power-down (APD) feature for the cab lights and fan circuit could further reduce consumption by about 15% to 2.5 MWh (6.8 kWh/day). With both deep-sleep and APD modes enabled, the elevator and cab drew a combined 100 W in standby mode. Without these features, standby power was about four times higher at about 400 W, and the elevator used about 80% more energy, or 5.3 MWh (14.5 kWh/day).

In one year, the solar PV array produced **4.2 MWh** (11 kWh/day). This level of production was achieved despite unavoidable afternoon shading from a neighboring tall building. Without shading and with ideal southern orientation, we estimate energy production could be approximately 30% higher. Depending climate and solar PV system specifications, a similar sized PV system could produce from 2.8 to 7.0 MWh.

A net annual energy surplus of 45% **(+1.3 MWh** or 3.6 kWh/day**)** is projected for the current system and with typical building activity. Doubling the elevator activity to a high-usage scenario during normal office hours would increase elevator consumption to the range of 3.7 to 4.1 MWh (APD enabled vs. disabled). In this case the system could still achieve the net-zero goal, though with a smaller margin.

In aggregate, elevators consume about 5 billion kWh of electricity per year. Eliminating their energy use entirely through a net-zero approach could reduce electric bills by up to $500 million per year.

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6 APPENDIX

6.1 Elevator Specifications

Table 6. Elevator specifications.

DESCRIPTION			
Manufacturer		thyssenkrupp	
Series		Synergy	
Type		Passenger	
Class		Class A, Freight Loading	
Machine		5001BL006	
SPECIFICATIONS		**VALUE**	**UNITS**
Stops		7x front	-
		0x rear	-
Rated Speed		200	fpm
	FLOORS	**HEIGHT**	
Travel Distance (Max.)	**B-F6**	**67.8**	**ft**
Inter-Floor Heights	F5-F6	11.5	ft
	F4-F5	11.5	ft
	F3-F4	11.5	ft
	F2-F3	11.5	ft
	F1-F2	12.0	ft
	B-F1	9.8	ft
Hoistway Area (Width x Depth)		**111**	**ft^2**
Hoistway Width		9.125	ft
Hoistway Depth		12.166	ft
Capacity		4,000	lbs
Max Unit Load		1,000	lbs
Max Axle Load		1,000	lbs
Max Sustaining Load		4,000	lbs
Full Load Mass (Actual)		16,245	lbs
Full Load Mass (Max)		16,523	lbs
Total Filler Weight		6,250	lbs
Total Counterweight Weight		(50%) 6,870	lbs
Total Car Weight		4,835	lbs
CONTROLLER	**INITIAL**	**UPGRADED**	
Model	TAC50-04	TAC32-T	-
Travel Distance (Max.)		2,000	ft
Car Speed (Max.)		3,000	fpm
Power Supply		480 V, 3Phase, 60 Hz	

6.2 Elevator Power Draw

Two circuits, (1) for the drive and controller and (2) for the cab lights and fan, were monitored to account for elevator energy consumption. This section summarizes power draw by mode observed during typical operation for both controllers. Because this elevator has a regenerative drive, power sometimes flows back into the electrical panel through the drive circuit when the cab travels upwards. This shows up as negative power draw.

The drive circuit power response is shown for a typical ride in Figure 12 with the original TAC504 controller. Initially the circuit draws about 380 W in standby mode. The cab then travels down to meet a passenger on the first floor, drawing up to 20 kW for about 15 seconds. Next, after a brief pause (people enter the cab and press the button for a floor), the circuit regenerates power during the upward trip. The circuit temporarily settles at a higher standby power level about 700 W, likely because of a cooling fan on the drive circuit. Eventually, after several minutes, the power returns to the low standby condition.

