中国光储直柔建筑发展战略路径研究
（二期）

Research on the Strategic Path of PEDF Buildings in China (Phase II)

子课题 1：建筑光伏利用模式与柔性评价方法
Task 1：Building-integrated Photovoltaic Utilization Patterns and Flexibility Evaluation Methods

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执行摘要

1. 建筑分布式光伏的迅速发展与消纳问题

- **建筑分布式光伏蓬勃发展。**近几年我国光伏发电装机容量增长迅速，其中分布式光伏的占比越来越大，而建筑业作为主要能源消费者和用地占用者，其在分布式光伏利用方面具有巨大潜力。但是由于光伏发电有其固有的间歇性、周期性，其与建筑用电存在时间尺度上的不匹配，为了减小电网调节压力、提高可再生能源利用率，建筑光伏的利用模式有待深入研究。

- **建筑光伏利用模式和柔性评价方法。**随着光伏技术发展、光伏电池价格迅速下降，建筑开始大规模装配分布式光伏，随着分布式光伏发电占建筑用电比例的提高，需要进一步探究不同建筑场景的自身可再生电力利用模式，并分析储能、柔性调节等在其中发挥的作用。另一方面，从整个建筑角度出发，要发挥其与电力系统的协同作用，需要深刻认识建筑中的柔性可调资源，将建筑中的柔性可调资源纳入到从容量和功率角度出发的常规储能资源刻画体系中，有助于对不同柔性可调资源进行统一的量化评价，可以帮助形成建筑区域广义储能资源的设计方法。

2. 分布式光伏发电与建筑用电匹配关系分析

- **建筑用电的季节变化受到气象变化影响，周内和日内变化受到人员作息影响。**如图 1 所示从季节变化看，不同建筑类型夏季 7 月的用电均高于过渡季 4 月和 10 月的用电，冬季 1 月的用电与建筑的采暖形式有关；从周内变化看，办公建筑周末用电低于工作日用电。如图 2 所示绝大多数建筑的用电峰值出现时间较少，大于 95%的峰值时间仅占全年的 1%以下。将建筑内的最大用电功率作为基准，可以计算出建筑的峰值功率等效利用小时数，这一数值通常集中在 2000 至 3500 小时之间，从建筑实际用电特征来看建筑侧配电容量的充分利用仍存在一定的优化空间。

