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An assessment of power flexibility from commercial building cooling systems in the United States ⋆

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Abstract

Understanding the varying characteristics and aggregate potential of power flexibility from different building types considering regional diversity is critically important to actively engaging building resources in future eco-friendly, low-cost, and sustainable power systems. This paper presents a comprehensive characteristics analysis and potential assessment of the power flexibility from heating, ventilation, and air conditioning loads in commercial buildings in the U.S. using a simulation-based method. Commercial buildings are first grouped by building type and climate region. The U.S. Department of Energy Commercial Prototype Building Models are used to represent an average building in each group and are simulated to characterize power flexibility. Based on building survey data, the number of commercial buildings in each group is estimated and used to calculate aggregate power flexibility. It is found that cooling loads in commercial buildings offer more flexibility for increasing power consumption than for decreasing it. The power consumption of commercial buildings in the U.S. can be increased by 46 GW and decreased by 40 GW on peak summer days. Among all commercial building types, standalone retail buildings provide the most absolute flexibility while medium office buildings have the most flexibility as a percentage of the rated power consumption.

Keywords: Commercial buildings, Demand response, EnergyPlus™, Power flexibility, Regional assessment

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1. Introduction

The recent decade has witnessed a rapidly increasing penetration of renewable generation around the world. In the U.S., the percentage of electricity generation from renewable energy increased from 9% to 17% during the period from 2008 to 2018 [1]. Renewable energy has the potential to supply 80% of total U.S. electricity generation by 2050 [2]. On the other hand, renewable generation introduces uncertainty and variability to supply-side resources, and thus presents challenges to reliable power system operation. Energy storage systems (ESS) [3] and flexible demand-side resources [4] can help to maintain power balance in the grid with high penetration of renewable energy. Given the high cost of ESS at current market rates, using flexible demand-side resources to serve the grid represents an innovative solution.

Among various demand-side resources, buildings as major electricity consumers have the greatest potential to provide flexibility. In the U.S., building load accounts for more than 70% of total electricity usage, and is a key contributor to system peak load [5]. On the other hand, power consumption from buildings is flexible and can be adjusted to serve the grid with little impact on customers. Many studies have been devoted to building control for grid services during the past few years. Just to name a few, the authors in [6] propose a supervisory control for the heating, ventilation, and air conditioning (HVAC) system in a commercial building to provide frequency regulation service. In [7], a state bin is used to model a population of thermostatically controlled loads (TCLs), and a model predictive control (MPC) scheme is designed to optimally control TCLs for frequency regulation. In [8], machine learning, optimization, and data structure are combined to realize demand responses from residential homes. A hierarchical control framework is proposed in [9] for integrated coordination between TCLs and other distributed energy resources to provide load-following service. A distributed control is proposed in [10] to provide generation following in the real-time energy market. In [11], the authors propose two control strategies to enable HVAC systems to provide frequency regulation services: an MPC for variable air volume HVAC systems and a rule-based control for aggregation of on/off HVAC systems. In [12], the authors propose a control strategy to use variable-speed pumps in HVAC systems for frequency regulation.

Those studies propose innovative building load control and scheduling methods for grid services but are based on detailed dynamics and constraints of individual devices. When scheduling a large number of flexible building loads for grid services, it is computationally expensive yet unnecessary to model and consider individual devices in detail. A simplified model that captures aggregate flexibility is convenient and useful for long-term planning and operational dispatch at the system level. Several research efforts have been dedicated to modeling and characterizing aggregate flexibility from building loads. For example, in [13], the authors propose an aggregate model to quantify the power flexibility of a population of heterogeneous residential air conditioning systems. A general battery model is proposed in [14] to succinctly characterize aggregate power flexibility from a collection of TCLs such as residential air conditioning systems and water heaters. In [15], the authors present an optimization method to estimate parameters of an aggregate flexibility model for commercial HVAC loads. A two-layer demand response flexibility estimation framework is developed in [16] to quantify power flexibility for different types of commercial buildings. In [17], the authors validate the analytical flexibility estimation method through simulation of high-fidelity residential building models. The authors in [18] estimate the flexibility from residential hot water systems in the Australian National Electricity Market and quantify the potential benefit of optimized control of these systems. In [19], a social network analysis is applied to cluster buildings based on historical data, and then an artificial neural network algorithm is proposed to estimate power usage profiles of buildings at campus or city district scale. In [20], flexibility estimation and control methods are presented for TCLs with lock time to provide regulation service.

Because of differences in the distribution of renewable resources and generation mix in different regions, assessment of power flexibility by building type and by region is critically important for understanding the technical and market potential of demand-side resources in future eco-friendly and sustainable power systems. Unfortunately, there are very limited efforts in this aspect. To characterize power flexibility from commercial buildings, 11 commercial buildings located in Southern California are studied in [21]. In [22], the authors evaluate the power flexibility from five office buildings located in two different climate zones. As for regional flexibility assessment, the authors estimate the flexibility potential from four residential TCLs in California for frequency regulation in [23]. In [24], a method is proposed to estimate regional flexibility from residential TCLs at the county, state, and climate zone levels using housing, population, weather station, and climate zone information. Commercial buildings account for 36% of the total electricity consumption in the U.S. [5] and have huge potential for grid services. Nevertheless, to the best of our knowledge, there is no existing study dedicated to understanding the regional power flexibility from commercial buildings. To bridge the gap, this paper presents a comprehensive power flexibility characterization and assessment for HVAC load in commercial buildings. The power flexibility is characterized using a simulation-based method with high-fidelity building models implemented in EnergyPlus™[25]. EnergyPlus™ is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting, plug and process loads—and water use in buildings. It provides integrated and simultaneous approximation of thermal zone conditions and HVAC system response, and heat balance-based solution of radiant and convective effects. Detailed methodology for modeling building energy consumption in EnergyPlus™ can be found in [26]. In particular, the U.S. Department of Energy Commercial Prototype Building Models [27] (hereinafter referred to as prototype buildings) are used to represent common commercial buildings in the U.S. The power flexibility of the prototype buildings in each climate zone is then estimated through a large number of simulations. Comprehensive analysis and thoughtful insights are provided on how power flexibility varies with building vintage, building type, and climate zone. Based on building survey data, the number of commercial buildings in each group is estimated and used to calculate aggregate power flexibility by building type and by climate region. The main contributions of this paper are twofold.