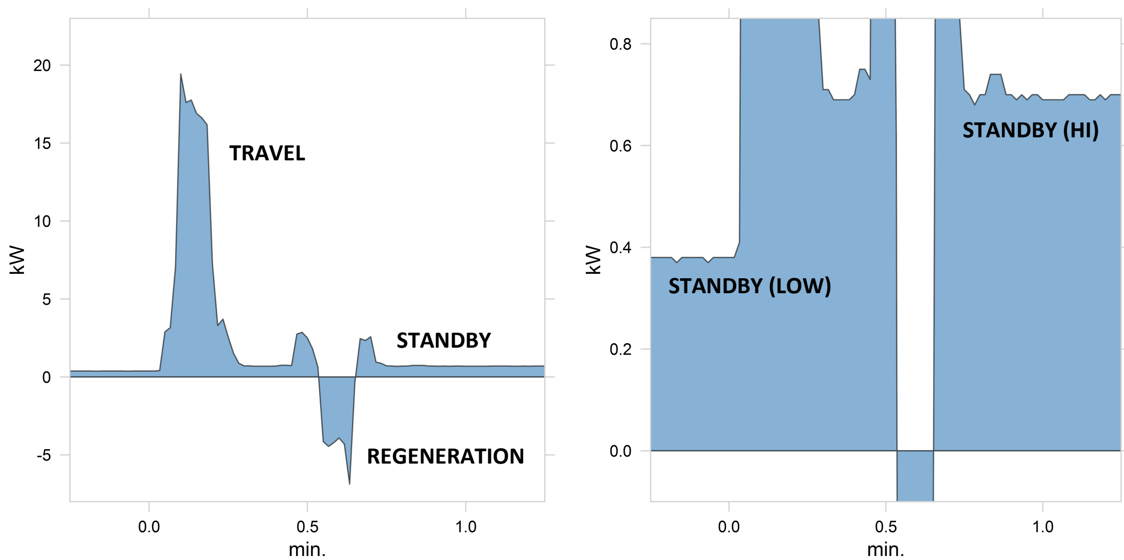

Figure 12. Typical drive circuit power draw pattern with the TAC504 controller. At scale (LEFT), zoomed (RIGHT).

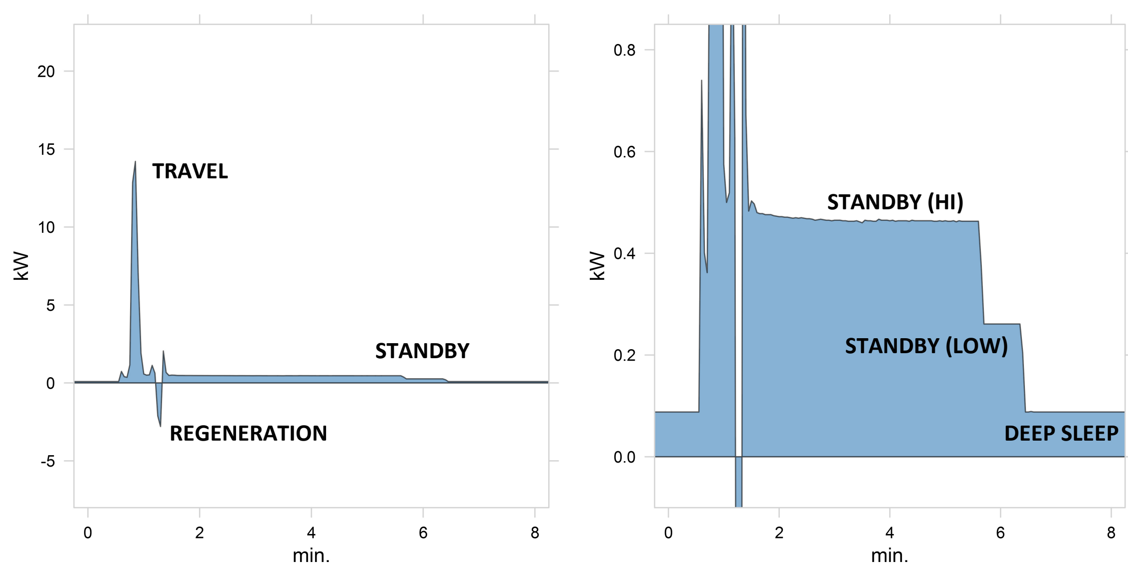

Figure 13. Typical drive circuit power draw pattern with the TAC32T controller. At scale (LEFT), zoomed (RIGHT)

A similar pattern for the newer TAC32T controller is shown in Figure 13. A longer timescale is used to indicate the time it takes to enter deep sleep mode (about 5 minutes). Deep sleep used 92 W. Additionally, both standby modes drew less power than the original controller (260 W and 460 W).

