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Edison Revisited: Should we use DC circuits for lighting in commercial buildings?

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ABSTRACT

We examine the economic feasibility of using dedicated DC circuits to operate lighting in commercial buildings. We compare light-emitting diodes (LEDs) and fluorescents that are powered by either a central DC power supply or traditional AC grid electricity, with and without solar photovoltaics (PV) and battery back-up. Using DOE performance targets for LEDs and solar PV, we find that by 2012 LEDs have the lowest levelized annualized cost (LAC). If a DC voltage standard were developed, so that each LED fixture's driver could be eliminated, LACs could decrease, on average, by 5% compared to AC LEDs with a driver in each fixture. DC circuits in grid-connected PV-powered LED lighting systems can lower the total unsubsidized capital costs by 4–21% and LACs by 2–21% compared to AC grid-connected PV LEDs. Grid-connected PV LEDs may match the LAC of grid-powered fluorescents by 2013. This outcome depends more on manufacturers' ability to produce LEDs that follow DOE's lamp production cost and efficacy targets, than on reducing power electronics costs for DC building circuits and voltage standardization. Further work is needed to better understand potential safety risks with DC distribution and to remove design, installation, permitting, and regulatory barriers.

1. Introduction

In 1891, as the "Battle of the Currents" was coming to a close, the board for the Chicago World's Fair received two bids to illuminate the world's first all-electric fair: General Electric proposed a $1.8 million (later reduced to $554,000) direct current (DC) generator and distribution network, while the Westinghouse Electric Company submitted the winning bid of $399,000 for an alternating current (AC) system (all costs in 1891 dollars) (Larson, 2003). The years that followed saw the decline of Thomas Edison's pioneering 110 V DC distribution systems. AC transmission and distribution became standard because the AC transformer made it possible to step voltage up for long distance power transfer and then back down for end use. High voltage AC achieved much greater efficiency for electric power transmission than low voltage DC, since resistive power losses grow as the square of the current, while the amount of power transferred is proportional to the product of voltage and current. In the early 20th century, high voltage DC transmission was not possible due to the lack of a "DC transformer."

However, in recent decades, new semiconductor materials and devices have been developed that can effectively function as a "DC transformer" with efficient (>80%) and reliable designs (80plus.org, 2010). Today, high-voltage DC (HVDC) (200–800 kV) has become the most cost-effective option for point-to-point electricity transmission across distances greater than 500–600 miles (e.g. connecting hydropower in the Pacific Northwest to loads in Los Angeles). At these distances, the cost savings from using two conductors for HVDC transmission versus three conductors for AC transmission (Schavemaker and van der Sluis, 2008) outweigh the higher cost of DC power electronics compared to AC transformers. However, the economics are such that AC remains the norm for all local transmission and distribution systems.

The objective of this paper is to assess the economics of DC distribution at the building level, which some analysts have proposed as an approach to reduce the cost and improve the efficiencies of power conversion (Babyak, 2006). There are two main motivations for our paper. First, DC building circuits could reduce or eliminate the proliferation of power supplies that convert AC grid power to various DC voltages for use in many commercial and residential loads, such as computers, consumer electronics, and LED lighting. Many small inefficient "wall warts" had efficiencies as low as 40% (Calwell and Reeder, 2002) before they became subject to national (and international) energy efficiency standards, such as the minimum efficiency standards programs established by the Energy Policy Act of 2005 and Energy Independence and Security Act of 2007 (EISA, 2007) in the United States. Similar programs exist at the regional level (e.g. the California Energy Commission) and in other nations (e.g. Australian Greenhouse Office) (Mammano, 2007).

Second, DC building distribution may improve the power conversion efficiencies and lower the cost of using distributed

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generation (DG) that can inherently or easily produce DC power. Since the 1970s, DG has seen a rebirth due to converging goals to improve overall efficiency in the use of primary energy, the divestiture of large generation by some utilities that have been restructured as "wires companies" (Strachan, 2000), growing consumer concerns about supply reliability, and concerns about lowering greenhouse gas emissions. Some DG technologies such as solar photovoltaics (PV) and fuel cells inherently produce DC power, while other DG sources such as microturbines (30 kW–1 MW) can easily produce DC power. Researchers have found that using DC distribution can reduce PV system capital costs by up to 25% by eliminating the inverter and increasing system efficiency so that a downsized PV array can provide the same electricity service (Jimenez, 2005; DTI, 2002). Using different assumptions, Hammerstrom (2007) reports that DC building circuits can only improve power conversion efficiency by 3% with the use of solar PV, fuel cells, or other DC DG, and impose a 2% energy efficiency penalty without DC DG. Given other uncertainties, whether these differences are significant is unclear.

The use of DC circuits would be a fundamental change in the electrical systems of commercial buildings and would pose many questions for engineering design, economics, and safety standards. Much previous research on building-level DC circuits has focused on those applications with the most favorable economics and high AC–DC power conversion losses due to the use of DG-backup systems, batteries, and uninterruptible power supplies (UPS), such as power plant auxiliary systems, telecommunications facilities, and data centers (Jancauskas and Guthrie, 1995; Yamashita et al., 1999; Belady, 2007; Pratt et al., 2007; Ton et al., 2008). Broader application of DC building circuits may also be feasible with existing power supply and circuit breaker technologies (Sannino et al., 2003), since laboratory tests confirm that many household devices can readily accept DC power (George, 2006).

While DC circuits are technically feasible and may be cost-effective in specialized applications such as data centers, it remains unclear whether they are cheaper than AC power for broader applications such as lighting in office buildings, the most common type of commercial buildings in the U.S. (EIA, 2008). Here, we conduct Monte Carlo simulations of the levelized annual costs (LACs) for the installation and operation of lighting in commercial office buildings under six scenarios, three using centrally rectified DC with dedicated distribution circuits to power LEDs or fluorescents and three using conventional AC to power LEDs or fluorescents. Specifically:

1) centrally rectified DC without PV;
2) centrally rectified DC with PV;
3) centrally rectified DC with both PV and battery backup;
4) conventional AC without PV;
5) conventional AC with PV; and,
6) conventional AC with both PV and battery backup.

We limit our analysis to lighting. Other applications such as HVAC could operate with DC, but do not share the potential advantage posed by lighting of replacing many small power supplies with one central supply.

With present fluorescent and LED efficacies, we find that centrally rectified DC LED lighting systems have the lowest annualized cost (LAC). DC circuits in grid-connected solar PV-powered LED lighting systems can lower the total unsubsidized capital costs of the system by 4–21% and LACs by 2–21% compared to a PV-AC lighting system, which may encourage some building owners to choose to install building-level DC circuits. However, DC circuits do not significantly accelerate the cost reductions of grid-connected PV-powered LEDs, since LED and PV costs are falling at a greater rate than power supply costs.

In the balance of the paper Section 2 provides detail about the key assumptions of our Monte Carlo simulation of commercial building DC lighting systems; Section 3 provides key results on the economics of centrally rectified DC LEDs, grid-connected PV-powered DC LEDs, and grid-connected PV-powered DC LEDs with battery back-up; and, we conclude in Section 4 with a discussion of policy implications.

2. Methodology

We constructed a model that, given a specification of office building geometry, occupancy, and lighting needs, estimates the power and energy consumption for the three DC and three AC scenarios listed above for LEDs and fluorescents, as seen in Fig. 1. As an illustrative case-study, we examine a hypothetical four-story, 48,000 ft^2 (4400 m^2) new construction commercial office building for 672 occupants, with 1900 klm in ambient lighting and 330 klm in task lighting, based on Illumination Engineering Society of North America (IESNA) illuminance requirements for office spaces (Navigant Consulting, 2002), in Pittsburgh, PA. Model specifications can easily be changed for alternate commercial building case studies.

The AC scenarios consider 277 V AC fluorescent fixtures and 277 V AC LED fixtures. The DC scenarios consider 249 V DC (i.e. rectified 277 V AC) fluorescent fixtures and 249 V DC LED fixtures. We hold constant the number of fixtures and the number of lumens (lm) provided by the several lighting fixtures. The lighting system power is therefore the free variable. The total lighting load is used to determine the wire lengths and diameters (gauges) for the ambient and task lighting systems. Details of the lighting system, power electronics characteristics, and wiring and circuit protection requirements are listed in Appendix A. We do not consider the use of daylighting or lighting controls, although in some settings these can be highly cost-effective approaches to achieving higher lighting efficiency (Jennings et al., 2000).

We compare the six scenarios with fluorescent and LED lighting systems on the basis of levelized annual costs (LAC) and capital costs. LAC is a useful metric for evaluating AC versus DC lighting systems because it allows the comparison of systems with many components of varying lifetimes, taking into account the time value of money. The LAC estimates, in 2012$/yr, are the sum of installation and capital costs for the lighting system (*CapLED*/*CapFL*), solar PV system (*CapPV*), and wiring and circuit breakers (*W*), levelized over their respective lifetimes, and annual lamp replacement labor costs (maintenance, *M*) and annual grid electricity costs (*E*) with $0.10/kWh rates, which can be defined as

$$LAC = CapPV \times CRF_p + CapLED \times CRF_L + W \times CRF_W + M + E \tag{1}$$

$$CRF_i = \frac{i}{1-(1+i)^{-lifetime_i}} \tag{2}$$

where CRF is the capital recovery factor and i is equal to a discount rate of 12 percent.