- This paper proposes an innovative method to employ high-fidelity models in power flexibility assessment to capture the impacts from building thermal dynamics, control systems, and various building operating conditions. Compared to existing methods based on simplified first-order thermal models, the proposed method improves the accuracy of the power flexibility assessment. The proposed excitation tests from relaxing the thermostat setpoints capture the impacts of control systems and building operating conditions on power flexibility from buildings.
- Key factors that affect power flexibility are identified through sensitivity analysis. We also set forth procedures to assess aggregate flexibility by build type and climate

region. Aggregate power flexibility from commercial building cooling systems is estimated for the entire U.S. for the first time.

The rest of this paper is organized as follows. The power flexibility characterization and assessment methods are described in Section 2. Section 3 presents simulation results and sensitivity analysis of power flexibility for individual prototype buildings. Aggregate flexibility results are presented and discussed in Section 4. Section 5 discusses the importance and explores the underlying meaning of this study. Finally, Section 6 offers concluding remarks.

2. Simulation-based Assessment Method

Commercial buildings with an inherent ability to store heat in thermal mass can vary their HVAC power consumption with little impact on customer convenience or comfort. For commercial HVAC systems, the flexibility describes their capability to temporarily deviate from the baseline (the power consumed without responding to needs from the grid), subject to zone temperature constraints. In the continental U.S., flexibility from buildings is most valuable during the daytime in summer, when regional and national system peaks typically occur and flexible resources become insufficient. Therefore, this paper focuses on flexibility assessment for commercial HVAC systems on summer days.

A simulation-based method is proposed to estimate aggregate power flexibility from HVAC systems in commercial buildings. The proposed method leverages the prototype buildings, which were designed and have been widely used to represent the average and typical power profiles of building groups categorized by building type and climate zone. The average power flexibility per building for each group is first estimated by simulating each individual prototype building in EnergyPlus^{TM} under different settings. The aggregate power flexibility is then generated by scaling the average power flexibility by the number of buildings in each group. With this method, the regional flexibility assessment only requires repeated simulation of the prototype buildings. On the other hand, simulating high-fidelity models under realistic settings captures impacts of different building characteristics, diversified use patterns, and various operating conditions in power flexibility assessment. Therefore, this assessment method maintains a good balance between simplicity and fidelity. Note that the step size for power flexibility assessment in this work is half an hour, which is sufficiently small for the purpose of resource expansion and planning studies. On the other hand, the resolution of EnergyPlus^{TM} simulation is set to be a minute to capture the thermal dynamics.

2.1. Commercial Buildings in the U.S.

In the U.S., commercial buildings are non-residential buildings owned, operated, and used by federal, state, and local governments as well as private companies. Commercial buildings are diverse in appearance and function. Therefore, flexibility assessment considering different types of commercial buildings is challenging. This study leverages the prototype buildings, including 14 commercial building types in 14 U.S. climate locations. The climate zones were developed by researchers at Pacific Northwest National Laboratory and adopted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Based on heating/cooling degree days and precipitation, the entire U.S. is divided into seven climate regions: Zone 1 (Very Hot), Zone 2 (Hot), Zone 3 (Warm), Zone 4 (Mixed), Zone 5 (Cool), Zone 6 (Cold), and Zone 7 (Very Cold). Those regions can be further divided into different categories by moisture regimes, denoted by A (Humid), B (Dry), and C (Marine). Please refer to [28, 29] for details. Those prototype buildings were developed to represent a cross-section of common commercial building types and reviewed extensively by building industry experts. To represent buildings with different vintages, five versions of prototype building models were designed based on ASHRAE Standard 90.1 [30], which defines minimum requirements for energy-efficient designs of commercial buildings and is updated every three years. Different versions of ASHRAE 90.1 reflect how building vintage affects the energy performance of commercial buildings. The prototype buildings are widely used in assessments of how different operation conditions, design, and control affect power and energy consumption from commercial buildings at large-scale [31–33].

In this study, power flexibility is estimated by simulating the prototype buildings. Note that there is a strict requirement on zone temperature in some commercial buildings, including hotels, hospitals, outpatient healthcare, apartments, and data centers in the large office buildings, which are excluded from the power flexibility assessment in this work. In addition, this paper focuses on flexibility assessment in the continental U.S. Therefore, the assessment excludes Alaska and Hawaii, and all other off-shore insular areas.

2.2. Power Flexibility from Individual Prototype Buildings

The power flexibility of an HVAC load in a commercial building is characterized by the maximum deviation from the baseline power consumption, subject to zonal temperature constraints. The flexibility limits can be mathematically expressed as

$$\overline{P}_k = \max_{\mathbf{T}_k \in \mathcal{T}_k} P_k - P_k{}^{\text{base}}, \tag{1a}$$

$$\underline{P}_k = \min_{\mathbf{T}_k \in \mathcal{T}_k} P_k - P_k{}^{\text{base}}, \tag{1b}$$

where $\overline{P}_k$ and $\underline{P}_k$ are the upper and lower limits of power flexibility at time step k, respectively, P_k^{base} is the baseline power consumption with the default control, P_k is a feasible power consumption, $\mathbf{T}_k$ is a vector of the zone temperature at time step k, and $\mathcal{T}_k$ is a set that contains all acceptable temperatures of zone i in a commercial building at time step k. To facilitate the comparison of power flexibility among different buildings, we also define the power flexibility ratio as the absolute power flexibility as a percentage of the rated power. The power flexibility can be readily calculated once the baseline, maximum, and minimum power are estimated.

