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BUILDING INTEGRATED COGENERATION SYSTEM DESIGN SIZING AND ANALYSIS FOR CLIMATE DISRUPTION

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ABSTRACT

Normalized historical weather files are often utilized in whole-building energy simulations to quantitatively determine performance. Predictive building thermal and energy demand response to climate disruption can be evaluated through statistical and hourly simulation-based procedures. The WeatherShift™ application provides an opportunity to dynamically investigate design sizing sensitivity and operation of building integrated cogeneration systems (BICS) to climate disruption scenarios using industry standard reference EnergyPlus Weather (EPW) weather files. In order to determine the impact of future climate change earlier in the integrated design processes as it relates to building integrated cogeneration system performance and design sizing, hourly energy and loads simulation analysis was carried out using a reference commercial prototype building with projected future global climate weather models for two representative concentration pathways for Climate Zone 5A, Chicago. The ASHRAE 90.1-2013 reference building model was iteratively simulated in EnergyPlus simulation program with associated EnergyPlus Weather (EPW) TMY3 weather file and then "shifted" for 2026-2045 future years using WeatherShift™ to produce hourly time-step thermal and electrical load profiles. The ability to test cogeneration resiliency from definitive climate science and projections provides a value proposition for building owners and operators in terms of climate preparedness and adaptation considerations. Specific to the distribution climate model projections and emissions scenario considered, the experimental simulated results indicate that an optimally sized cogeneration system can maintain total fuel and energy cost, source energy, and greenhouse gas emissions savings relative to an ASHRAE 90.1-2013 minimally energy compliant reference building models.

INTRODUCTION

The 21st century has led to an overwhelming consensus in global warming albeit uncertainty in its anthropogenic influences and possible solutions. According to Sisterson (Borzo, 2015), "These changes will be profound, affecting health, economics, politics, biodiversity and settlement patterns around the world." Thus, the impact of climate change/disruption in the built environment must be considered by building design professionals so that design decisions and operational strategies ensure sustainability. The term *climate disruption* was first proposed by John Holdren (McMahon, 2015) is preferred to describe inadvertent changing global weather patterns both in intensity and duration and its future impact and threat to global socio-economics notwithstanding temperature-rise alone. The built-environment, in particular commercial and residential building sectors, can have a profound effect in reducing greenhouse gas emissions where 39% of carbon dioxide emissions in the United States are associated with fossil fuel emissions that provide heating, cooling, lighting, and electrical power for equipment and systems (Larsen, et al., 2011). Increasing concentrations of greenhouse gas emissions will continue to influence the warming of the Earth's atmosphere. Stabilizing concentrations to avoid further damaging global warming can only occur from the optimum resource allocation of limited fossil fuels for energy and thermal generation. Combined electrical and thermal energy systems (i.e., cogeneration systems) will likely play an integral role in future energy supplies because they can yield higher overall system fuel utilization and efficiency, and thus produce fewer greenhouse gas emissions, than traditionally separate systems.

Building energy simulation software with hourly input metrological data is an essential design tool to

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quantitatively investigate energy and thermal performance of the built environment in response to normalized historical weather patterns. Performance-based risk assessments for commercial and residential buildings have been evaluated with many disparate climate models and methodologies (Kershaw, Eames, & Coley, 2011) (Jentsch, Bahaj, & James, 2008) (Chan, 2011) (Nik, 2016) (Chakraborty, Elzarka, & Bhatnagar, 2016). Building thermal and energy demand subject to future climate disruption can be evaluated through statistical and hourly simulation-based procedures (Mingya, Yiqun, Zhizhong, & Peng, 2016). The direct and indirect impacts of climate change on district heat demand by Andric et al. with a resistance-capacitance model demonstrated a heat demand density decrease in 2050 within the range of 6.7-37.1% of the reference year considered (2010) and chosen weather scenario (Andric, et al., 2016). Pengyuan et al. simulated future energy use pattern for residential and office buildings in various U.S. cities based on hourly weather morphing methods showed a greater inclination of electricity use rather than fossil fuels from climate change extending the duration of cooling seasons while shortening heating seasons (Pengyuan & Ali). However, performance resiliency analysis for building integrated cogeneration systems (BICS) subject to future climate model projections and emissions scenarios is currently lacking in current literature. Thus, the hourly variation to a building's heat-to-power ratio (HPR), a normalized ratio of total thermal load over the total electrical load, subject to future climate conditions should be well understood for building integrated cogeneration systems for the heat-to-power ratio is critical to a system's efficiency selection of appropriate generation sets (Spiewak, 1987).