Lighting and PV systems have a range of possible costs given the range in the efficiencies and costs of DC and AC circuit components, as shown in Table 1. In addition, there is considerable natural and site-specific variability in solar radiation, which is an important parameter in the size and cost of the solar PV module and overall LACs in the PV-integrated scenarios. To represent a range of LACs, these metrics were calculated using a Monte Carlo simulation of 1000 runs, which randomly sampled from uniform distributions of the input parameters to generate a range of output values from which statistics are generated (details available in Appendix B).

2.1. Grid-connected DC lighting system design

For the grid-connected DC lighting systems, centralized AC–DC power supplies (rectifiers) on each floor convert AC grid power to the voltage required by the lighting systems, as shown

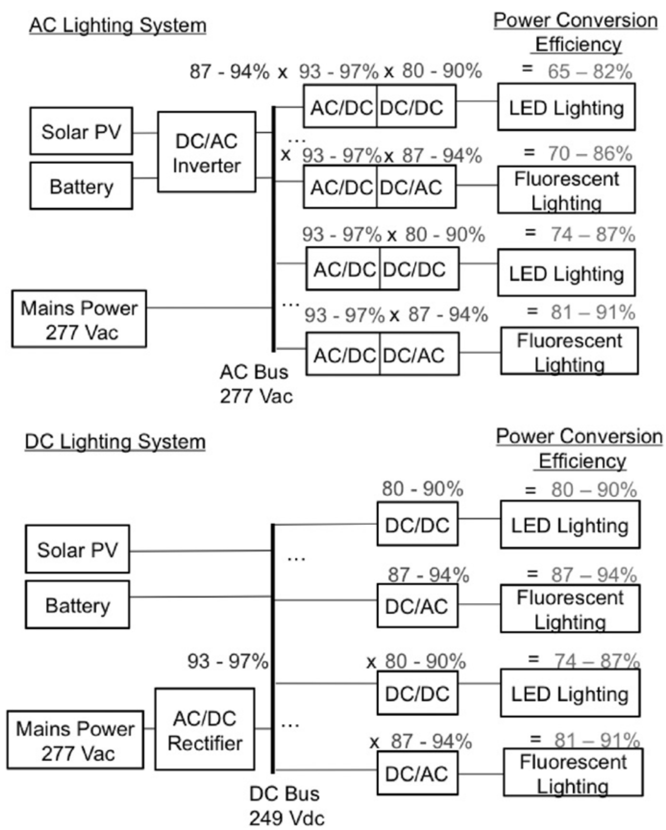

Fig. 1. Schematic of commercial office building lighting system with AC vs. DC architectures. If lighting fixture-level DC/DC power supplies could be eliminated for LED lighting systems, power conversion efficiencies would be improved to 93–97%. DC lighting systems could provide 8–17% greater power conversion efficiencies when used with grid-connected solar PV and battery back-up.
Sources: (Jimenez, 2005; George, 2006; Pratt et al., 2007).

schematically in Fig. 1. This design is similar to Redwood Systems' (2010) 48 V low-voltage LED lighting system and Emerge Alliance's 24 V design (Symanski and Watkins, 2010), which combine DC wiring with centralized LED drivers and advanced lighting controls to achieve energy savings. The economics of building-level DC circuits would then depend on the costs and energy efficiencies of centralized AC–DC power supplies and lamp load-level DC power supplies, such as fluorescent ballasts and LED drivers, versus those of the load-level AC ballasts and drivers needed with conventional AC building circuits. Centralized power supply capital costs, which depend primarily on output power rating, and energy efficiency calculations are listed in Appendix A.

Today, DC power supplies at the level of individual lamps, such as fluorescent ballasts and LED drivers, are often more expensive than their AC counterparts because DC power supplies are niche products with small market volumes. However, if building-level DC circuits were widely implemented, DC power supplies may become cheaper than AC power supplies because both are similar in design, but DC power supplies do not require circuitry such as AC–DC rectifier, power factor (PF) correction, and radio frequency interference (RFI) suppression. AC power supplies need PF correction because they often introduce harmonics and other power quality issues into the electric system (Salomonsson and Sannino, 2006) and RFI suppression to avoid interrupting or degrading the performance of other electronic devices. Instead, the central AC–DC power supply performs these functions and the lamp-level DC power supplies perform other functions, such as maintaining the high frequencies and voltages required to fire a fluorescent lamp or regulating the current to prevent damage to an LED device. With the current AC transmission and distribution system, AC–DC conversion, PF correction, and RFI suppression are required in each DC device, imposing an energy efficiency penalty and added cost.

To represent the best case scenario for DC lighting circuits and exclude the transition costs of creating a market for DC power supplies, we make a few simplifying assumptions about the cost of DC fluorescent ballasts and LED drivers. DC fluorescent ballasts are assumed to be half the cost of AC fluorescent ballasts. We also assume that an industry voltage standard is established, and that LED manufacturers design the lamps accordingly, so that LED drivers can be eliminated from DC LED lighting systems. Completely eliminating the driver is a strong assumption given the need for current regulation in LED devices, so we test the sensitivity of DC LED LACs to the relative cost of DC LED drivers versus AC LED drivers.

Table 1
2010–2030 LED, PV, and battery projections.
Sources/Notes: SSL costs (except for drivers) are from R&D targets in DOE (2011b). SSL Driver costs are assumed to be 12–15% (Philips Lighting Company official (2009)) of integrated lamp costs in 2010, and then decline by 6% annually from 2010–2030 (Darnell Group, 2005). PV module costs and efficiencies are from Curtright et al. (2008) and IEA (2010) and inverter and balance of plant (BOP) costs are from RMI (2010) for the lower estimate and half of PV module costs from Curtright et al. (2008) for the upper estimate. Lead-acid battery costs are from a sample of Grainger.com products, assuming costs decline at 1.5% annually.

	2010		2012		2015		2020		2030	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
SSL int.-lamp cost ($/klm)	38	52	18	24	8.5	12	4.3	5.8	1.7	2.3
SSL device efficacy (lm/W)	114	154	150	202	190	258	219	261	224	266
SSL thermal eff (%)	81	89	82	90	84	91	86	92	88	93
SSL driver eff (%)	83	87	84	88	87	91	90	94	90	94
SSL fixture eff (%)	81	89	82	90	85	91	87	92	89	94
SSL driver cost ($/W)	0.58	1.33	0.51	1.17	0.43	0.98	0.31	0.72	0.17	0.39
PV module cost ($/$W_p$)	2.3	6.1	2.1	5.7	1.9	5.3	1.2	3.9	0.2	2.6
PV conversion efficiency (%)	13	20	14	21	15	23	16	25	18	30
Inverter cost ($/$W_p$)	0.25	0.47	0.17	0.35	0.10	0.23	0.08	0.17	0.05	0.10
BOP costs ($/$W_p$)	1.9	3.1	1.2	2.8	0.6	2.6	0.5	2.0	0.4	1.3
Battery cost ($/Wh)	0.30	0.80	0.29	0.78	0.28	0.74	0.26	0.69	0.22	0.59

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2.2. Solar photovoltaic system design (without energy storage)

For the solar PV scenarios, we model a grid-connected commercial building with a solar PV array with fixed-tilt at latitude that supplies supplementary electricity in a climate such as in Pittsburgh, PA. Load profiles and solar PV output for the maximum, minimum and mean solar insolation levels in Pittsburgh, PA, are shown in Fig. 2. We model polycrystalline silicon solar PV, since it is readily available in the marketplace and subject to future R&D improvements. Hourly and monthly average solar radiation data were obtained from the National Renewable Energy Laboratory (NREL)'s National Solar Radiation Database. Using these data, the model estimates hourly and monthly grid- and solar PV-electricity consumption. The choice of the building site should not affect the relative levelized costs of DC versus AC distribution since parameters that vary by region such as insolation and electricity prices are held constant across all scenarios. However, variations in insolation do affect the size and total capital costs of the PV panel, which constitute a major portion of the LAC in the PV-integrated scenarios. Since Pittsburgh is a relatively cloudy site (NOAA, 2010), we estimate an upper bound on absolute LACs with DC circuits and solar PV in the U.S.

Sizing the solar PV system is an important design consideration to minimize DC circuit LAC. An oversized PV system that produces more electricity than daily load requirements could require an inverter to sell the excess electricity to the electric grid, DC energy storage, or would waste excess PV electricity. All these options would increase the levelized cost of the system (Jimenez, 2005). Sizing the PV panel to minimize LAC is a rational approach, but this would not allow a comparison of scenarios with and without PV when PV LCOEs are greater than grid electricity prices (since the optimal PV size would then be zero watts). Given our interest in exploring not only the least cost scenarios, but also those that would increase the environmental sustainability of the overall system, we opted for a scenario where the solar PV array is sized to power the "base load" ambient lighting systems during the sunniest month of the year using the "peak hours approach" (Masters, 2004). The PV panel is modeled to provide equal energy end-use (lighting) service in lumen-hours (lm-h) for all four lighting system options, in the case without energy storage, using

$$PV(\text{kW}) = \frac{L}{\eta_{PV} \times I \times inv} \quad (3)$$

where PV is the peak installed power capacity of the solar panel in kW_p, L is the building lighting system electricity load (kWh/day) in the sunniest month of the year, July, in Pittsburgh, η_{PV} is the module efficiency of the solar panel, which is between 12–18% (Curtright et al., 2008; DOE, 2007b), I is the daily insolation (h/day of peak sun$=1\ \text{kW/m}^2$) in Pittsburgh in July, inv is the inverter efficiency, which is (87–94%) for the AC cases (and obviously 100% otherwise) (George, 2006). In months with less solar radiation, grid electricity supplies the part of the load not powered by solar PV. A consequence of the model's PV sizing rule is that each scenario has a different solar electricity production and solar PV module size, which varies between 16–42 kW_p or 1200–3300 ft^2 of the 12,000 ft^2 office building roof space, holding constant delivered lighting service in lm-h/ft^2.