2.2.1. Baseline Power Estimation

The baseline is the building power consumption with the existing supervisory control defined in the prototype building models. As an example, Fig. 1 plots the cooling temperature setpoint, the temperature of an example zone, and the baseline power consumption of the large office building in climate zone 4B on a hot summer day. There are three periods with different operating schedules and settings:

- Occupied period (5:00–21:00): The cooling setpoint is 24 ^oC. The fan speed is continuously adjustable.
- Unoccupied period (0:00–3:00 and 21:00–0:00): The cooling setpoint is 26.7 ^oC. The fan is switched between on and off, depending on whether the zone temperature is within the deadband.
- Transition period (3:00–5:00): The hourly cooling setpoint is linearly decreased to 24 ^oC over time. During this period, the fan speed is switched between on and off.

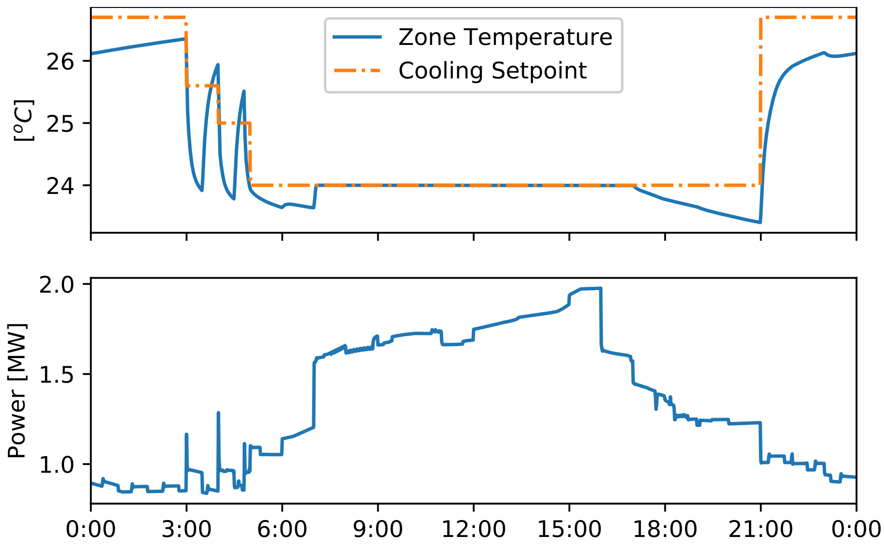


Fig. 1: Cooling temperature setpoint and simulated temperature of an example zone (upper) and building power consumption (lower) of the large office building in climate zone 4B on a hot summer day.

The baseline power profiles can be readily extracted by running EnergyPlus^{TM} simulations of prototype buildings.

2.2.2. Maximum and Minimum Power Estimation

There are different control methods for adjusting HVAC power consumption. Regardless of control objective or grid services, the acceptable temperature range of occupants must be considered. Therefore, the feasible power consumption range can be estimated by simulating a building with zone thermostat setpoints equal to their maximum or minimum. For example, to obtain the maximum (or minimum) power consumption during the period from 13:00 to 13:30, the zone thermostat setpoints remain the same before 13:00 and are increased (or decreased) by 1.11^oC for that period, as illustrated in Fig. 2. With two simulations per period, 96 simulations are needed to repeat the same process for all half-hour periods throughout the day for each prototype building.

2.3. Numbers of Commercial Buildings

The number of buildings in each group is needed to estimate the aggregate power flexibility. There is no publicly accessible data on building numbers by building type and by climate zone. In this paper, we adopt the method proposed in [34] to estimate the building numbers. Specifically, the number of buildings in each group is estimated

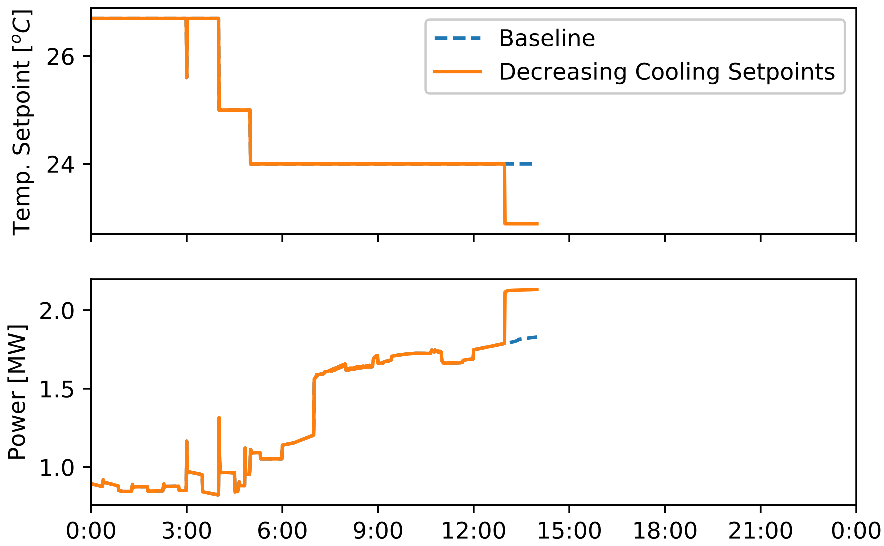


Fig. 2: Decreasing temperature setpoints to estimate the maximum power consumption from 13:00 to 13:30 of the same building in Fig. 1.

as

$$N_{j,s} = \omega_{j,s} N_{tot} \,, \tag{2}$$

where $N_{j,s}$ is the number of commercial buildings of type j in climate zone s, $\omega_{j,s}$ is the ratio of the number of commercial buildings of type j in climate zone s to the total number of commercial buildings in the U.S., and N_{tot} is the total number of commercial buildings in the U.S.