METHODOLOGY

Further to the development of commercial prototype buildings database (U.S. Department of Energy, 2014) by the U.S. Department of Energy and researchers at Pacific Northwest National Laboratory (PNNL), the design sizing of part-load operating generation sets are evaluated for prototype reference commercial buildings Office Large, Apartment High-rise, Hospital, Hotel, and School Secondary in Climate Zone 5A, Chicago, IL, eGRID Subregion RFC West on the basis of economic costs, annual source energy use, and greenhouse gas emissions subject to the WeatherShift™ future climate weather data. The WeatherShift™ time series application (Arup North America Ltd., Argos Analytics LLC, and Slate Policy and Design, 2015), generates 8,760 hourly future climate weather data for simulating building and urban performance based on the IPCC AR5 for both the RCP4.5 and RCP8.5 emissions scenarios using General Circulation Models (GCMs). GCMs outputs have the potential to provide geographically and physically consistent estimates of regional climate change (Intergovernmental Panel on Climate Change, 2013). This application provides an opportunity to dynamically investigate design sizing sensitivity and operation of BICS to climate disruption scenarios, according to Intergovernmental Panel on Climate Change (IPCC) research, using industry standard reference EnergyPlus Weather (EPW) weather files. In preparation of the Fifth Assessment Report (AR5) Intergovernmental Panel on Climate Change (IPCC) researchers developed and applied a new approach in achieving specific climate change targets through Representative Concentration Pathways (RCPs) scenarios (Intergovernmental Panel on Climate Change, 2009). The new RCPs compared to other prominent published sets of IPCC emissions scenarios (i.e. SA90, and IS92, SRES), are unencumbered by fixed assumptions related to population growth, economic development, or technology (Bjornaes, 2013). The intensity of forced radiation proceeds the RCP scenario and includes four grades: RCP2.6 (low emissions), RCP4.5 and RCP6 (intermediate emissions), and RCP8.5 (high emissions).

The analysis however does not consider future escalations for fuel and energy costs. The WeatherShift™ tool is utilized only for weather-based loads analysis. The reference commercial prototype buildings models that meet the minimum requirements for the energy-efficient design of buildings according to ANSI/ASHRAE/IESNA Standard 90.1-2013, using Performance Rating Methodology (PRM), were iteratively re-simulated (native EnergyPlus version 8.0.0 model input files (.idf) were upgraded to v8.5.0) with reference hourly EnergyPlus Weather (EPW) Typical Meteorological Year (TMY3) weather file (30-year average of weather data) for Chicago, IL and then "shifted" for 2026-2045 future years at RCP4.5 and RCP8.5 emissions scenarios at various warming percentiles (5%, 10%, 25%, 50%, 75%, 90%, and 95%). This provides a range of possible climatic outcomes considering uncertainty in climate change models. Figure 1 illustrates the shift in ambient dry-bulb temperature for intermediate emissions (RCP4.5) and high emissions (RCP8.5) representative concentration pathways at escalating warming percentiles 5% and 95% only for peak and minimum dry-bulb hourly temperature profiles with reference to the Chicago, IL typical meteorological year weather data. The peak profile is representative of a 24-hour day in July and the minimum profile is representative of 24-hour day in January. The shifted hourly weather profile

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(i.e. increase in dry-bulb temperature at peak and minimum) ranges from 1.0 to 3.4 degrees Celsius for RCP4.5 and 0.5 to 3.5 degrees Celsius for RCP8.5.