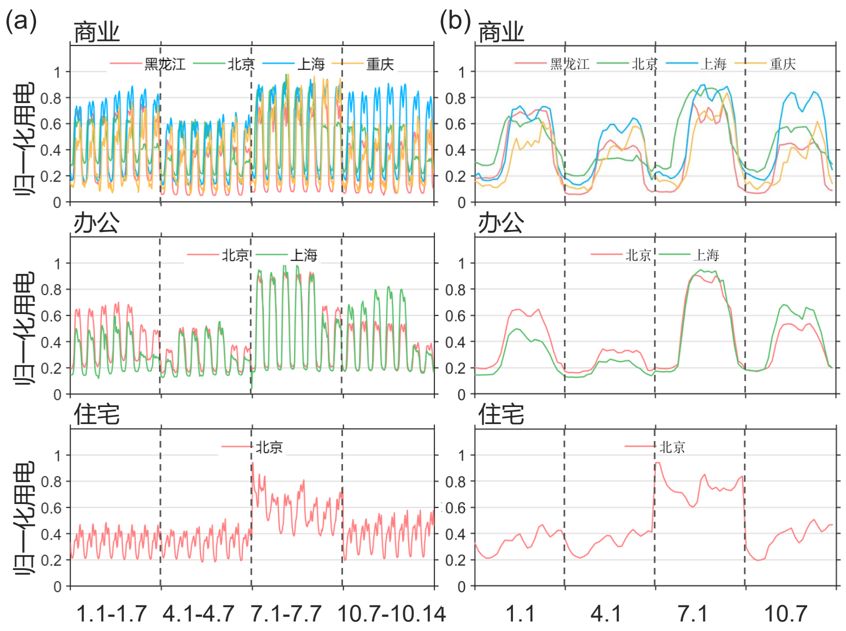


图 1 典型建筑逐小时用电曲线：(a)不同季节四个典型周曲线；(b)不同季节四个典型日曲线

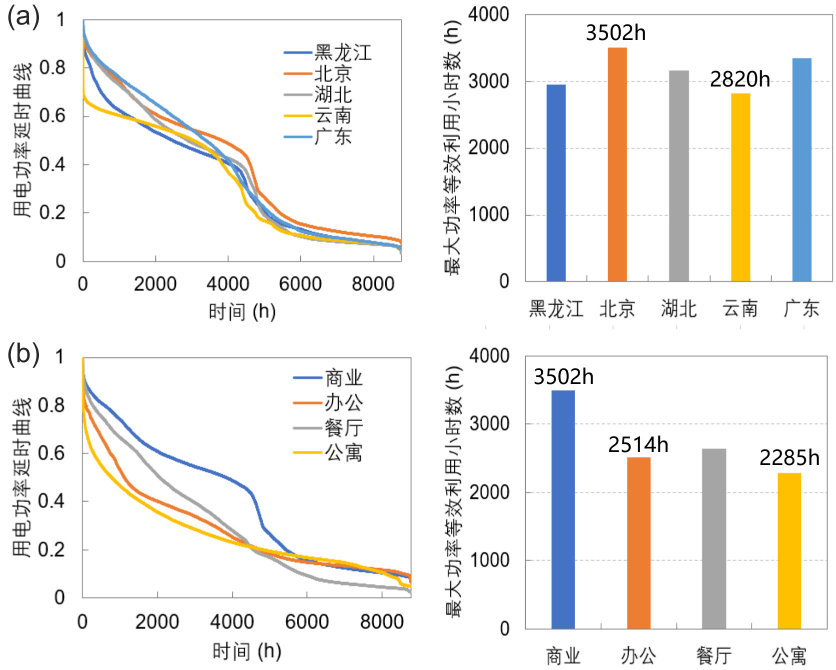


图 2 典型建筑年用电功率延时曲线和峰值功率等效利用小时数：(a)不同气候区商业建筑；(b)北京不同类型建筑

- **光伏发电与建筑用电曲线形状上的不匹配关系以日内不匹配为主导。**采用不匹配系数刻画光伏发电与建筑用电曲线的形状差异，先将发电与用电曲线除以各自的平均值进行标准化，标准化用电曲线减去发电曲线得到的不保障用电部分进行滑动平均分解，可以得到日、周、季节三个不同时间尺度的不匹配系数。由于光伏发电与建筑用电均存在明显的以日为周期的波动，不同典型建筑的不匹配系数均以日不匹配系数为主导。如图 3 不同气候区商业建筑的年不匹配系数接近，但是不同时间尺度分