While N_{tot} can be readily obtained from the U.S. Energy Information Administration's Commercial Buildings Energy Consumption Survey (CBECS) [35], $\omega_{j,s}$ is not directly available. Herein, a commercial database called Mcgraw Hill Construction (MHC) Data [36] is used to estimate $\omega_{j,s}$. The MHC data covers all new buildings and existing facilities from 2003 to 2007. The data represents a set of more than 250 thousand individual records of commercial buildings constructed across the U.S., covering a total of 8.2 billion square feet, and is considered to be a good representation of the whole commercial building stock in the U.S. The building types in the MHC data are the same as the ones in the CBECS, instead of the prototype buildings. Therefore, the CBECS building types need to be mapped to the prototype building types, and then used to estimate $\omega_{j,s}$. Finally, the number of commercial buildings in each group ($N_{j,s}$) is calculated and shown in Table 1. It is found that the building numbers vary significantly by building type and climate zone. For example, the total number of standalone retail buildings is about 1,121 thousand while the total number of large offices is only

Table 1: Number of commercial buildings (thousand) by type and climate zone

Zone	Office			Restaurant		Retail	Mall	School		Warehouse
	Large	Medium	Small	Quick	Full			Prim.	Sec.	
1A	0.37	4.42	28.00	5.73	3.01	16.49	11.20	1.58	1.40	12.31
2A	1.19	27.80	354.93	67.24	35.22	163.20	80.79	23.16	13.24	91.33
2B	0.22	9.98	96.47	14.89	8.20	37.23	20.68	4.08	2.00	20.47
3A	1.64	26.19	321.17	74.72	37.12	175.36	83.23	23.44	16.47	104.59
3B	1.05	24.46	158.39	46.36	15.84	91.91	51.02	11.07	7.13	81.03
3C	0.43	4.65	25.93	5.08	1.93	14.05	8.43	1.18	0.96	5.42
4A	4.16	40.70	312.15	65.31	42.42	187.11	82.22	22.20	17.51	86.23
4B	<0.01	1.25	15.79	3.91	1.94	8.75	1.83	0.75	0.55	2.39
4C	0.57	6.70	40.88	10.50	3.41	31.49	8.71	2.33	2.11	15.35
5A	1.62	36.25	306.88	94.31	47.73	252.1	83.41	22.83	19.86	126.20
5B	0.44	11.70	107.34	18.83	10.36	58.24	16.42	5.55	3.81	24.27
6A	0.49	10.21	80.46	18.62	10.34	69.71	12.45	4.17	3.62	16.42
6B	<0.01	1.19	10.08	2.27	1.33	6.70	1.30	0.93	0.75	1.73
7	0.04	1.12	10.79	2.62	1.22	7.97	0.55	0.58	0.65	1.53

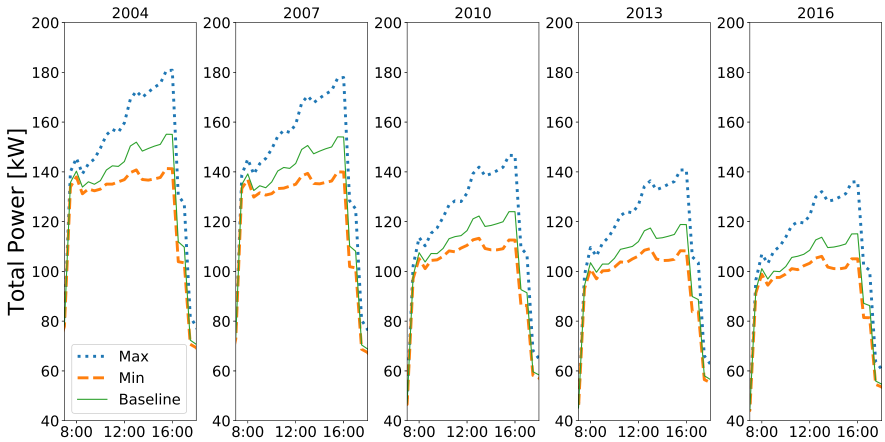
12 thousand. About 22% of standalone retail buildings are located in climate zone 5A, but only 6% in climate zone 7, even though the areas of the two zones are similar in size.

3. Flexibility from Individual Prototype Buildings

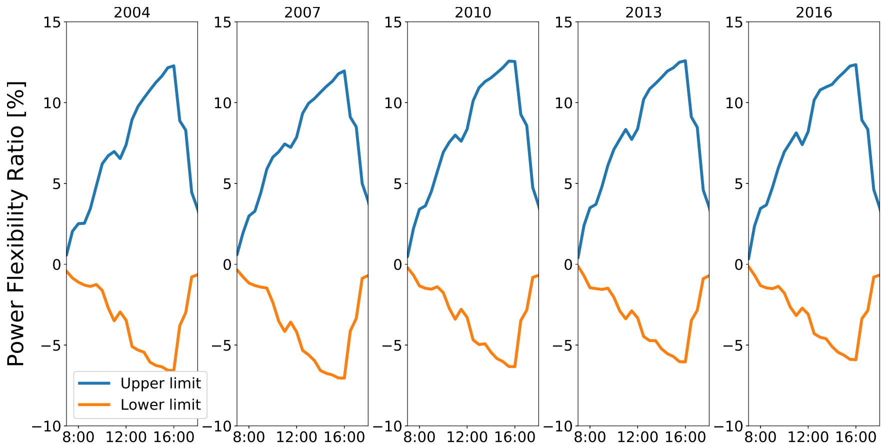
Key factors that affect the power flexibility from a prototype building include 1) building vintage, 2) building type, 3) climate zone, 4) temperature setpoint deviation, and 5) time duration. Sensitivity analysis was performed to understand how power flexibility varies with these factors. In all simulations, the typical meteorological year data including the dry-bulb temperature and solar radiation at the locations of the prototypical buildings is used as inputs. The default simulation date is August 1.

When varying temperature to provide power flexibility, thermal comfort requirement for occupants must be satisfied. ASHRAE Standard 55 recommends indoor temperature to be in a range of 73–79^oF. A common practice in building control is to have a setpoint of 75 or 76^oF. In this study, when estimating power flexibility, the default setpoint deviation is set to be 2^oF (1.11^oC) to ensure the indoor temperature is within a preferable range. Such a deviation is also used in several existing studies on demand response and grid services from commercial buildings, such as [37].

Note that we have studied how individual factors affect power flexibility for all the 10 building types in 14 climate zones. Instead of reporting detailed simulation results of all case studies, this section highlights key properties and presents a characteristics analysis with representative results illustrated by examples.



(a) Total power consumption



(b) Power flexibility ratio

Fig. 3: The power flexibility of the medium office building in climate zone 5A.