The hourly predictive thermal and electrical load profiles are generated from the EnergyPlus (U.S. Department of Energy Building Technologies Office, 2015) re-simulated reference commercial prototype building models and are used as an input parameter in DOCHP (Zakrzewski, 2017). DOCHP (Design and Optimization of Combined Heat and Power) is a load-based natural gas generation set cogeneration system optimization and analysis tool that combines generalized natural gas generation set performance curves and hourly building energy simulation outputs to model the dynamic part-load operation of a generation set based on hourly time-step thermal and electrical load profiles. The optimal generation set design sizing respective to the reference commercial prototype buildings is determined by an evolutionary genetic algorithm solver with a maximum operational cost savings objective based on two common load following operation modes: electrical load following (ELF) and thermal load following (TLF). The optimal generation set design sizing is then tested against the various emissions scenarios in the DOCHP tool to determine if the building integrated energy and thermal generation sets can maintain total fuel and energy cost, source energy, and greenhouse gas emissions savings relative to the ASHRAE 90.1-2013 minimally energy compliant reference building model.

RESULTS

The scenario-based technical analysis herein illustrates the sensitivity of the reference commercial prototype buildings heat-to-power ratio optimum generation set design sizing and building integrated cogeneration system ability to maintain reductions in fuel and energy costs (most influential performance parameter constraint) subject to future climate weather.

The percent difference in reference prototype commercial building heat-to-power ratio (Figure 2) ranges from 7.4%/6.6% to 24.5%/24.7% for Office Large, 3.6%/3.3% to 11.7%/11.9% for Apartment High-rise, 3.5%/3.5% to 11.1%/11.5% for Hospital, 6.0%/5.6% to 20.8%/21.0% for Hotel, and 6.1%/6.0% to 20.8%/21.1% School Secondary for representative concentration pathways RCP4.5/RCP8.5 respectively. Office Large demonstrates the greatest heat-to-power ratio sensitivity to the “shifted” climate weather data with a RCP4.5/RCP8.5 percentage range difference of 17.0%/18.1%.

Figure 3 examines how the warming percentile, representative concentration pathway, and operational mode can influence the optimal design sizing of the generation set. Utilizing the shifted hourly thermal and electrical load profiles, each reference commercial prototype building is re-analyzed in the DOCHP tool to determine the optimal generation set design sizing at minimum combined fuel and energy costs using the genetic algorithm solver. Reference commercial prototype building School Secondary illustrates the greatest change in optimal cogeneration design sizing at 59.2%/58.9% for RCP4.5/RCP8.5 (TLF combined average across all warming percentiles) relative to the normalized weather file cogeneration design sizing. The average change in optimal cogeneration design sizing for other reference commercial prototype buildings for RCP4.5/RCP8.5 results in -0.3%/0.0% and 9.8%/9.8% respectively for ELF and TLF Office Large, -7.0%/4.3% and -4.7%/-1.2% respectively for ELF and TLF Apartment High-rise, 7.6%/7.4% and 4.4%/5.2% respectively for ELF and TLF Hospital, 3.3%/0.3% and 1.6%/-0.3% respectively for ELF and TLF Hotel Large and, 1.5%/0.8% and 59.2%/58.9% respectively for ELF and TLF School Secondary.

Normalized hourly weather data is often used to evaluate the part-load performance of a generation set. By utilizing shifted weather data, the initial design sizing of the generation set can be tested for design resiliency to ensure that tolerance levels for fuel and energy costs are within acceptable performance ranges. Thus, Table 1 evaluates the design sizing and analysis of combined heat and power systems for climate disruption. The sensitivity of each reference commercial prototype building is illustrated for each representative concentration pathway, warming percentile and load following operation mode. The building integrated cogeneration system fuel and energy cost savings at 0% warming percentile baselines the performance of the optimally sized BICS utilizing the reference EnergyPlus Weather (EPW) weather file. Proceeding fuel and energy cost savings at increasing warming percentiles illustrates the optimally sized BICS (fixed parameter) subject to the shifted weather data (iterative).

CONCLUSION

In order to determine the impact of future climate change earlier in the integrated design processes as it relates to building integrated cogeneration system performance and design sizing, hourly energy and loads simulation analysis was carried out using reference commercial prototype buildings with projected future global climate weather models for two representative concentration pathways for Climate Zone 5A, Chicago. The ASHRAE 90.1-2013 reference building model was

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iteratively simulated in EnergyPlus simulation program with associated EnergyPlus Weather (EPW) TMY3 weather file and then “shifted” for 2026-2045 future years using WeatherShift™ to produce hourly time-step thermal and electrical load profiles for use with the DOCHP tool. The ability to test cogeneration resiliency from climate science and projections provides a value proposition for building owners and operators in terms of climate preparedness and adaptation considerations and thus presents another useful application of the DOCHP tool. Specific to the distribution climate model projections and emissions scenario, the simulated results indicated that an optimally sized cogeneration system can maintain total fuel and energy cost savings relative to an ASHRAE 90.1-2013 minimally energy compliant reference building model. Therefore, building integrated cogeneration systems are adaptable to climate model projections and future greenhouse gas emissions scenarios.