Power draw for a typical week (2017-03-01) is shown in Figure 14. Weekends show inactivity (standby-power only), while weekdays follow typical office occupancy patterns. A sample workday is shown in Figure 15.

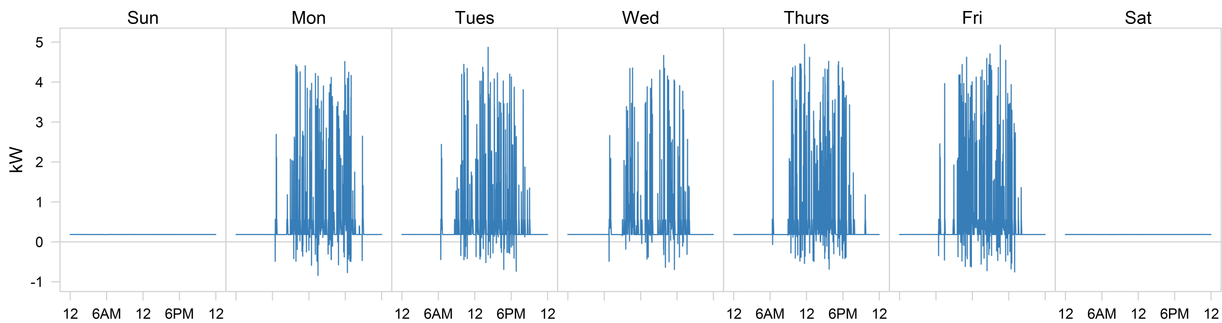

Figure 14. Typical workweek elevator power draw.

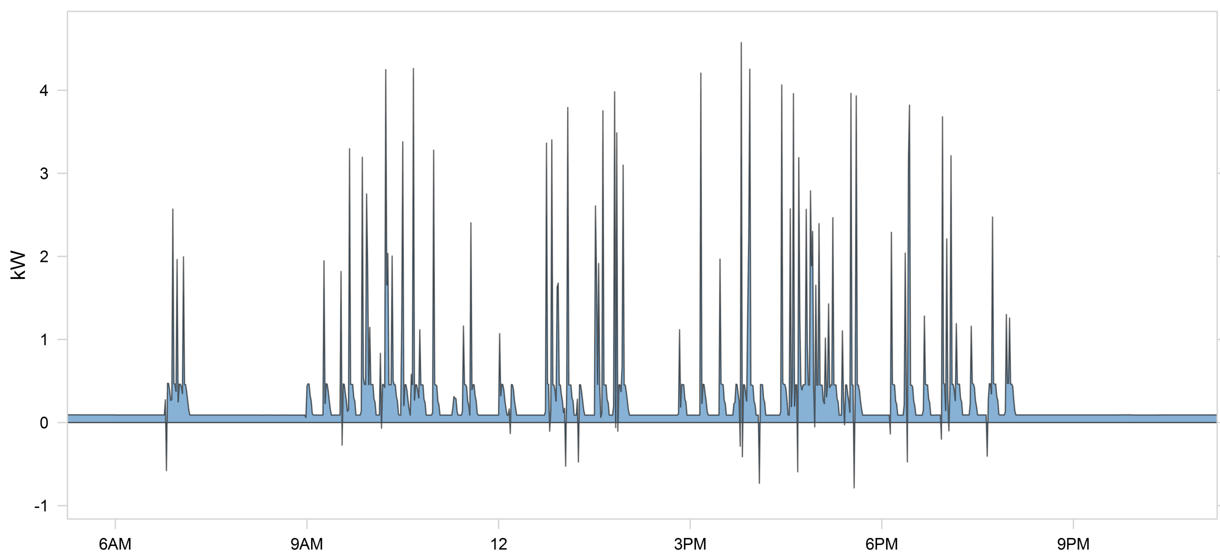

Figure 15. Typical workday elevator power draw.