解成分的占比略有差异；办公、商业等日间用电为主的建筑不匹配系数较小，而公寓以夜间用电为主不匹配系数最大。

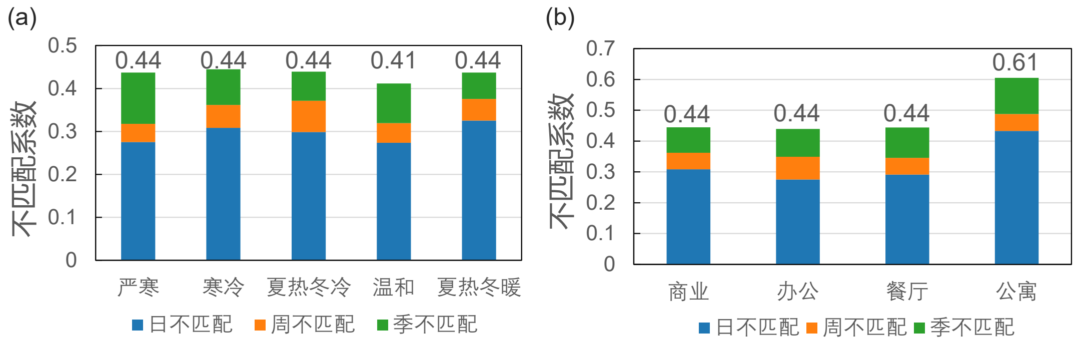


图 3 典型建筑不同时间尺度不匹配系数计算结果：(a)不同气候区商业建筑；(b)北京不同类型建筑

- **用光伏自消纳率与自保障率组成的匹配性图同时刻画供需在时间和规模上的匹配性。**自消纳率为光伏发电中被建筑消纳的比例，而自保障率为光伏发电被建筑消纳部分占建筑总用电的比例。构建自消纳率、自保障率组成的二维图如图 4。关注逐时的光伏发电与建筑用电关系时，横坐标为 100%表明任何时刻光伏都能被建筑消纳，对应了“只进不出”型建筑；纵坐标为 100%表明任何时刻光伏都能保障建筑用电，对应了“只出不进”型建筑；横纵坐标均为 100%时表明光伏可以保障全部用电同时光伏也能被全部消纳，对应了“不进不出”型建筑；此外的其他情况下建筑与电网双向互动，为“有进有出”型建筑。“有进有出”型建筑在增加储能或采用柔性调节时，如果忽略造成的损耗，光伏发电建筑用电比值的变化较小，因此状态点将沿着其与原点的连线向右上角移动。

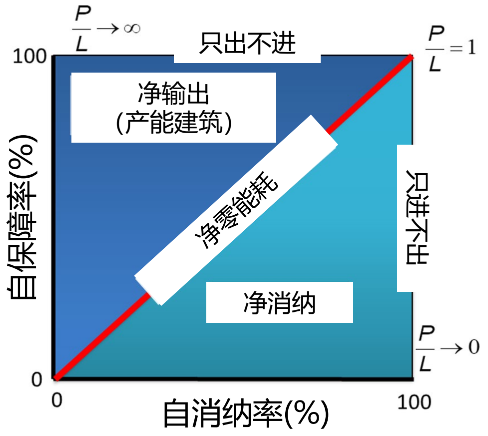


图 4 用自消纳率-自保障率二维图反映发电用电匹配关系

3. 分布式光伏消纳模式分类研究

- **不同光伏发电占比下达到消纳极限所需的储能容量存在差异。**如图 5(a)

增加储能或柔性调节，可以使建筑与电网实现单向交互或成为孤岛型建筑。如图 5(b)展示了增加储能时商业建筑光伏消纳状态点的变化情况，其中标准化储能容量为真实储能容量除以年平均用电功率单位为小时。当发电用电比小于 1 时，光伏消纳的极限是完全自消纳，由于商业建筑日间用电较多，增加少量储能即可趋近于“只进不出”型；而当发电用电比大于 1 时，消纳的极限是光伏完全保障建筑用电，由于光伏发电仅在日间，要完全保障夜间用电仍需要较大的储能容量，因此实现“只出不进”型建筑储能需求较大。