2.3. Integrated solar PV array and battery storage design

To demonstrate how the addition of energy storage (in the form of simple lead-acid batteries) would influence the LACs of the four main lighting options, we also explore the case where the solar PV and energy storage system provides a fixed proportion of total lighting load, shown in Fig. 2; this proportion is held constant across scenarios for comparison. We chose lead-acid batteries for simplicity and since they are a mature battery technology. In this case, the solar PV array is sized for a load of bL where $b \le 1.0$ corresponds to the fraction of the lighting load served by the integrated PV-battery system. The lead acid battery bank is sized according to

$$B = \max_t \left[\frac{PV \times I_t - bL_t}{V \eta_d} \right] \quad (4)$$

where B is the battery size in amp-hours (Ah), defined as the maximum state of charge needed to store any PV output not used by the lighting load at a given hour over the year, PV is the size of the photovoltaic array in kW_p, I_t is the hourly insolation, and V is the system voltage of the solar PV array and lighting system, and η_d is the battery discharge efficiency. In our model, we ignore the excess electricity stored in the battery at the end of the year; it could be used for other end-uses for the commercial building. For this design, we assume the same system voltage for the lighting and power generation system to preclude the use of additional power electronics, as seen schematically in Fig. 1. We vary the proportion of electricity provided by PV and energy storage for the AC and DC fluorescent and LED lighting systems, and compare LACs with the base case AC fluorescent lighting system without solar PV.

3. Results

3.1. The economics of grid-powered DC LEDs

Fig. 3 shows the results for the grid-powered scenarios. In 2012, LED lamps (either DC or AC) are the lowest-cost options

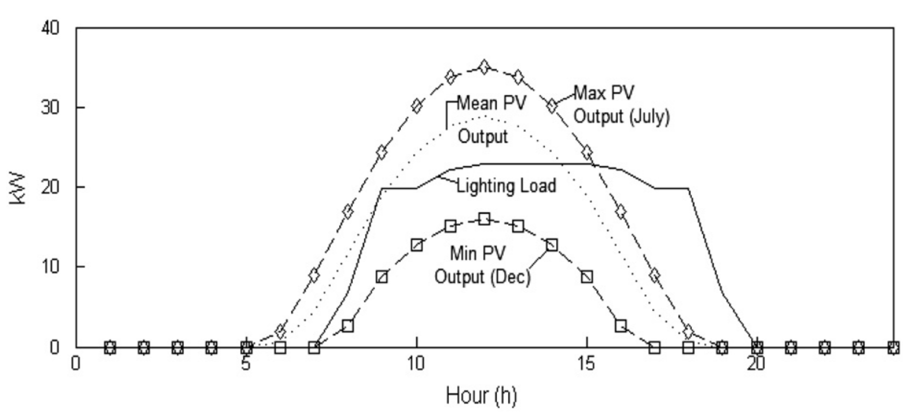

Fig. 2. Load profiles for LED Lighting system vs. solar PV output in Pittsburgh, PA. Load profiles generated from PV-integrated DC LED lighting systems with 100% of the load electricity requirements (on average over the year) provided by PV and energy storage.
Sources: (NREL, 2010; NOAA, 2010).

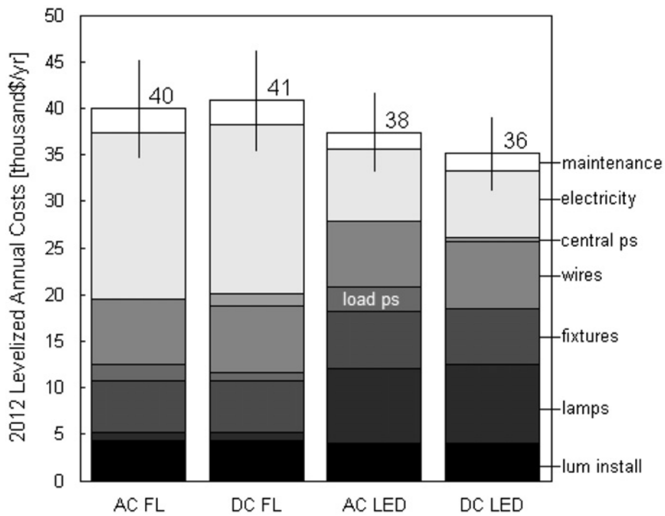

Fig. 3. Levelized annual costs for AC vs. DC fluorescent and LED lighting systems. These results assume that DC circuits eliminate the need for LED drivers, and calculate LAC with a discount rate of 12% and electricity price of $0.10/kWh. Error bars represent plus or minus one standard deviation of the LAC distribution. The LED cost of $18–24/klm for an integrated lamp is from DOE's 2012 R&D targets (2011b). LED and fluorescent lamp and fixture costs are listed in Appendix B. AC *FL*=277 V AC fluorescent lighting systems, DC *FL*=249 V DC fluorescents, AC *LED*=277 V AC LEDs, DC *LED*=249 V DC LEDs. *Lum install*=*luminaire installation cost*, *lamps+fix*=*lamp plus fixture equipment cost*, *ps*=*power supply*.

for commercial office lighting systems on the basis of levelized annual costs (LACs). The ranges in Fig. 3 and results reported in the paper all correspond to plus or minus one standard deviation from the mean. As Fig. 3 shows, removing the drivers and adding the central power supply for a DC LED lighting system would lead to a 5% (or ~$2000/yr) reduction in the levelized annual costs (LAC) of the "best" (lowest cost and most-efficient) LED lighting system compared to the best AC LED lighting system in 2012. However, there is a range of costs and efficiencies for LED lighting system components, so that switching AC grid power with centrally rectified DC for LED lighting systems could lead to an increase of 5% to a decrease of 15% in LACs (or +$2000/yr to −$6000/yr) and an increase of 2% to a decrease of 14% in capital costs (or +$5000 to −$27,000). AC and DC fluorescents have similar LACs and capital costs. The LED lighting options have 5–13% lower LACs and 30–40% higher capital costs than the fluorescent options due to the high capital cost of LED lamps. A commercial building of this size would spend roughly $26,000/year on lighting electricity costs, using EIA's (2008) end-use energy consumption estimates, due to overlighting (Dau, 2003) and the limited use of incandescent lamps. In contrast, our base case AC fluorescent lighting system has an annual electricity cost of $18,000/yr and we estimate that DC LEDs correspond to a reduction in overall electricity costs of 60% (to $7000/yr) compared to the AC fluorescent base case.

From a policy perspective, it is more important to assure that manufacturers can produce LEDs that follow DOE's lamp

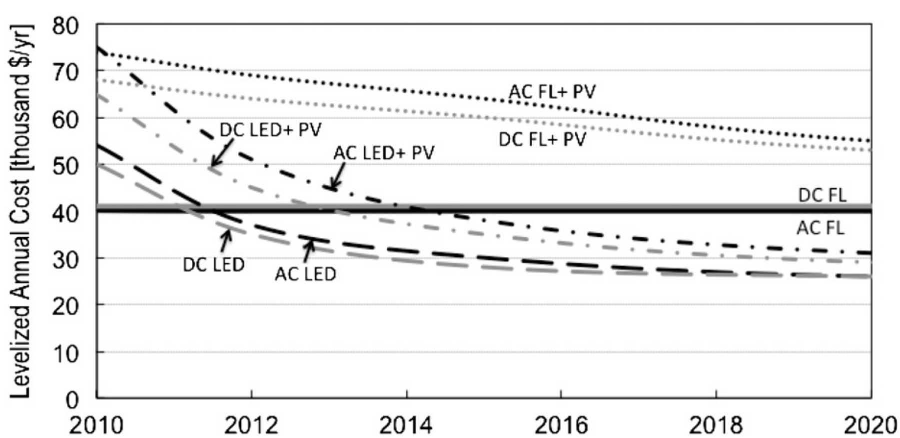

Fig. 4. 2010–2020 LAC projections for grid-connected AC vs. DC fluorescent and LED lighting systems. Results do not decline significantly between 2020–2030 and are excluded from the figure. The electricity price assumed is $0.10/kWh, and the discount rate is 12%. LED projections are from DOE R&D targets (2011b) and solar PV projections are from Curtright et al. (2008). These results assume that DC circuits eliminate the need for LED drivers and a PV inverter.