3.1. Building Vintage

All five versions of the prototype buildings with different vintages are simulated to estimate their power flexibility on different summer days. For a given prototype building, the baseline, maximum, and minimum power consumption vary slightly with building vintage and a noticeable decrement from version 2007 to 2010 is detected. On the other hand, the power flexibility ratio profiles remain almost the same and the difference in absolute flexibility is insignificant. As an example, Fig. 3 plots the results for the medium office building in climate zone 5A. Therefore, the selection of different versions does not affect the power flexibility assessment results much. In this paper, version 2013 is used to estimate aggregate power flexibility.

3.2. Building Types

As expected, different types of buildings exhibit different power flexibility characteristics. A boxplot of power flexibility ratios for different building types during the

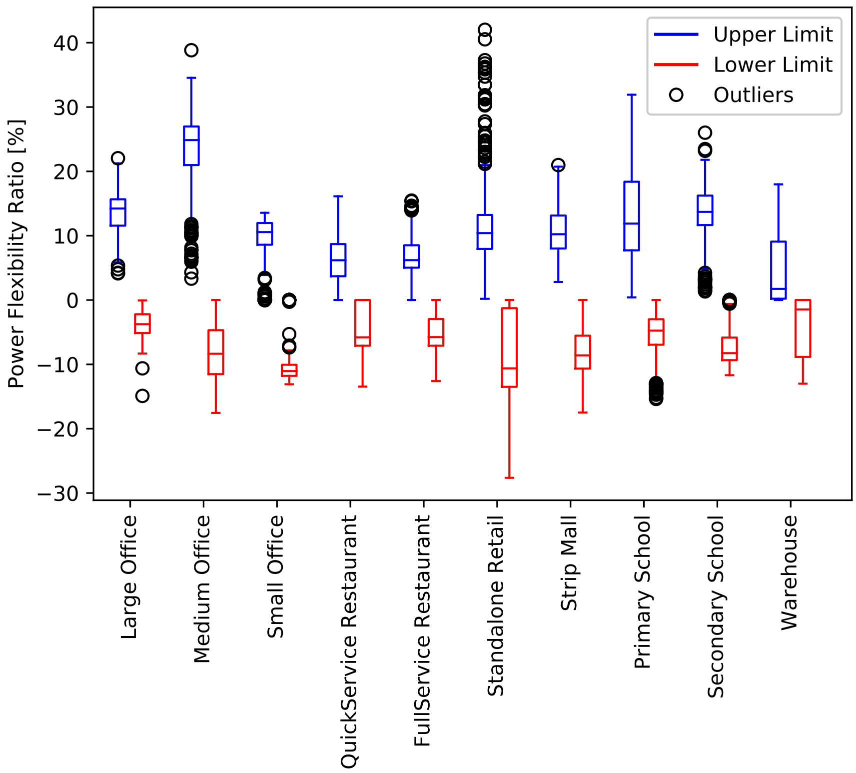


Fig. 4: Distribution of power flexibility ratio by building types.

daytime (7:00–18:00) is provided in Fig. 4. The following observation can be made:

- The mean flexibility ratio for increasing power consumption for all building types is between 5-15% except for the medium office and warehouse buildings.
- The mean flexibility ratio for decreasing power consumption for all building types is between 5-10% except for the small office building (around 11%).
- The medium office buildings have the largest flexibility ratio in increasing power consumption, with a median value of 25%.
- The warehouses have the lowest median value of power flexibility ratio in both directions, as the power consumption is mainly due to the internal heat gain and therefore is relatively insensitive to changes in temperature setpoints.

The results are also studied to better understand how daily power flexibility profiles vary with building types. Due to space limitation, only the profiles for the large and small office buildings are provided in Fig. 5. The two building types are selected as they represent different HVAC types and (built-in vs. packaged system) and different levels of thermal mass.

Small office buildings can be cooled down fast and therefore their temperature

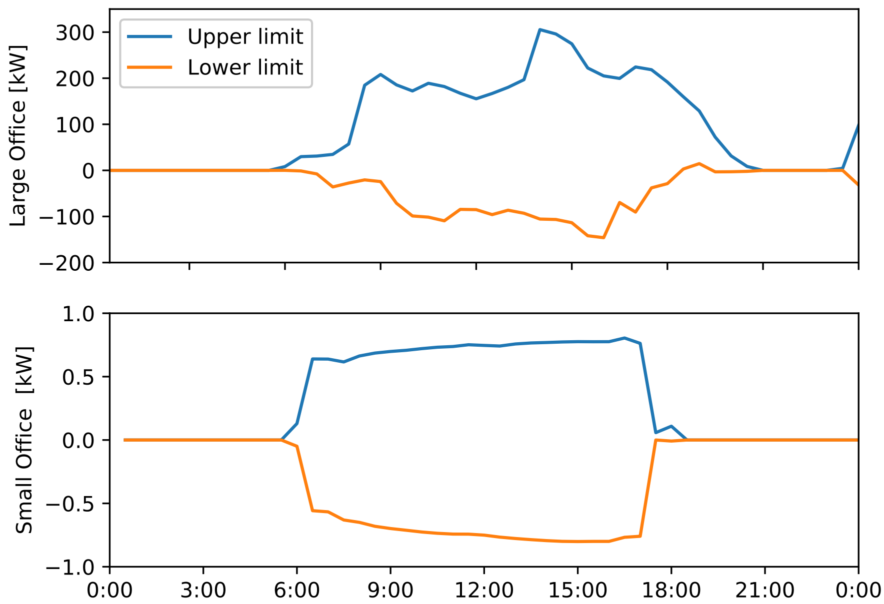


Fig. 5: The power flexibility of large office buildings (upper) and small office buildings (lower) in climate zone 4B.

setpoints during unoccupied periods are higher than those of large office buildings. The baseline power consumption during the unoccupied period is close to zero and a small change in temperature setpoints typically does not affect the HVAC power consumption. Therefore, the HVAC power consumption in small office buildings is only flexible during the daytime. In addition, as packaged HVAC systems are usually controlled by discrete on-off control, the change in HVAC power by the setpoint is also discrete. Therefore, power flexibility during the daytime is relatively flat.