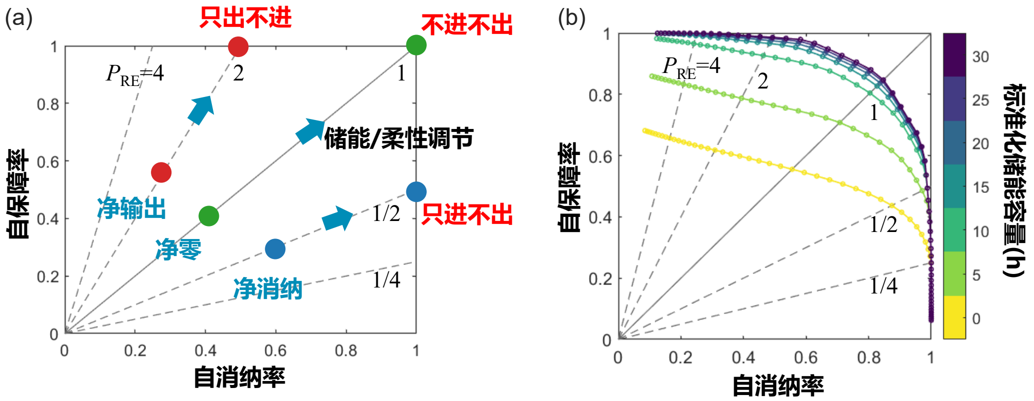


图 5 不同发电用电比下增加储能/柔性调节使建筑与电网单向互动或成为孤岛型建筑：(a)示意图；(b)商业建筑案例

- **城市建筑一般光伏发电占比较低，可通过增加储能或柔性调节成为“只进不出”型建筑。**如图 6，左侧蓝色线段为数值为 1 的等自消纳率线，右侧蓝色线段为数值为 1 的等自保障率线。其将建筑光伏消纳模式分为了 4 类，左上角区域代表了光伏完全自消纳的“只进不出”型建筑，右上角区域代表了建筑用电完全自保障的“只出不进”型建筑，下方区域代表了建筑与电网双向互动的“有进有出”型建筑，上方的红色线段代表了不需要与外电网互动的“不进不出”型建筑。净消纳建筑要实现“只进不出”所需的标准化储能容量与光伏发电占比呈正相关。

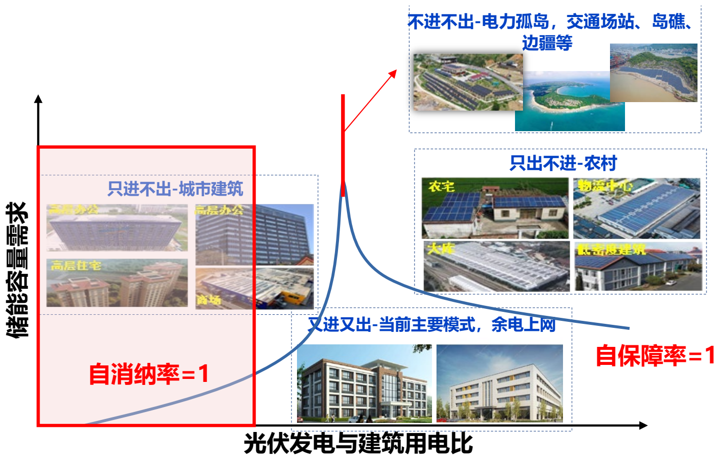


图 6 增加储能/柔性调节使净消纳建筑成为“只进不出”型建筑

- **单位面积能耗强度低、楼层较少的建筑可以转变为“只出不进”型建筑。**

其可以成为向外界稳定输出电力的分布式电源，与示意图图 7(a)右上区域对应。如图 7(b)所示，当光伏发电建筑用电比大于 1 时，若光伏发电量增加建筑实现“只出不进”所需的储能容量降低，但是降低到一定程度后变化速度放缓，光伏发电占比极大时同样需要一定量的储能才能实现“只出不进”。因为光伏发电存在日内的间歇性，光伏发电量较多时仍然需要投入一定储能才能满足夜间等时段的电力需求。