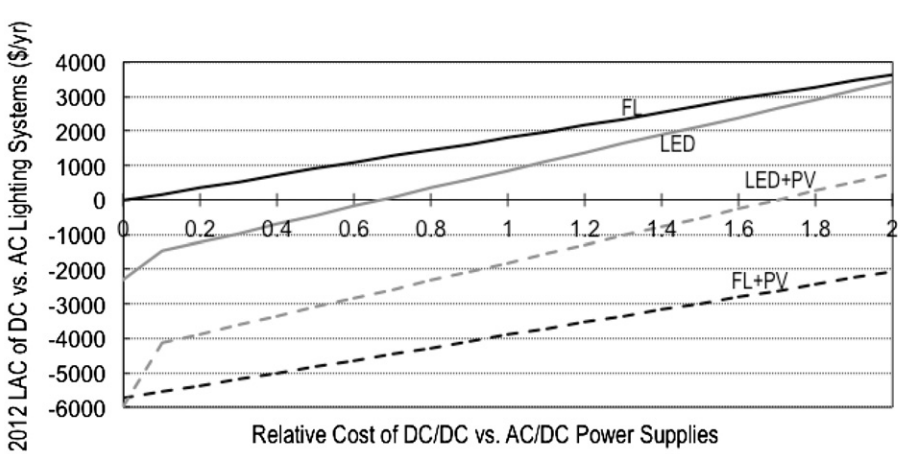

Fig. 5. Economics of DC lighting systems depend on the relative cost of DC vs. AC load power supplies, i.e. fluorescent lamp ballasts and LED drivers. Each scenario compares the LAC of the DC lighting system minus the LAC of the AC lighting system.

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production-cost and efficacy targets than it is to reduce power electronics costs with DC building circuits and voltage standardization. This can be seen in our simulations in Fig. 4, in which both DC and AC LED lighting systems have matched AC fluorescent lighting system levelized annual costs by 2012, with the difference between AC and DC LED lighting systems declining over time. Compared to AC LED lighting systems, DC LED lighting systems reduce LACs by 6% (or $2000) in 2015 and by less than 2% (or $<$ $500) in 2020. These LAC calculations most sensitive to the discount rate, luminaire fixture efficiencies, lighting requirements for the building, LED prices, and LED lifetimes.

The results in Figs. 3 and 4 use the strong assumption that a DC voltage standard is in place so that no load-level DC drivers are needed for the LED lighting systems. However, as discussed previously, DC drivers may be needed to provide current regulation or other functions, whether or not a DC voltage standard is in place.

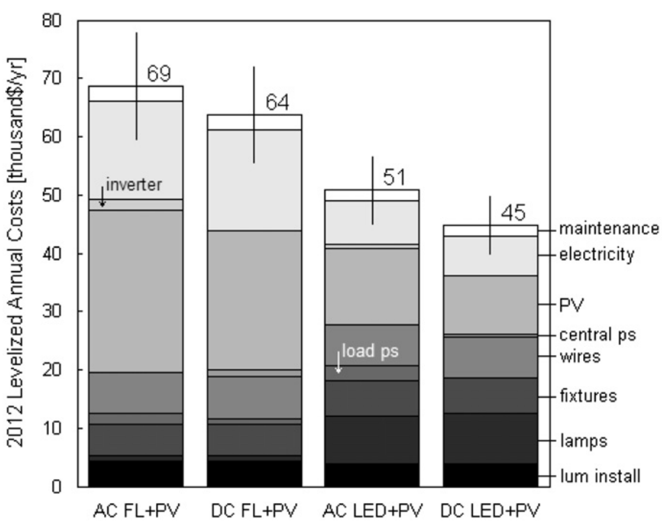

Fig. 6. Levelized annual costs (in 1000$ per year) for grid-connected PV-powered AC and DC lighting systems. For these results, the discount rate=12% and electricity price=$0.10/kWh. Error bars represent plus or minus one standard deviation of the LAC distribution. These results assume that DC circuits eliminate the need for LED drivers. The LED cost of $18–24/klm for an integrated lamp are from DOE's 2012 LED R&D targets (2011b), and solar PV costs of $2.3–6.1/Wp are from Curtright et al. (2008). LED and fluorescent lamp and fixture costs are listed in Appendix B. AC *FL+PV*=277 V AC fluorescents integrated with a 43 kW solar PV system, DC *FL+PV*=249 V DC fluorescents integrated with a 37 kW solar PV system, AC *LED+PV*=277 V AC LEDs with a 23 kW solar PV system, and DC *LED+PV*=249 V DC LEDs with an 18 kW solar PV system. *Lum install=luminaire installation cost, lamps+fix=lamp plus fixture equipment cost, ps=power supply.*

Thus, in Fig. 5, we relax the no-driver assumption to examine the breakeven DC driver/ballast cost for a DC lighting system to be lower-cost on a levelized annual cost basis than an AC lighting system. DC LEDs are lower cost than AC LEDs while DC drivers are less than 70% of the cost of AC drivers. Solar PV-powered DC LEDs are lower cost than their AC counterparts while DC drivers are less than 170% of the cost of AC drivers. Grid-powered DC fluorescents are always more expensive than AC fluorescents and solar PV-powered DC fluorescents are always less expensive than their AC counterparts under the range of power supply costs considered.

3.2. The economics of grid-connected PV-powered DC LEDs

Using a PV array output with the same voltage as the lighting system, one can eliminate an inverter (DC–AC) and other power electronics. By eliminating the inverter and load-level DC fluorescent ballasts and LED drivers, the PV arrays can be downsized by the extent of power conversion efficiency improvement, 14% and 22% with DC fluorescents and LEDs, respectively, and still provide the same amount of ambient lighting service in lm-h/ft^2. Fig. 6 shows that using the "best" (most-efficient) DC system with grid-integrated PV and LED lighting reduces LACs by 12% (or ~$6000/yr) and capital costs by 13% (or ~$39,000) compared to the "best" PV-powered AC LED system. When considering the range in costs and efficiencies for PV and LED system components, DC circuits could lower LACs by 2–21% (or ~$2000/yr to $10,000/yr) and could lower capital costs by 4–21% (or ~$16,000 to $62,000) compared to a similar AC system.

The main cost drivers for a grid-integrated PV array powering an LED lighting system are the PV array and LEDs. By 2013, grid-integrated PV-powered LEDs match the LACs of grid-powered AC or DC fluorescents. However, even in 2020, the LACs of PV-powered DC LEDs are 12% higher than the LACs of AC or DC LED lighting systems without PV power, as seen in Fig. 4.

3.3. The economics of grid-connected PV-powered DC LEDs with battery back-up

Using DC distribution with solar PV and batteries can eliminate the need for several power conversion stages, enabling the battery to provide power when the sun is covered by clouds or at night, instead of using electricity from the grid. Today, crystalline silicon solar PV, lead-acid batteries, and LED lighting are far too expensive to compete with grid-connected AC fluorescent lighting systems (Curtright et al., 2008). However, if LEDs follow DOE's R&D targets for cost reductions (2011b) and solar PVs follow a path toward $0.60–2.60/W$_p$ by 2030, which is the 95% confidence

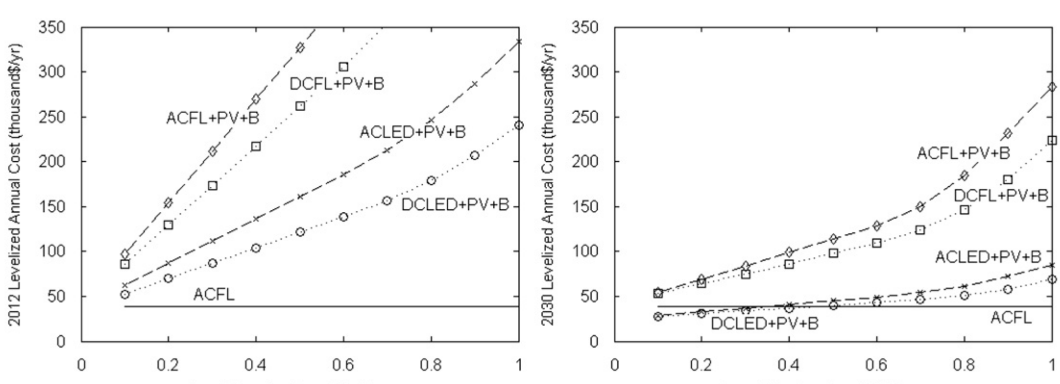

Fig. 7. 2012 and 2030 lighting system LAC projections vs. fraction of load provided by solar PV and batteries

interval for crystalline silicon PV capital costs estimated by experts in Curtright et al. (2008), our simulations suggest that it will be cost-effective for a grid-connected PV with battery back-up to power up to 15% of the load from a DC LED lighting system by 2020, and up to 40% of DC LED lighting loads by 2030, compared to using grid-powered AC fluorescent lighting systems as seen in Fig. 7.

4. Discussion and conclusion

In 2012, assuming that the U.S. Department of Energy LED performance forecasts are correct, the use of LEDs for commercial building lighting systems appears to be a cost-effective strategy for reducing electricity consumption and associated CO_2 emissions whether the lamps are powered by AC or DC. These projections may be optimistic, however, since we do not account for manufacturing and retail mark-ups (by a factor of 3) for the capital costs of LED products. In addition, the efficacy of common (vs. best-in class) commercially available products tends to be lower than DOE projections. Simulations in this work suggest that DC circuits could lead to an increase of 5% to a decrease of 15% in levelized annual costs (LACs) and an increase of 2% to a decrease of 14% in capital costs for LED lighting systems compared to AC LEDs, provided that a DC voltage standard were established for building distribution and LED luminaires so that drivers in individual fixtures could be eliminated. The specific DC voltage standard chosen has limited impact on lighting system LACs because wiring energy losses and switch costs, which depend on distribution voltage, are small compared to the LED lighting and solar PV capital costs. If drivers are necessary, DC LEDs remain the lowest LAC option while DC drivers are under 70% or under 170% of the cost of AC drivers, in the grid-connected or solar-PV powered cases, respectively. DC circuits with solar PV-integrated LEDs (with grid power as needed and no battery storage) may match the LAC of grid-powered AC fluorescent lighting systems by 2013 but do not match the LAC of grid-powered DC LEDs, the lowest cost lighting option, before 2030. If states with solar provisions in state Renewable Portfolio Standards or states with PV subsidies (DSIRE, 2010) required all new construction of commercial office PV applications to use DC circuits, the LACs of the installations in 2012 could decline by 2–21% and capital costs could decline by 4–21%, further stretching subsidy dollars, whether in the form of electricity production or power capacity investment subsidies. However, given the large cost barriers that PV has yet to overcome, it is not clear that such subsidies would be good public policy.