Table 7. Elevator power draw by mode.

POWER (W)	CONTROLLER TAC504	TAC32T	NOTES
DRIVE CIRCUIT			
deep sleep	-	90	
low standby	385	273	
hi standby	699	453	
CAB CIRCUIT			
lights off + fan off	9	9	spot measured, standby mode
lights on + fan off	50	50	spot measured
lights on + fan low	92	92	spot measured, default mode
lights on + fan hi	115	115	spot measured

Simple linear regression models relating the number of trips to the daily energy consumption, Figure 16, were developed to calculate full-year energy consumption with deep sleep mode enabled. The slope is similar for each case indicating the incremental power per ride does not depend strongly on the controller. More importantly, the y-intercepts differ, reflecting the significant differences in standby power.

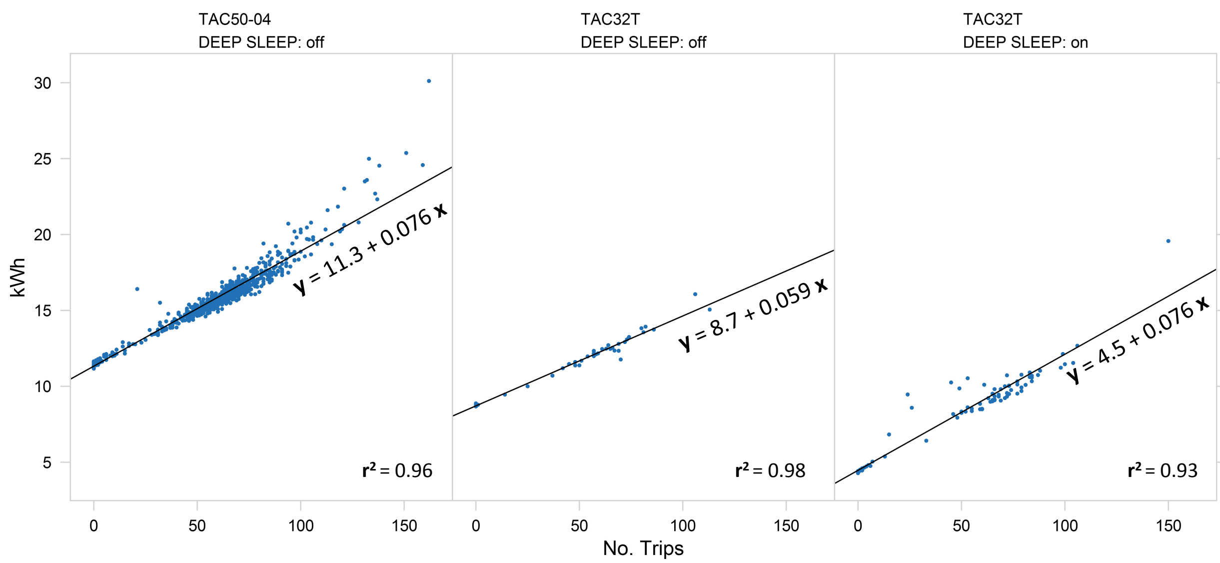

Figure 16. Daily elevator energy use vs. number of trips by elevator configuration.

6.3 Solar Panel Specifications

Table 8. Solar photovoltaic system specifications.