Large office buildings have large thermal mass and therefore slower thermal dynamics. The temperature setpoints during the unoccupied period can only be slightly higher than during the occupied period. Otherwise, the indoor air temperature cannot be reduced to the desired temperature by the starting time of the occupied period. Therefore, a small change in temperature setpoint affects HVAC power consumption and flexibility can be provided throughout a day. In addition, as built-in HVAC systems are usually controlled by continuous controllers, the change of HVAC power by the setpoint can be continuous. Therefore, the flexibility varies throughout the day. Moreover, the fan power in large office buildings increases as temperature setpoints decrease but remains flat as temperature setpoints increase. This is a key reason why the large office building is more flexible in increasing power consumption than in decreasing it.

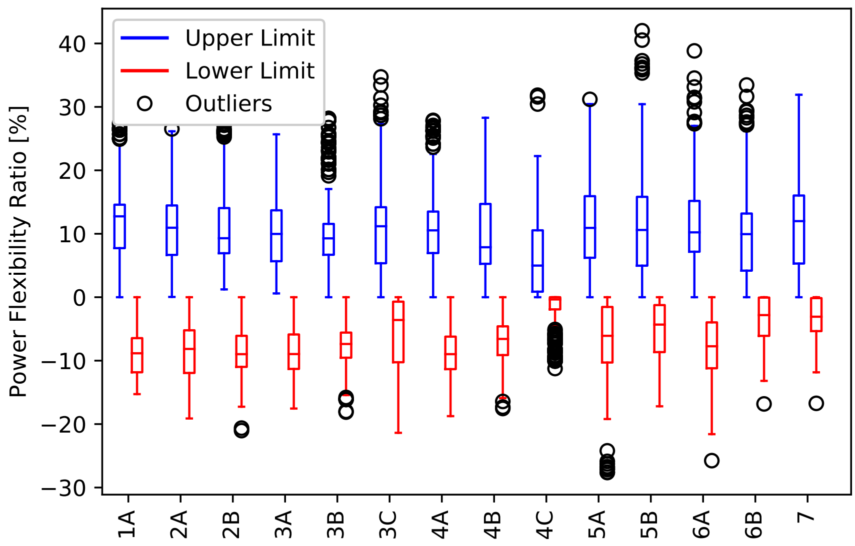


Fig. 6: Distribution of power flexibility by climate zones.

3.3. Climate Zone

To understand how power flexibility varies with climate zone, statistical information is extracted and studied by building type. A box plot of power flexibility ratios for each climate zone is provide in Fig. 6. Again, the power flexibility for increasing power consumption is generally higher than for decreasing power consumption for all zones. The median values of the upper bound and the lower bound are 10-15% and 5-10%, respectively, for most of the climate zones. Compared with the distribution of power flexibility ratio by building type shown in Fig. 4, the distribution by climate zone is much less diversified. This means the power flexibility ratio is less sensitive to climate zone than to building type.

3.4. Temperature Setpoint Deviation

Simulation results suggest that power flexibility is generally proportional to changes in temperature setpoints for all types of commercial buildings. As an example, the power flexibility with two different temperature setpoint deviations is plotted in Fig. 7 for both the large office building in climate 5B and the small office building in climate zone 4B, respectively. Note that when the cooling load is at the HVAC system capacity during unusually hot summer hours, the power consumption cannot be increased by further reducing temperature setpoint.

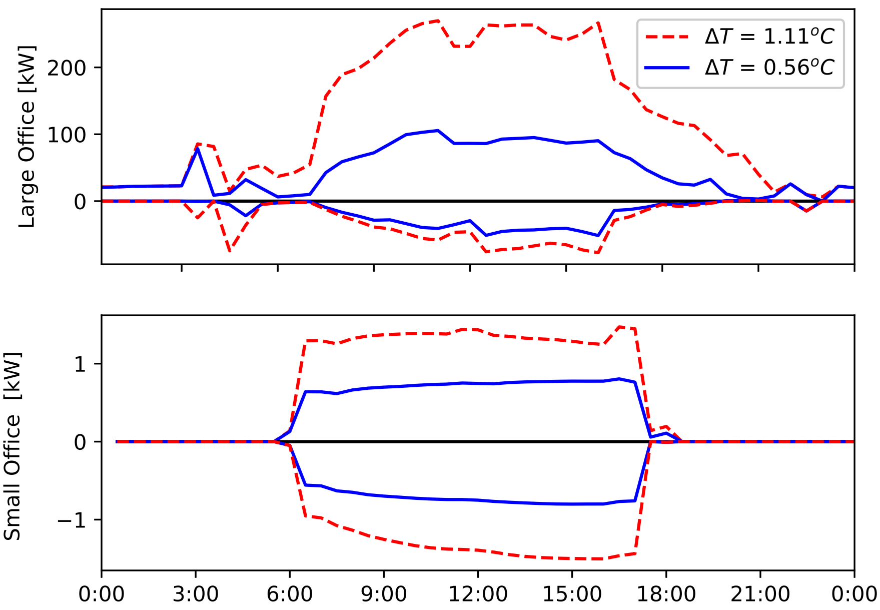


Fig. 7: Power flexibility vs. temperature setpoint deviation for the large office building in climate zone 5B (upper) and the small office building in climate zone 4B (lower).

3.5. Time Duration

Sensitivity analysis was performed to study the impacts of time duration required from different grid services on power flexibility. The time duration for sustained power deviation is set to be 15-60 minutes. It was found that the magnitude is not sensitive to time duration within the range. As an example, results for the small office building (4B) are plotted in Fig. 8.

Note that the power flexibility estimated in this study is mainly for slow grid services, such as ramping service and peak demand management. To estimate flexibility from buildings for fast grid services, such as frequency regulation, building dynamics with minute or second time scale are required but cannot be captured by EnergyPlus^{TM}, as explained in [38].

4. Aggregate Flexibility Assessment

The power flexibility of each prototype building can be used to represent the average value per building in each building group collected by building type and climate zone. Using the average flexibility profiles together with the building numbers of individual groups in Table 1, the aggregate power flexibility by climate zone and by building type is estimated and analyzed as follows.