There are several limitations to using DC distribution for LED lighting systems. First, there is a considerable range in the capital costs and energy efficiencies of various models of central AC–DC power supplies and drivers in individual fixtures. Detailed benchmarking of baseline capital cost and energy efficiencies of LED luminaire drivers would be needed to design a set of replacement central AC–DC power converters that provide cost savings. Second, the main cost driver for the LAC for LED lighting systems is the capital cost of the LED itself, which is 22% of the AC LED lighting system LAC, rather than LED driver costs, which are only 7% of LAC in 2012. Although 5% LAC savings, on average, may be realized by switching from an AC LED lighting system to a DC LED lighting system in 2012, these cost savings are non-significant and small relative to the Department of Energy's R&D targets that capital costs for LEDs (in $/klm) will decline by over 10% annually during 2010–2020 through research and development (R&D). Third, as the AC LED driver and PV inverter steadily improve in energy efficiency and decline in cost, the savings in LACs and capital cost with DC circuits diminish over time. However, the use of DC circuits for a wider variety of end-use applications, such as building HVAC systems, computers, etc., where load-level power supply costs are flat or even slightly increasing over time (Darnell Group, 2011), might lower transition costs.

In the long term, DC building circuits can only lower costs if high-power AC–DC centralized power supplies can provide cheaper alternative to power factor correction and RFI suppression in many load-level power supplies. However, the century-long lock-in to AC systems poses a formidable barrier to the implementation of DC circuits in buildings. Power supplies, circuit protection, and other components designed for AC systems enjoy economies of scale in manufacturing, strong demand, and a large pool of trained engineers and technicians to control design and installation costs. At present, the small market for DC systems and small pool of qualified technicians results in high mark-ups for central AC–DC power supplies of kW-output power capacity, DC circuit protection, and installation; these mark-up factors have been ignored in our analysis. Standardization as well as training efforts would be essential if a transition to DC building circuits were to occur.

There are currently several industry-led standards for DC circuits in a variety of applications which may be adapted for commercial building lighting systems, such as the Emerge Alliance-led 24-V standards for lighting and 380-V standards for home appliances and plug-in hybrid electric chargers (Symanski and Watkins, 2010), the 12 V standard for automobile drivetrains, the Universal Serial Bus (USB) 5 V, 12 V, and 24 V standards for powering computer electronics, and the IEEE-led 48 V power over ethernet (PoE) (IEEE, 2009) standard and efforts to develop a Universal Power Adapter for Mobile Devices (UPAMD) standard (IEEE, 2010). The application of some of these standards could help the development of a centralized AC–DC power supply market, a prerequisite for the wider application of DC circuits in commercial buildings.

Unless society places a higher value on power factor correction, RFI suppression, and improving reliability by minimizing power electronics components, at present the economics of DC building circuits are marginal. Thus, there is limited justification for strong technology-push subsidies to support a transition to DC building circuits at this time. However, the economics of DC building circuits may improve with more research and development in power electronics to support a variety of LED architectures, whether with centralized or load-level drivers. In addition, the regulator can ensure the development of any safety standards needed with DC wiring, especially for insulation and arc-quenching (see Appendix A) needed with high voltage DC circuits, in order to level the playing field and to avoid picking winners in a second round of the "Battle of the Currents."

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Appendix A. Lighting system, power electronics, and wiring system characteristics

The modeled lighting systems consist of a 1900-klm ambient lighting system with 366 recessed troffer fixtures with 5300 lm

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Table A1
Base-case fluorescent and LED lighting system parameters.

	AC FL		DC FL		AC LED		DC LED	
	Ambient	*Task*	*Ambient*	*Task*	*Ambient*	*Task*	*Ambient*	*Task*
FL lamp cost: \$/fixture	11–27	1.5–2.5	11–27	1.5–2.5				
LED lamp cost: 2010\$/klm					86–116		86–116	
Lamp efficacy (lm/W)	86	78	86	78	125–169		125–169	
Fixture efficacy (lm/W)	53	24	56	25	99	92	114	105
Fixture efficiency (%)	72%	37%	72%	37%	87%	80%	87%	80%
Calc: system power (W)	99	20	94	19	53	5	46	5

Notes: The number of lighting fixtures and lighting system power are calculated from building geometry and IESNA lumen requirements of 40 lm/ft^2 for office buildings (Navigant Consulting, 2002), holding fixture lumens constant across scenarios. For details see Appendix B in the online version. Cost per fixture obtained from Grainger.com (2010). Fluorescent lamp efficacies from Navigant Consulting (2002). LED ambient fixture efficiency and fluorescent fixture efficiencies are from DOE (2011b, 2007a). LED task fixture efficiency is from DOE (2011b). LED fixtures have higher efficiencies than their fluorescent counterparts due to the directional nature of LED lumen output.

Table A2
Lighting system power supply parameters.

	AC–DC central power supply		DC–DC load power supply		Fluorescent ballasts	
	FL	*LED*	*LED ambient*	*LED task*	*AC*	*DC*
Converter type	Buck	Buck				
V_{in} (V)	277	277	242	242	277	242
V_{out} (V)	242	242				
Calc: *efficiency* (%)	93 ± 1%[a]	93 ± 1%[a]	84–92%[b]	84–92%[b]	85–109%[c]	91–112[d]
Calc: *L* (H)	8×10^{-7}	2×10^{-6}				
Calc: *C* (F)	10×10^{-8}	7×10^{-8}				
Calc: (R_{ON}, R_L, R_D)/*Rload* (%)	1%	1%				
Calc: *Rload* (Ohm)	1 ± 0.1	2 ± 0.3				

[a] AC–DC central power supply efficiencies are calculated assuming a buck converter topology, see Table A-3 for costs and (Erickson, 2001) for efficiency analysis.
[b] AC LED driver efficiencies are from R&D targets in (DOE, 2011b).
[c] Ballast efficiency is defined as the ratio of rated lamp power over lamp and ballast power consumption. If the ballast is designed to run lamps at less than their rated power, the ballast's nominal efficiency will be greater than 100%, yet the lamp will produce fewer lumens than if run at rated power. Ballast efficiency, together with ballast factor, determines the light output and power consumption of the fluorescent lamp and ballast system. AC fluorescent ballast efficiencies are from GE, Philips, and Osram Sylvania lamp catalogs.
[d] DC fluorescent ballast and DC driver efficiencies are assumed to be equal to AC ballast/driver efficiency divided by rectifier efficiencies of 93–97% from Pratt et al. (2007).

per fixture and a 330-klm task lighting system with 672 desk-level under cabinet fixtures with 490 lm per fixture, with technical and cost parameters shown in Table A1. A complete list of model parameters is provided in Appendix B of the online version. DC fluorescent ballasts and LED driver efficiencies were assumed to be equal to the respective AC ballast/driver efficiency divided by the efficiency of a rectifier. The DC lighting system is modeled as a circuit connecting the 277 V AC distribution system to a full-bridge rectifier with a non-isolated buck converter, which produces 249 V DC output for each floor-level lighting system of the building. LED driver, centralized rectifier, and fluorescent ballast technical parameters and energy efficiency calculations are shown in Table A2. Centralized power supply costs depend primarily on output power rating, as shown in Table A3. We ignore issues of standby-mode power consumption for fluorescent ballasts because DOE (2011a) has determined that it only applies to dimming ballasts, which we do not consider. We also assume that LED drivers have zero off-state power consumption, which would meet the 2011 Energy Star standards for all LED lighting fixtures except those with motion- or photo-sensors or for use with multiple fixtures (EPA, 2011).

For the base case, annual lighting electricity intensity for the AC fluorescent lighting system is 2.3–4.9 (base case: 3.6) kWh/ft^2, assuming ambient lights operate between 2500 and 5600 h/yr and task lights operate between 1500 and 2500 h/yr. This lighting electricity intensity is just over half the average values for U.S. commercial office buildings as reported by the EIA (1992) (6.1 kWh/ft^2) , LBNL's Lighting Market Sourcebook (5.2 kWh/ft^2) (Vorsatz et al., 1997), and the EIA's 2008 Commercial Building Energy Consumption Survey (CBECS) (6.8 kWh/ft^2). This difference arises primarily from the assumption that an energy-conscious office building owner would design lighting fixtures to provide the IESNA minimum lumen requirement of 40 lm/ft^2,

Table A3
AC–DC power supply costs.
Source: Philips Lighting Company official (2009).