SYSTEM DETAILS		
Manufacturer	Sun Power	-
Module Model	X20-250-BLK-AC	-
Number of Modules	15	-
System Capacity	3.75	kW
DC Electrical Data at Standard Test Conditions	**VALUE**	**UNITS**
Nominal Power (P_{nom})	250	W
Avg. Panel Efficiency	20.3	%
Rated Voltage (V_{mpp})	42.8	V
Rated Current (I_{mpp})	5.84	A
Open-circuit Voltage (V_{oc})	50.9	V
Short-circuit Current (I_{sc})	6.20	A
Power Temperature Coefficients (P)	-0.30	%/K
Voltage Temperature Coefficients (V_{oc})	-25.6	mV/K
Current Temperature Coefficients (I_{sc})	3.5	mA/K
AC Electrical Data	**VALUE**	**UNITS**
Output @ 240 V (min./nom./max.)	211/240/264	V
Output @ 208 V (min./nom./max.)	183/208/229	V
Operating Frequency (min./nom./max.)	59.3/60.0/60.5	Hz
Output Power Factor (min.)	0.99	-
AC Max. Cont. Output Current @ 240 V	0.99	A
AC Max. Cont. Output Current @ 208 V	1.14	A
AC Max. Cont. Output Power	238	W
DC/AC CEC Conversion Efficiency	95.0	%

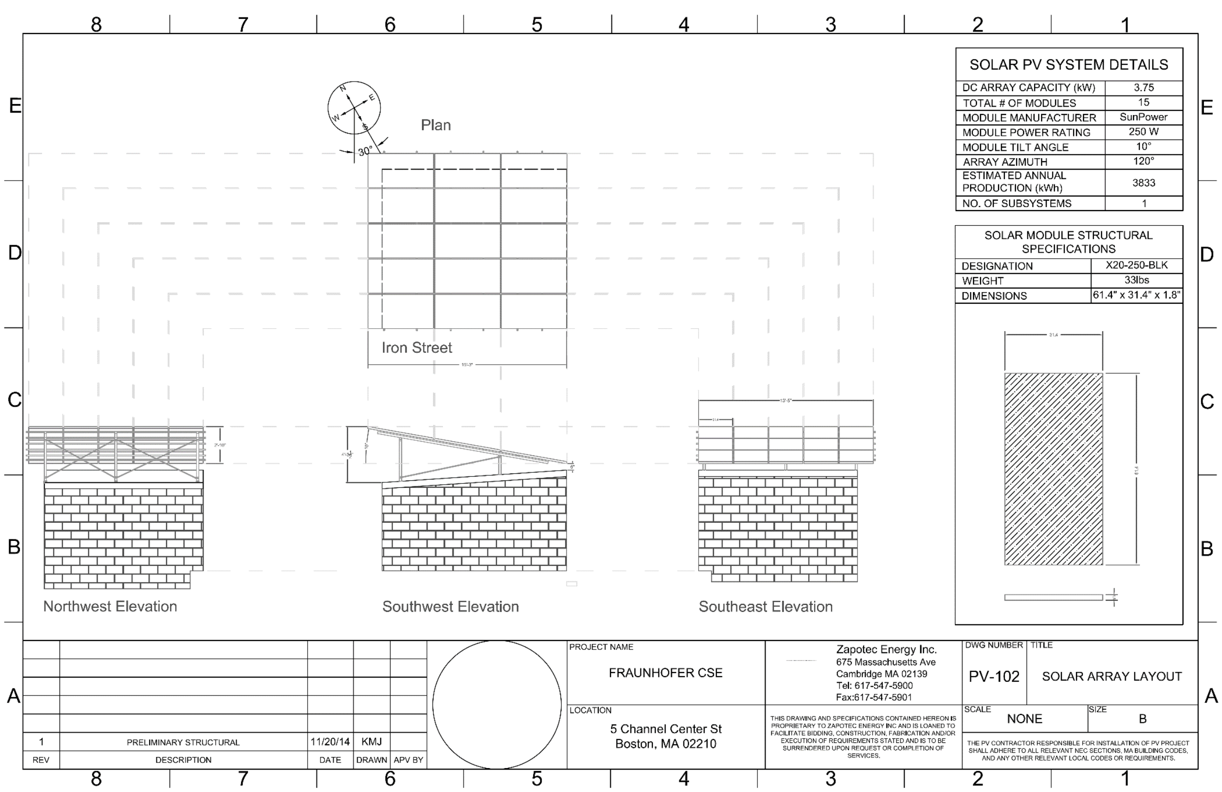

Figure 17. Solar PV design specifications.