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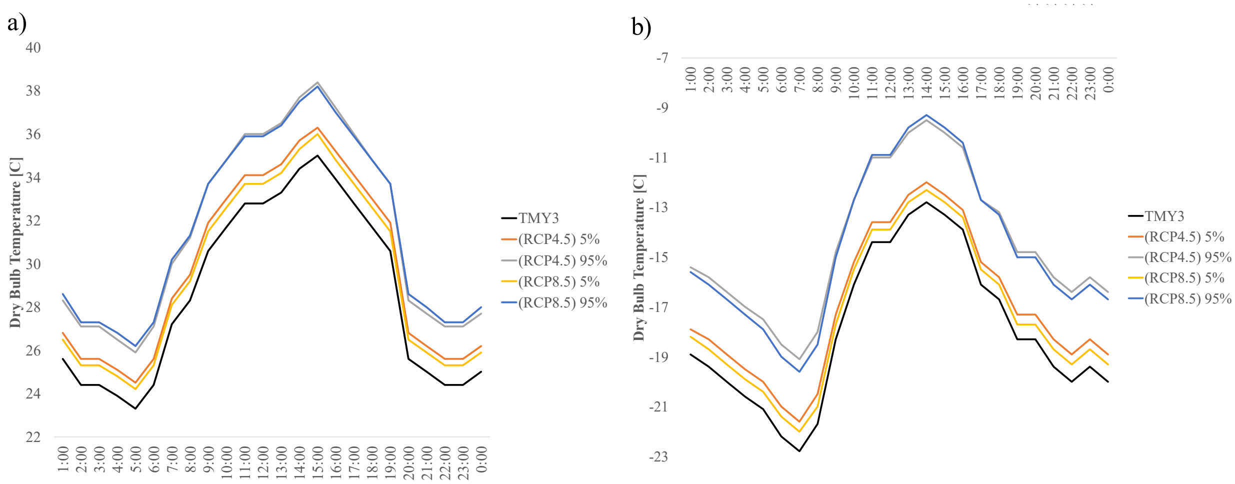

Figure 1 - Shifted Chicago, O'Hare International Airport EPW File Peak Hourly Dry-Bulb Temperature Profile for Representative Concentration Pathways Intermediate Emissions (RCP4.5 and RCP8.5) at 5% and 95% Warming Percentile as a Function of Time a) for Peak Dry-Bulb Temperate and b) and Minimum Dry-Bulb Temperature.