Output power rating (W)	Cost (\$/W)
0–50	0.10
51–150	0.34
150–250	0.18
250–500	0.17
500–1000	0.20
1000–50,000	0.17

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while the EIA estimated that the average U.S. office has a mean illumination level of 45–91 lm/ft^2 (1992), which arguably means that it is overlit (Dau, 2003). Varying the amount of total lumens provided would change the absolute value of the estimated levelized annual cost in the results section, but not the ordering from least to most expensive. In addition, the model excludes less efficient incandescent lighting in the base case lighting system because, given the voltages assumed, the efficiency of these resistive elements are not affected by the use of AC versus DC. In addition, because replacing incandescent lamps with fluorescent or LED lamps can lower levelized annual cost of lighting (DOE, 2011b; Azevedo et al., 2009), including incandescent lamps in the base case would artificially inflate the levelized cost benefits of DC circuits with an LED or fluorescent lighting system. We exclude issues of color quality in the present analysis.

The wiring system is sized to meet lighting system current requirements, subject to copper conductor current limits and National Energy Code maximum voltage drop limits of 5% per string. These two constraints on the wiring system limit maximum wire lengths. Since we are modeling a new commercial building, the LAC calculations include wiring costs. Cables that provide a direct connection from the central power supply on each floor to the AC grid are assumed to be common to all cases and are not included in the model. We assume four circuit breakers per floor for the ambient lighting system; these costs were explicitly included in the LAC calculations, with prices obtained from manufacturer datasheets (see details in Appendix B of the online version). Circuit breakers (switches) for the task lighting systems are assumed to be integrated in the fixture design and are not explicitly included in the model.

While electrical safety is not the focus of this study, higher voltage DC wiring poses a greater arc hazard than AC circuits and requires specialized circuit breakers and protection (Salomonsson and Sannino, 2007). AC circuit breakers function by opening the circuit, which typically forms an arc that is extinguished when the voltage waveform passes through zero. Arcs in high voltage (>50 V) DC wiring systems can occur through a loose wiring connection or damaged insulation between cables of different polarity or between an electrical circuit and ground (Dargatz, 2009). DC wiring can cause arcing even at currents under the threshold at which the circuit protection operates. Thus, some DC wiring may need additional arc-quenching insulation and fault-detection and special signage for first-responders and other emergency service personelle. These additional costs imposed by safety considerations for DC wiring are excluded in our analysis.

Appendix B

See Table B1 for more details.

Table B1
Engineering design and economic model inputs and outputs.

Parameter	Symbol	Unit	Description/Equation/Reference	Minimum/ Nominal value	Maximum value
Engineering model					
Building input parameters					
Office width	w	ft	Office building width	100	
Office breadth	b	ft	Office building breadth	120	
Office height	h	ft	Office building height	8	
Number of floors	nf		Number of floors	4	
Square feet per person	sqftpp	ft^2	Square feet per office occupant, average value from http://www.officespace.com/SpaceCalc.cfm	75	
Cube rows	cr		Number of cubicle rows	6	
Desk space	dk	ft^2	Desk space	12	
Building output parameters					
Floorspace	fs	ft^2	$fs = w \times b \times nf$	48,000	
Number of occupants	ocp		$ocp = fs/sqftpp$	672	
Cube columns	cc		$cc = ocp/(4 \times nf \times cr)$, rounded	7	
Task light space	tls	ft^2	$tls = dk \times cc \times cr \times nf \times 4$	8064	
Lighting system input parameters					
Lumen requirement	lmft	lm/ft^2	Navigant Consulting, 2002	40	
Ambient lighting annual operating hours	aaoh	h	Annual operating hours for ambient lighting from Navigant Consulting (2002).	2500	5600
Task lighting annual operating hours	taoh	h	Annual operating hours for task lighting from Energy Solutions (2004).	1500	2500
Fluorescent (FL) ballast factor	Bf		From GE, Philips, and Osram Sylvania, Inc. (OSI) Lamp Catalogs	0.84	0.92
T8 FL efficacy	t8efc	lm/W	From GE, Philips, and OSI Lamp Catalogs	80	92
FL lamps per ambient fixture	flpaf			3	
FL lamps per task fixture	flptf			1	
LED lamps per ambient fixture	lpaf			12	
LED lamps per task fixture	lptf			1	
T8 watts	t8w	W		32	
T12 FL efficacy	t12efc	lm/W	From GE, Philips, and OSI Lamp Catalogs	70	86
T8 FL lifetime	t8lf	h	T8 fluorescent lamp lifetime in hours, from GE, Philips, and OSI Lamp Catalogs	16000	24000
T12 FL lifetime	t12lf	h	T12 fluorescent lamp lifetime in hours, from GE, Philips, and OSI Lamp Catalogs	16000	24000
T8 FL ballast lifetime	t8blf	h	T8 fluorescent ballast lifetime in hours, from GE, Philips, and OSI Lamp Catalogs	32000	48000
T12 FL ballast lifetime	t12blf	h	T12 fluorescent ballast lifetime in hours, from GE, Philips, and OSI Lamp Catalogs	32000	48000

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Table B1 (*continued*)

Parameter	Symbol	Unit	Description/Equation/Reference	Minimum/ Nominal value	Maximum value
Ac T8 FL ballast efficiency	acT8beff	%	Ballast efficiency equals the ratio of rated lamp power over lamp-and-ballast power consumption. From lamp catalogs	0.85	1.09
AC T12 FL ballast efficiency	acT12beff	%	Ballast efficiency equals the ratio of rated lamp power over lamp-and-ballast power consumption. From lamp catalogs	0.9	0.98
FL ambient fixture efficiency	afefffl	%	DOE, 2007a	0.65	0.8
FL task fixture efficiency	tfefffl	%	DOE, 2007a	0.3	0.5
LED lifetime	ledLf	h	DOE, 2011b	40000	60000
LED driver lifetime	ledDrvLf	h	DOE, 2011b	40000	60000
LED ambient fixture efficiency	afeffled	%	Average (0.87) from DOE, 2007a	0.77	0.97
LED tasklight fixture efficiency	tfeffled	%	Average (0.80) from DOE, 2011b	0.70	0.90
Maximum LED efficacy	maxEfcled	lm/W	Tsao, 2004	400	
Maximum FL efficacy	maxEfcfl	Lm/W	Derived from Tsao (2004), FL are 25% efficient at 85 lm/W, max efficacy $=4\times 85$ lm/W	340	
Lighting system output parameters					
Ambient LED lamp watts	alw	W	$Lpaf/(naf\times ledEfc\times thermEff\times lpaf\times afeffled)$; LED efficacy and thermal efficiency R&D targets in Table 1	Varies	
Ambient fixture watts	afwfl/led	W	($lpaf$ or $flpaf$) $\times$ ($t8w$)/($t8beff$ or $drvEff$); driver efficiency R&D targets in Table 1	Varies	
Ambient fixture efficacy	afefcfl/led	lm/W	$thermEff\times$ ($t8$- or led-Efc) $\times$ ($afefffl/led$) $\times$ (ac/dc, $T8beff$ or $ledDrvEff$) $\times$ ($t8blf$); thermal efficiency R&D targets in Table 1	Varies	
Number of ambient fixtures	naf		$round(lmft\times fs/(afw\times afefc))$	360	
Tasklight LED lamp watts	tlw	W	$Lpaf/(ntf\times ledEfc\times thermEff\times lptf\times tfeffled)$; LED efficacy and thermal efficiency R&D targets in Table 1	Varies	
Tasklight fixture watts	tfwfl/led	W	$lmft\times dk/tfefc$	Varies	
Tasklight fixture efficacy	tfefcfl/led	lm/W	$thermEff\times$ ($t12$- or led-Efc) $\times$ $tfefffl/led\times$ (ac/dc, $t12beff$ or $drvEff$) $\times$ ($t12blf$); thermal efficiency R&D targets in Table 1	Varies	
Number of tasklight fixtures	ntf		$ntf=cc\times cr\times nf\times 4$	672	
Central power supply input parameters					
Input voltage	Vg	Vac		277	
Output voltage	V	Vdc		48, 60, 250	
Diode forward voltage drop	VD	V		0.35	1.7
Switching period	Ts	s		0.0001	
Central power supply lifetime	psLf	h	http://www.testequity.com/products/1691/	30000	40000
Central power supply internal parameters					
Load resistance	Rload	W	$Rload=V/I$	Varies	
Inductor resistance	RL	W	$RL=0.01\times Rload$	Varies	
Switch transistor on resistance	Ron	W	$Ron=0.01\times Rload$	Varies	
Diode resistance	RD	W	$RD=0.01\times Rload$	Varies	
Voltage ripple	ΔV	V	$\Delta V=0.05\times V$;	Varies	
Duty cycle	D		$D=(V\times(RL+RD+Rload)+VD\times Rload)/(Rload\times(Vg+VD)+V\times(RD-Ron))$	Varies	
D-prime	D′		$D'=(1-D)$	Varies	
Inductor current	IL	A	$IL=(D\times Vg-D'VD)/(RL+D\times Ron+Rload)$	Varies	
Capacitor	C	F	$C=(D\times Ts\times(Rload\times IL-V)/(2\times DV\times Rload))$;	Varies	
Inductor	L	H	$L=(D\times Ts\times(Vg-IL\times(Ron+RL)-V)/(2\times D\times IL))$;	Varies	
Central power supply output parameter					
Converter efficiency	PSη	%	$\eta=(1-D'\times VD/(D\times Vg))/(1+(RL+D\times Ron+D'\times RD)/Rload)$	93%	
PV, wiring, electrical system input parameters					
AC operating voltage	acOpV	Vac		277	
DC operating voltage	dcOpV	Vdc		249	
Wire installation time	wit	h/ft	http://www.turtlesoft.com/construction-costs/Electric-Rough/Romex_6_3.htm	0.026; (1hr/38 ft)	
Wire life	wlf	y		25	
Inverter efficiency	invEff	%	George (2006)	0.87	0.94
Inverter lifetime	invLife	y		10	
Rectifier efficiency	rectEff	%	Pratt et al. (2007)	0.93	0.97
Battery lifetime	battLife	y		10	
Battery charge efficiency	battChEff	%	Messenger and Ventre, 2010	95	
Battery discharge efficiency	battDEff	%	Messenger and Ventre, 2010	95	
Battery cost	battCost	$/Ah	Grainger.com products, assuming 1.5% cost decline per year. See Table 1	varies	
PV, wiring, electrical system internal parameters					
Ambient fixture current	afc	A	$afw/(acOpV$ or $dcOpV)$	Varies	
Ambient wire current rating	awc	A	Min AWG table current s.t. (AWG table current $>=afc$) & $awvd<=0.05\times(acOpV$ or $dcOpV)$	12	
Ambient wire resistance rating	awr	Ω/1000 ft	Wire resistance corresponding to cable with current rating awc in AWG table	2.53	
Ambient wire voltage drop	awvd	V	$awl\times afc\times awr/1000$	Varies	
Ambient wire gage	afwg		Wire gage corresponding to cable with current rating awc in AWG table	14	
Tasklight fixture current	Tfc	A	$tfw/(acOpV$ or $dcOpV)$	Varies	