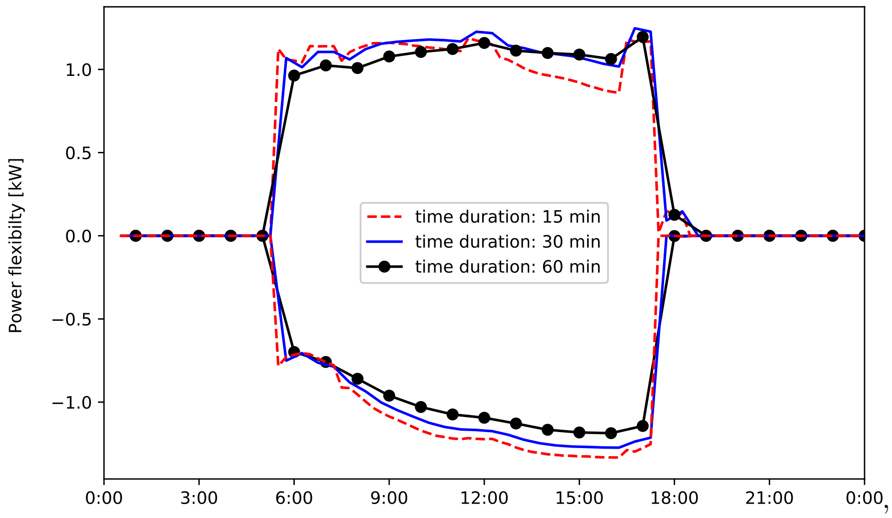


Fig. 8: The power flexibility of the small office (4B) with different time duration

4.1. Power Flexibility by Climate Zone

Figure 9 plots the aggregate power flexibility from commercial HVAC loads in different climate zones. The ratio of building number in each climate zone is provided in Fig. 10. Key observations and insights are provided as follows.

- The aggregate power flexibility varies much throughout the day. The power flexibility during daytime is much larger than in the early morning and at night, when most commercial buildings are not occupied and HVAC systems become less active. The national power consumption from all flexible commercial HVAC systems can be increased up to 46 GW and decreased up to 40 GW.
- According to [39], the existing intra-hour balancing power capacity is about 20 GW.

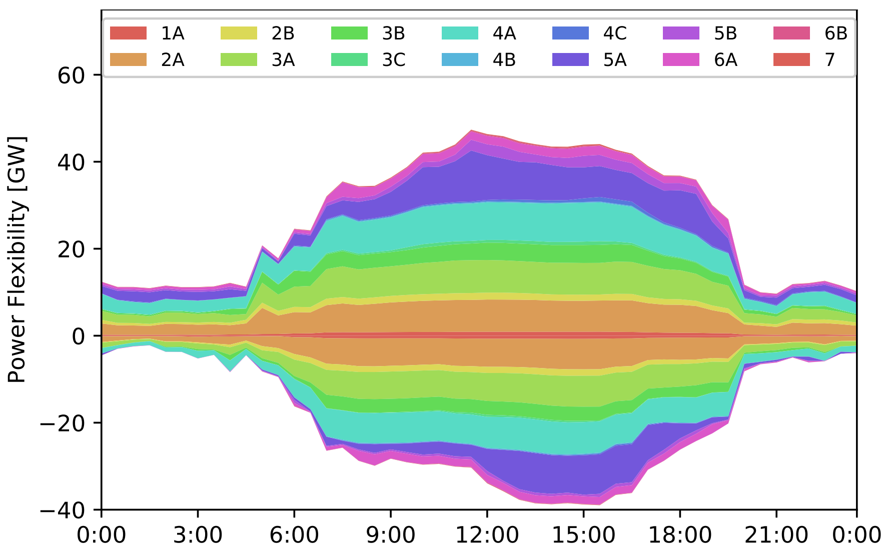


Fig. 9: Aggregate power flexibility from HVAC loads in commercial buildings by climate zone.

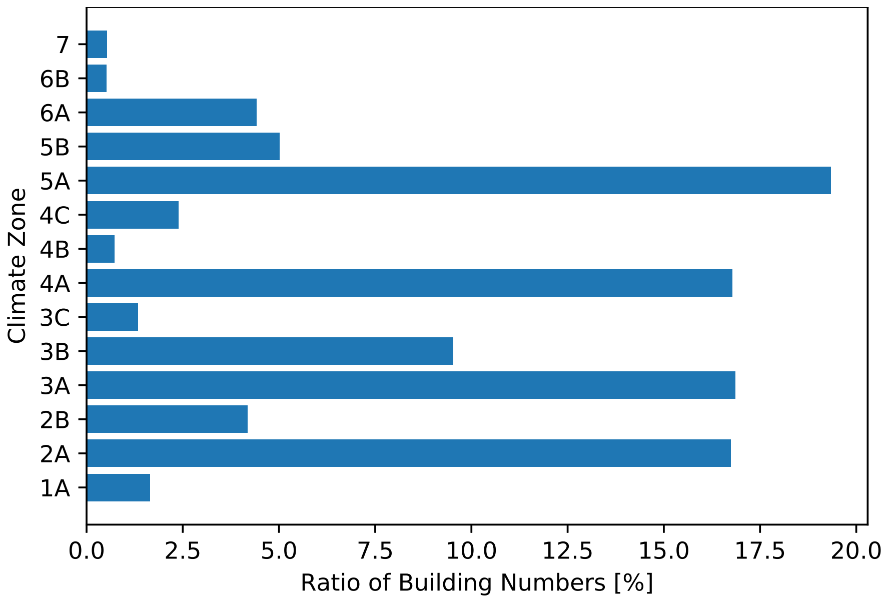


Fig. 10: Numbers of commercial buildings by climate zone.

The balancing capacity during the daytime can be doubled if half of the power flexibility potential can be used.