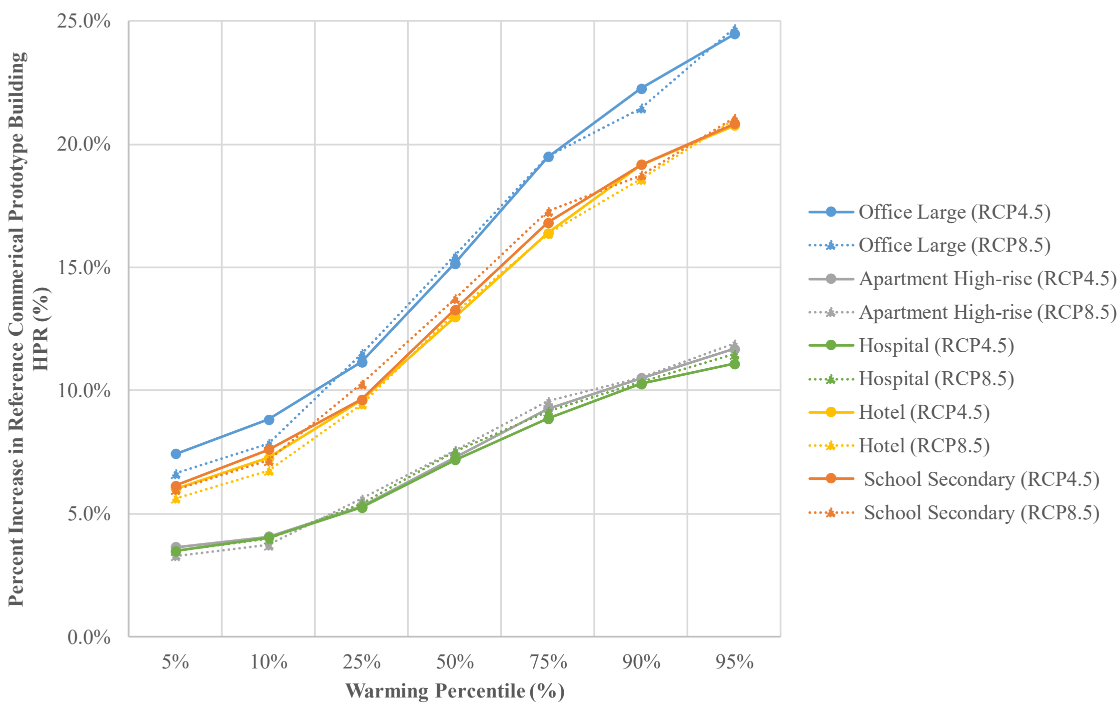

Figure 2 - Percent Difference in Reference Commercial Prototype Building HPR Subject to Representative Concentration Pathways and Warming Percentiles.

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Table 1 - Building Integrated Cogeneration System Change in Fuel and Energy Cost Savings Performance Sizing Subject to Warming Percentile, Representative Concentration Pathways, and Operation Mode.

Building Integrated Cogeneration System	RCP and Operational Mode	Warming Percentile (%) 0%	5%	10%	25%	50%	75%	90%	95%
Office Large	RCP4.5 ELF	3.70%	3.20%	3.20%	3.10%	2.80%	2.60%	2.50%	2.40%
	RCP8.5 ELF		2.90%	2.90%	2.80%	2.60%	2.40%	2.20%	2.20%
	RCP4.5 TLF	0.50%	1.30%	1.20%	1.10%	0.80%	0.70%	0.60%	0.50%
	RCP8.5 TLF		0.90%	0.90%	0.90%	0.60%	0.50%	0.30%	0.30%
Apartment High-rise	RCP4.5 ELF	6.50%	6.10%	6.40%	5.70%	6.00%	6.00%	6.00%	6.10%
	RCP8.5 ELF		5.80%	5.90%	6.00%	5.70%	5.60%	5.30%	5.60%
	RCP4.5 TLF	5.70%	5.20%	5.20%	4.30%	4.80%	5.10%	5.00%	4.40%
	RCP8.5 TLF		5.70%	4.70%	4.80%	4.60%	4.40%	4.30%	4.30%
Hospital	RCP4.5 ELF	13.10%	12.60%	12.60%	12.40%	12.20%	12.00%	11.90%	11.80%
	RCP8.5 ELF		12.30%	12.20%	12.20%	11.90%	11.90%	11.60%	11.50%
	RCP4.5 TLF	10.40%	10.00%	10.10%	10.00%	9.80%	9.70%	9.60%	9.60%
	RCP8.5 TLF		9.80%	9.70%	9.70%	9.40%	9.50%	9.20%	9.30%
Hotel	RCP4.5 ELF	19.50%	18.90%	18.90%	18.60%	17.60%	17.40%	17.80%	17.50%
	RCP8.5 ELF		18.40%	18.40%	18.30%	17.90%	17.60%	17.10%	17.10%
	RCP4.5 TLF	16.40%	15.70%	15.70%	15.30%	14.90%	14.50%	14.20%	13.90%
	RCP8.5 TLF		15.30%	15.30%	15.10%	14.40%	14.10%	13.60%	13.50%
School Secondary	RCP4.5 ELF	7.70%	6.50%	6.20%	5.70%	4.80%	4.30%	3.70%	3.30%
	RCP8.5 ELF		5.90%	5.80%	5.40%	4.50%	3.80%	3.00%	2.90%
	RCP4.5 TLF	8.90%	7.60%	7.40%	6.80%	6.00%	5.30%	4.70%	4.40%
	RCP8.5 TLF		7.00%	6.90%	6.50%	5.60%	4.90%	4.10%	4.00%