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Table B1 (*continued*)

Parameter	Symbol	Unit	Description/Equation/Reference	Minimum/ Nominal value	Maximum value
Tasklight wire current rating	twc	A	Min AWG table current s.t. (AWG table current $>=tfc$) & $twvd<=0.05\times(acOpV$ or $dcOpV)$	12	
Tasklight wire resistance rating	twr	Ω/1000 ft	Wire resistance corresponding to cable with current rating twc in AWG table	2.53	
Tasklight wire voltage drop	twvd	V	$twl\times afc\times awr/1000$	Varies	
Tasklight wire gage	tfwg		Wire gage corresponding to cable with current rating awc in AWG table	14	
Hourly insolation by month	solRad	W/m^2	Masters (2004)	Varies	
PV, wiring, electrical system output parameters					
Ambient fixture wire length	Awl	ft	$(w\times cr/4+b/2)\times 4\times nf$	Varies	
Task fixture wire length	Twl	ft	Assumes central circuit box and radial cables to each desk with varying length	Varies	
Lighting load	LkW	kW	if DC, $(naf\times afwfl/led+ntf\times tfwfl/led)/PS\eta$, else $naf\times afwfl/led+ntf\times tfwfl/led$	Varies	
PV panel size	pvkW	kW	See Eq. 4	Varies	
PV electricity output	pvkWh	kWh	$pvkW\times(0.97\times 0.96\times invEff\times(1-0.005\times(celltemp\text{-}25))\times solRad/1000$, calculated hourly, aggregated to daily averages per month	Varies	
Grid electricity consumption	gridkWh	kWh	For each month, hourly grid kWh for the $avg\ day=naf\times afwfl/led-hrlyPV$kWh, aggregated for aaoh $hours/year+ntf\times atoh\times tfwfl/led$ (tasklight electricity consumption), if excess PV electricity, assume used by exogenous loads	Varies	
Economic model inputs					
Lighting system cost input parameters					
T8 lamp cost	t8c	$/3-lamps	Assume ambient fixtures use three 4-foot t8 lamps in a recessed troffer fixture. Costs from Grainger.com	3.75	9
Fluorescent ambient fixture cost	afcfl	$/fix	Costs from Grainger.com	17	97
T12 lamp cost	t12c	$/lamp	Assume tasklights use one 2-foot t12 lamp in an undercabinet fixture	1.5	2.5
Fluorescent tasklight fixture cost	tfcfl	$/fixture	Costs from Grainger.com	23	43
AC T8 ballast cost	t8balc	$/ballast	Costs from Grainger.com	11	24
AC T12 ballast cost	t12balc	$/ballast	Costs from Grainger.com	5	9
LED ambient fixture cost	afcled	$/fixture	Costs from Grainger.com	19	99
LED tasklight fixture cost	tfcled	$/fixture	Costs from Grainger.com	31	46
Technician level I labor rate	tech1	$/h		10	20
Technician level II labor rate	tech2	$/h		40	68
Fluorescent ballast installation time	bInst	h		0.5	
Lamp installation time	lInst	h		0.25	
Luminaire installation time	lumInst	h		0.5	
LED driver installation time	dInst	h		0.5	
Lighting system cost output parameters					
Luminaire cost, lamp	(a/t)LumC-l	$	Same calculations for ambient or task lighting. For LEDs: $costPerKlm\times ledEfc\times(alw\times lpaf\times naf$ or $tlw\times lptf\times ntf)/1000$; For FL: $flpaf\times t8c$ or $flptf\times t12c$	Varies	
Luminaire cost, fixture	LumC-fx	$	$naf\times afcfl/led$ or $ntf\times tfcfl/led$	Varies	
Luminaire cost, ballast or driver	LumC-lps	$	For FL: $naf\times t8balc$ or $ntf\times t12balc$; For LEDs: $(naf\times afwled$ or $ntf\times tfwled)\times DrvCostPerW$; Driver cost per Watt estimates in Table A-3.	Varies	
Luminaire cost, installation	LumC-in	$	$Tech2\times lumInst$	Varies	
Luminaire cost, annual maintenance	LumC-m	$	$lInst\times tech1\times(aaoh/t8lf$ or $taoh/t12lf$ or $aaoh/ledLf$ or $taoh/ledLf)+tech2\times(aaoh/t8blf\times bInst$ or $taoh/t12blf\times bInst$ or $aaoh/ledDrvLf\times dInst$ or $taoh/ledDrvLf\times dInst)$	Varies	
Central power supply cost input parameter					
Power supply installation time	psInst	h		1	
Central power supply cost internal parameter					
Output power	Pout	W	LkW/nf	Varies	
Central power supply cost output parameter					
Central power supply cost, equipment	psC-eq	$	$psCostPerW\times Pout$, see Appendix A for power supply costs	Varies	
Central power supply cost, installation	psC-in	$	$tech2\times psInst$	Varies	
Central power supply cost, maintenance	psC-m	$	$Tech2\times psInst\times aaoh/psLf$	Varies	
PV, wiring, electrical system cost input parameters					
Inverter cost	invC	$/Wp	RMI, 2010	Varies	
PV balance of plant cost	bop	$/Wp	RMI, 2010; Curtright et al., 2008	Varies	
250 V DC switch cost	Sw250	$/switch	http://www.abb.com/product/seitp329/19130a55833d8efdc1256e89004019e9.aspx; half list price; assume 4 switches per floor, task lamp switches built into fixture	115	155

Table B1 (*continued*)

Parameter	Symbol	Unit	Description/Equation/Reference	Minimum/ Nominal value	Maximum value
48 V DC switch cost	Sw48	\$/switch	http://www.abb.com/product/seitp329/19130a55833d8efdc1256e89004019e9.aspx; list price	10	13
60 V DC switch cost	Sw60	\$/switch	http://www.abb.com/product/seitp329/19130a55833d8efdc1256e89004019e9.aspx; half list price	59	80
277 V AC switch cost	Sw277	\$/switch	http://www.drillspot.com/products/43243/Maple_Chase_ET1100_Electronic_Light_Switch	49	67
PV, wiring, electrical system cost output parameters					
ambWireCost, equip	aWireC-eq		$wire\ cost/ft \times awl + nf \times 4 \times (sw48 \text{ or } sw60 \text{ or } sw250 \text{ or } sw277)$	Varies	
ambWireCost,installation	aWireC-in		$awl \times wit \times tech2$	Varies	
TaskWireCost, equip	tWireC-eq		$wire\ cost/ft \times twl$	Varies	
TaskWireCost,installation	tWireC-in		$twl \times wit \times tech2$	Varies	
PV panel costs	pvC	\$	$1000 \times pvkW \times (bop + pvPanelCostPerW)$; *PV panel* costs in Table 1	Varies	
Economic input parameters					
Discount rate	R			0.12	
Time period	τ	Years		20	
Electricity price	E	\$/kWh		0.1	
Economic output parameters					
Cap			$aLumC + LumC + aWireC + tWireC + psC$	Varies	
pv cap			*PV panel + bop costs*	Varies	
Lac			See Eqs. (1)–(2)	Varies	
Npv			See Eq. (3)	Varies	
Environmental input parameters					
Electricity CO_2 intensity	eCO_2	Ton CO_2/kWh	EPA, 2007	0.001	
Electricity SO_2 intensity	eSO_2	Ton SO_2/kWh	EPA, 2007	$2.63 \times 10-6$	
Electricity NO*x* intensity	eNO_x	Ton NO*x*/kWh	EPA, 2007	$9.68 \times 10-7$	
Environmental output parameters					
Cost of CO_2 conserved	CO_2C	\$/ton CO_2	$(lacscenario - acacfl)/(CO_2acfl - CO_2\text{-}scenario)$	Varies	
Cost of SO_2 conserved	SO_2C	\$/ton SO_2	$(lacscenario - lacacfl)/(CO_2acfl - SO_2\text{-}scenario)$	Varies	
Cost of NO_x conserved	NO_xC	\$/ton NO_x	$(lacscenario - lacacfl)/(CO_2acfl - NO_x\text{-}scenario)$	Varies	
Monte Carlo parameter					
n			Number of runs in simulation	1000	

References

80plus.org, 2010. 〈http://www.80plus.org/〉.