- The shape of the aggregate flexibility profile is favorable to the power grid because a lack of generation capacity or flexibility typically occurs during the daytime. For example, the commercial HVAC load can be increased to absorb extra solar generation or decreased to mitigate risk from insufficient generation. The flexibility in the early morning and late afternoon can be used to follow fast ramping in solar generation.
- Climate zones 2A (Hot and Humid), 3A (Warm and Humid), 4A (Warm and Humid), and 5A (Cool and Humid) account for most of the national power flexibility. This is mainly because a large portion of commercial buildings are located in these zones, as shown in Fig. 10.
- The number of commercial buildings in climate zone 2B is almost three times that of climate zone 1A, but their aggregate flexibility are close to each other. This is mainly because the higher outdoor temperature in zone 1A leads to higher flexibility per building.

4.2. Power Flexibility by Building Type

Figure 11 plots the aggregate power flexibility from commercial HVAC loads by building type.

- The standalone retail buildings represent a large portion of the national power flex-

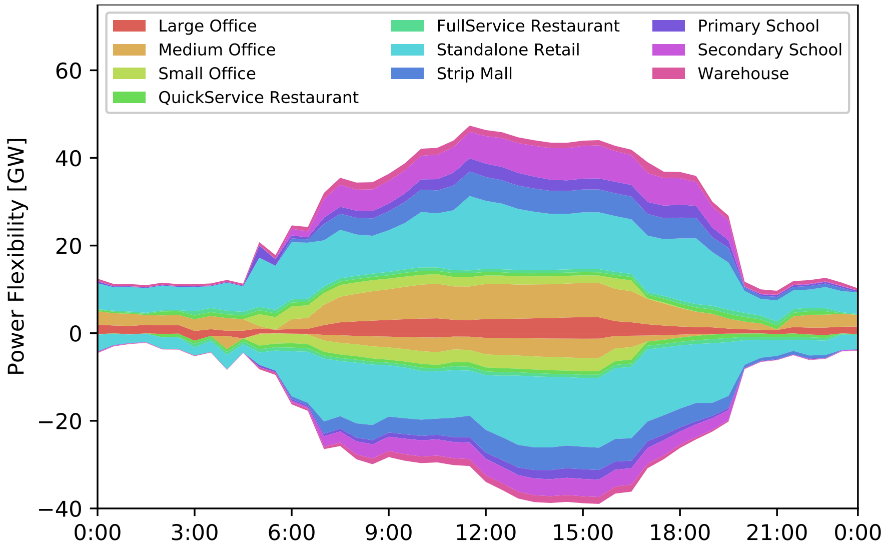


Fig. 11: Aggregate power flexibility from HVAC load in commercial buildings by building type.

ibility from commercial HVAC loads. They account for about 40% of the national flexibility during the daytime and a higher percentage during other time periods. On the other hand, the standalone retail buildings only account for 21% of the total commercial buildings in the U.S. This indicates that the power flexibility from different building types varies significantly, which is consistent with Fig. 4.

- Other key contributors to the power flexibility include secondary schools, strip malls, and medium offices. These three types of buildings together with standalone retail buildings account for more than 80% of the national power flexibility. Enabling communication and control technology in these buildings is the key to actively involving commercial HVAC loads in future power system scheduling and dispatch platform.
- The small office buildings represent 36% of the number of commercial buildings in the U.S., but do not contribute much to the total power flexibility. One main reason is that their floor area is typically small.

5. Discussion

This paper presents, for the first time, assessment methods and results of aggregate power flexibility from commercial buildings for the entire U.S. The proposed methods and analysis results can help utilities better understand the potential of commercial buildings as one of the most important demand-side resources. It could become a starting point to model and represent flexible building loads in long-term power system planning studies and develop cost-effective solution to future sustainable and reliable grid with high renewable penetrations. The analysis in this paper is helpful for utilities to estimate cost-effective demand response (DR) potential from commercial buildings and design DR programs to improve customer participation. The assessment results also assist policy makers and funding agencies to prioritize various demand-side resources, and thereby identify the critical research areas and support the development of enabling technologies.

The study on commercial buildings in the U.S. is a showcase of the proposed simulation-based method. The same method can be used for flexibility characterization and potential estimation in other countries and regions, for which high-fidelity models are available to represent the building population. For example, high-fidelity models are presented in [40] to represent typical buildings in Paris, France. It is also very likely that many flexibility characteristics remain the same as fundamentals of heat transfer and physical laws behind building design and control are universal.

Note that this study excludes hotels, hospitals, outpatient healthcare, apartments, and data centers in large office buildings. While they may have a significant amount of power flexibility, those buildings have more strict requirements on temperature and other control outputs, making power flexibility estimation more challenging. For example, according to ANSI/TIA-942-A, Telecommunications Infrastructure Standard for Data Centers [41], the indoor humidity level must to be controlled within certain ranges. Because the temperature and humidity levels are highly coupled, power flexibility cannot simply be estimated by exploring different temperature setpoints. For hotel buildings, the allowable temperature range for the swimming pool area may vary depending on local climate conditions. Dedicated methods are required to estimate flexibility for these buildings, which is a very interesting future work direction.

6. Conclusions

In this study, a simulation-based method is proposed to assess power flexibility from HVAC loads in commercial buildings. Leveraging the prototype building models, a large number of simulations are performed to characterize power flexibility from different types of buildings in different climate zones in the U.S. Key factors that affect power flexibility are identified and analyzed to enhance the understanding of using building resources for grid services. Different building datasets are used to estimate the number of commercial buildings by climate zone and by building type. The obtained numbers are used to estimate the aggregate flexibility potential at the climate zone and national levels. It is found that cooling loads in commercial buildings offer more flexibility for increasing power consumption than for decreasing it. The power flexibility ratio is less sensitive to climate zone than to building type. The power consumption of commercial buildings in the U.S. can be increased by 46 GW and decreased by 40 GW on peak summer days. The shape of the aggregate flexibility profile is generally favorable to the power grid. Standalone retail buildings, secondary schools, strip malls, and medium offices are the top four building types, representing more than 80% of the national power flexibility. Enabling communication and control technology in these buildings is the key to actively involving commercial HVAC loads in future power system scheduling and dispatch platform.

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