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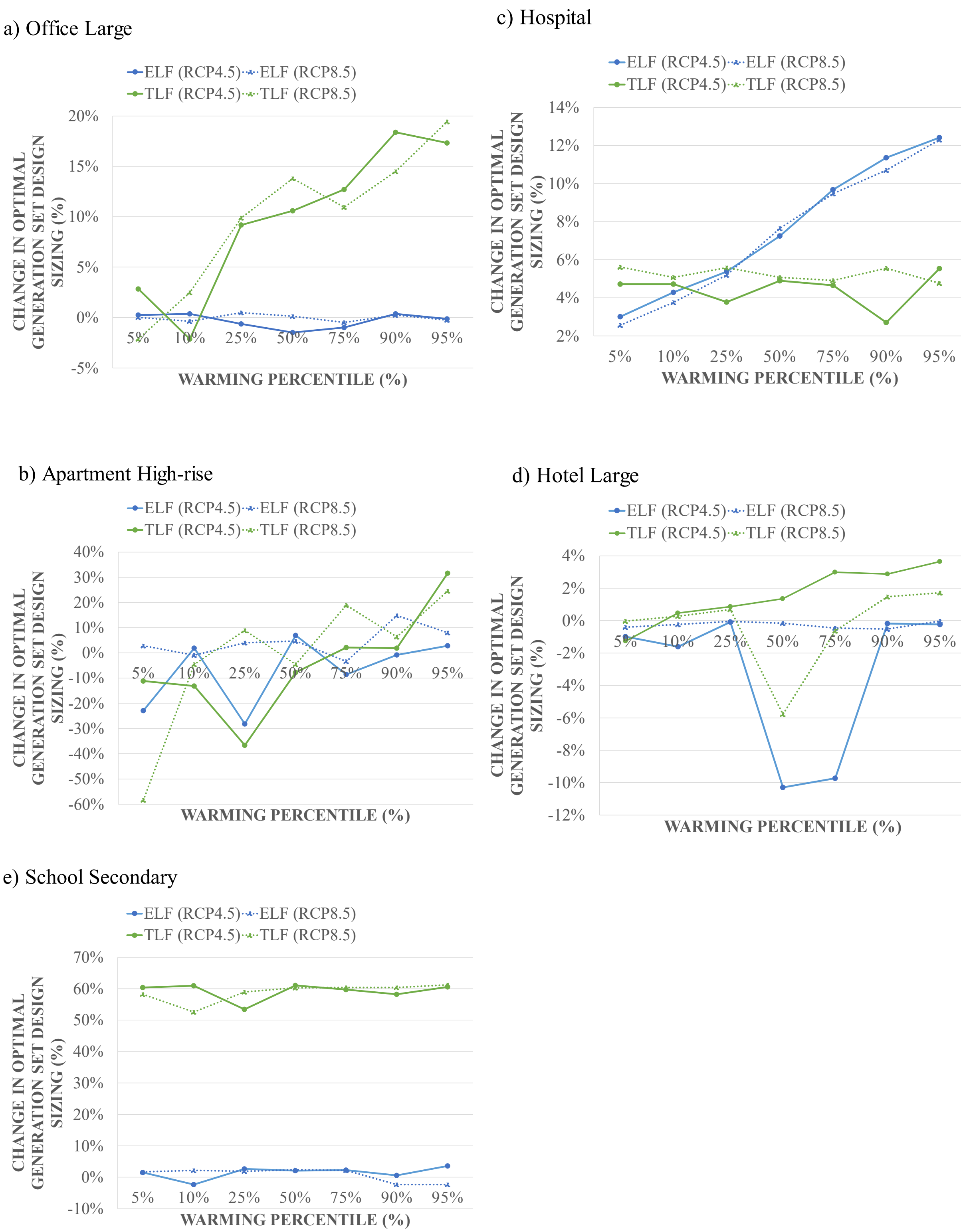

Figure 3 - Reference Commercial Prototype Building Change in Optimal Generation Set Design Sizing Subject to Warming Percentile, Representative Concentration Pathways, and Operation Mode for Optimal Fuel and Energy Cost Savings.

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