Azevedo, I.L., Morgan, M.G., Morgan, F., 2009. The transition to solid state lighting. The Proceedings of the IEEE 97 (3), 481–510.

Babyak, R., 2006. Current thinking. Appliance Design Magazine 〈http://www.appliancedesign.com/Articles/Departments/8184f80593d3a010VgnVCM100000f932a8c0〉.

Belady, C., 2007. In the data center, power and cooling costs more than the IT equipment it supports. Electronics Cooling 〈http://electronics-cooling.com/articles/2007/feb/a3/〉.

Calwell, C., Reeder, T., 2002. Power Supplies: A Hidden Opportunity for Energy Savings Ecos Consulting for Natural Resources Defense Council.

Curtright, A.E., Morgan, M.G., Keith, D.W., 2008. Expert assessments of future photovoltaic technologies. Environmental Science & Technology 42 (24), 9031–9038.

Dargatz, M., 2009. DC arc faults and PV system safety. Renewable Energy World, 7 〈http://www.renewableenergyworld.com/rea//news/article/2009/12/dc-arc-faults-and-pv-system-safety〉.

Darnell Group, 2011 in Powerpulse.net. "AC–DC Pricing Trends Diverge from the Historic Norm." 〈http://www.powerpulse.net/story.php?src=r4;storyID=24942〉.

Darnell Group, 2005 in DOE, 2006. "The Current and Projected Future Market for Battery Chargers and External Power Supplies." 〈http://www1.eere.energy.gov/buildings/appliance_standards/residential/battery_external.html〉.

Dau, W., 2003. "The right amount of light". Buildings 97, 8.

DTI, 2002. "The Use of Direct Current Output From PV Systems in Buildings." 〈http://www.berr.gov.uk/files/file17277.pdf〉.

DOE, 2011a. "Energy Conservation Standards for Fluorescent Lamp Ballasts: Final Rule." Federal Register, 76 FR 70548. 〈http://www1.eere.energy.gov/buildings/appliance_standards/residential/fluorescent_lamp_ballasts.html〉.

DOE, 2011b. Solid-State Lighting (SSL) Multi-Year Program Plan (MYPP), Washington, DC.

DOE, 2007a. Commercially Available LED Product Evaluation Reporting program: CALiPER 3, Washington, DC.

DOE, 2007b. National Solar Technology Roadmap: Wafer-Silicon PV, Washington, DC.

DSIRE, 2010. "State RPS Policies with Solar/DG Provisions." Database of State Incentives for Renewables and Efficiency. 〈http://www.dsireusa.org/〉 Accessed 18 December 2010.

EIA, 1992. "Energy Consumption Series: Lighting in Commercial Buildings." 〈http://tonto.eia.doe.gov/ftproot/consumption/0555921.pdf〉.

EIA, 2008. 2003 Commercial Buildings Energy Consumption Survey. Washington, D.C. Tables C13A, E5. 〈http://www.eia.doe.gov/emeu/cbecs/〉.

Energy Independence and Security Act (EISA), 2007. (P.L. 110-140) Section 301. "Efficiency Standards for Class A External Power Supplies.".

Energy Solutions, 2004. "Analysis of Standard Options for Under Cabinet Fluorescent Fixtures Attached to Office Furniture." For Pacific Gas and Electric Company.

EPA, 2011. "ENERGY STAR Luminaires V1.1 Final Specification." 〈http://www.energystar.gov/index.cfm?c=new_specs.luminaires〉.

EPA, 2007. "EGrid 2007: U.S. National Average Data for Year 2005." 〈http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html〉.

Erickson, R., 2001. Fundamentals of Power Electronics, second edition Kluwer Academic Publishers, Norwell, MA.

George, K., 2006. "DC power production, delivery and utilization". Electric Power Research Institute White Paper.

Hammerstrom, D.J., 2007. "Ac versus DC distribution systems: Did we get it right?" In: Proceedings of the IEEE Power Engineering Society General Meeting, 2007. 〈http://ieeexplore.ieee.org/xpl/freeabsall.jsp?arnumber=4275896〉.

IEEE, 2009. IEEE Standard for Information Technology: 802.3at-2009. 〈http://standards.ieee.org/findstds/standard/802.3at-2009.html〉.

IEEE, 2010. IEEE Standard for a Universal Power Adapter for Mobile Devices: P1823. 〈http://standards.ieee.org/develop/project/1823.html〉.

International Energy Agency (IEA), 2010. "Technology roadmap: Solar photovoltaic energy." 〈www.iea.org/papers/2010/pv_roadmap.pdf〉.

Jancauskas, J.R., Guthrie, R.L., 1995. "Elimination Of Direct Current Distribution Systems From New Generating Stations." In: Proceedings of the Nuclear Science Symposium and Medical Imaging Conference.

Jennings, J.D., Rubinstein, F.M., DiBartolomeo, D., Blanc, S.L., 2000. "Comparison of Control Options in Private Offices in an Advanced Lighting Controls Testbed." LBNL-43096.

Jimenez, A., 2005. Photovoltaic Power Generation with Innovative Direct Current Applications: Feasibility and Example Site Evaluation EPRI Technical Update# 1011533.

Larson, E., 2003. Devil in the White City. Vintage Books, New York, NY.

Mammano, B. 2007. "Improving Power Supply Efficiency—The Global Perspective." Texas Instruments Training Report: Topic 1. 〈http://training.ti.com/courses/coursedescription.asp?iCSID=57748〉.
Masters, G., 2004. Renewable and Efficient Electric Power Systems. Wiley-Interscience, Hoboken, NJ.
Messenger, R., Ventre, J., 2010. Photovoltaics System Engineering, third ed. CRC Press, Boca Raton, FL.
Navigant Consulting, 2002. Lighting Market Characterization, 1. IESNA Lighting Standard Referenced in Table 4-1.
NOAA, 2010. "Ranking of Cities Based on % Annual Possible Sunshine in Descending Order from most to Least Average Possible Sunshine." 〈http://www.ncdc.noaa.gov/oa/climate/online/ccd/pctposrank.txt〉.
NREL, 2010. National Solar Radiation Database. 〈http://rredc.nrel.gov/solar/old_data/nsrdb/〉.
Philips Lighting Company official, 2009. Personal communication. August 30.
Pratt, A., Kumar, P., Aldridge, T.V., 2007. "Evaluation of 400 V DC distribution in telco and data centers to improve energy efficiency." In: Proceedings if the Telecommunications Energy Conference, Rome, Italy.
Redwood Systems. 2010. "Two Case Studies Verifying Substantial Energy Savings From Redwood Lighting Controls." 〈http://redwoodsystems.com/solutions/white-papers/〉.
Rocky Mountain Institute (RMI), 2010. "Achieving Low-Cost Solar PV: Industry Workshop Recommendations for Near-Term Balance of System Cost Reductions." 〈http://rmi.org/rmi/SolarPVBOS〉.
Salomonsson, D., Sannino, A., 2007. Low-voltage dc distribution system for commercial power systems with sensitive electronic loads. IEEE Transactions on Power Delivery 22 (3), 1620–1627 〈http://dx.doi.org/10.1109/TPWRD.2006.883024〉.
Salomonsson, D., and Sannino, A., 2006. "Centralized ac/dc power conversion for electronic loads in a low-voltage dc power system." In: Proceedings of the Power Electronics Specialists Conference, 2006. Jeju, Korea. 〈http://dx.doi.org/10.1109/PESC.2006.1712251〉.
Sannino, A., Postiglione, G., Bollen, M., 2003. Feasibility of a dc network for commercial facilities. In: Proceedings of the IEEE Transactions on Industry Applications, vol. 39 (5), pp. 1499–1507.〈http://dx.doi.org/10.1109/TIA.2003.816517〉.
Schavemaker, P., van der Sluis, L., 2008. Electrical Power System Essentials. Wiley & Sons, Ltd, London.
Strachan, N.D., 2000. "Adoption and Supply of a Distributed Energy Technology." Ph.D. Dissertation. Carnegie Mellon University.
Symanski, D., Watkins, C., 2010. 380V Data Center at Duke Energy. Emerging Technology Summit Presentation. Sacramento, CA, 9 November 2010. 〈http://www.emergealliance.org/Resources/Education.aspx〉.
Ton, M., Fortenbery, B., Tschudi, W., 2008. "DC Power for Improved Data Center Efficiency." Berkeley, CA.
Tsao, J.Y., 2004. Solid state lighting: lamps, chips, and materials for tomorrow. IEEE Circuits and Devices Magazine, 3.
Vorsatz, D., Shown, L., Koomey, J., Moezzi, M., Denver, A., Atkinson, B., 1997. Lighting Market Sourcebook for the U.S.. Lawrence Berkeley National Laboratory 〈http://www.osti.gov/bridge/purl.cover.jsp?purl=/582218-ZfuTmH/webviewable/〉.
Yamashita, T., Muroyama, S., Furubo, S., Ohtsu, S., 1999. "270 V DC system—a highly efficient and reliable power supply system for both telecom and datacom systems." In: Proceedings of the International Telecommunications Energy Conference, Copenhagen, Denmark.