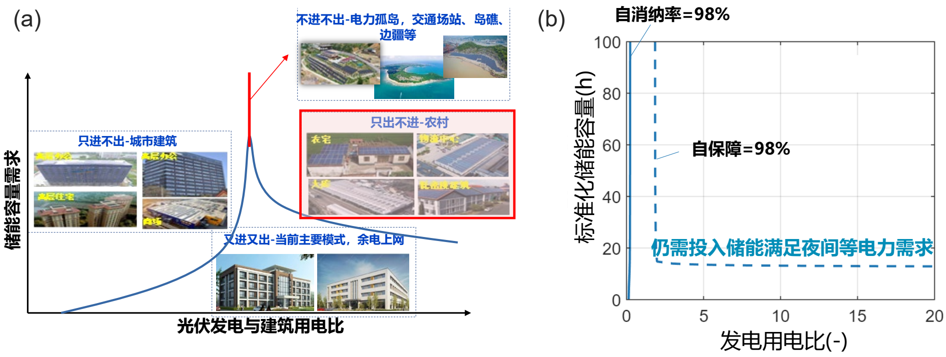


图 7 (a) 增加储能/柔性调节使净输出建筑成为“只出不进”型建筑；(b)发电用电比较大时实现 98%自保障率所需储能容量

- **要保障孤岛型建筑正常运行，需要克服光伏发电与建筑用电间的季节不匹配问题，这需要配置容量较大的长周期储能。**如图 8(a)，当光伏发电建筑用电比接近 1 时建筑为净零能耗建筑，增加储能可以使得建筑自消纳率、自保障率都变为 1，成为“不进不出”的孤岛型建筑。如图 8(b)一年用电量为 1840 万 kWh 的海南建筑要构建孤岛电力系统，需要~20 万 kWh 储能容量，所需储能容量巨大。在实际应用中，需要根据不同情况和需求，采用灵活的用电方式、选择合适的储能技术来满足孤岛型建筑的电力需求，以保证建筑在合理的成本投入下能够获得可靠的电力供应。

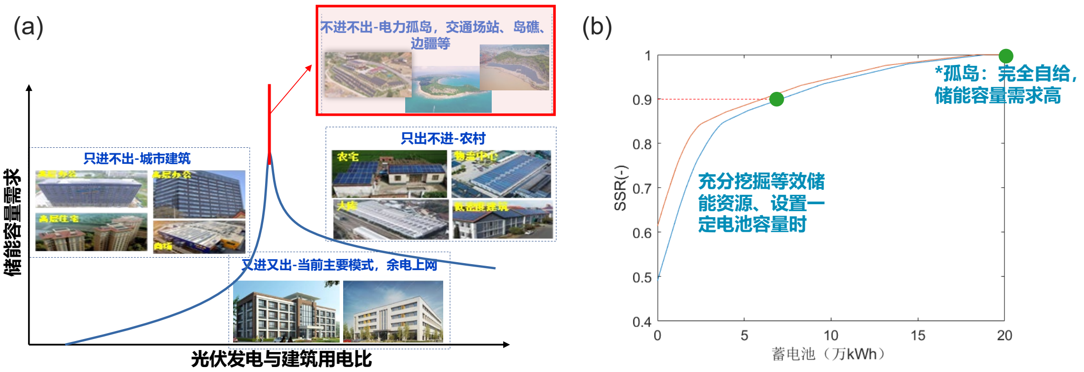


图 8 (a) 增加储能/柔性调节实现孤岛型建筑；(b)年用电量为 1840 万 kWh 的海南建筑实现孤岛运行所需储能容量

4. 建筑柔性用能资源特征调研与分析

- **有效挖掘虚拟储能潜力，可大幅减少传统储能投资，满足可再生能源发**

展对于储能的迫切需求。现有储能技术各自具有优势和局限，单一技术无法满足所有调蓄需求。用户侧的虚拟储能资源根据终端实际使用需求，通常可分为电能储存和热能存储，如图 9 所示。对于电能存储，电动汽车已超过消费电子产品成为主要应用板块。因此，带有智能充放电系统的电动汽车和各类可储能电器设备是最具潜力的终端电力虚拟储能。对于热能存储，暖通空调系统占建筑运行能耗的 30%~80%，且通常具有冷热蓄存能力。上述三类虚拟储能资源都与建筑区域能源系统的规划设计和运行调控密切相关。

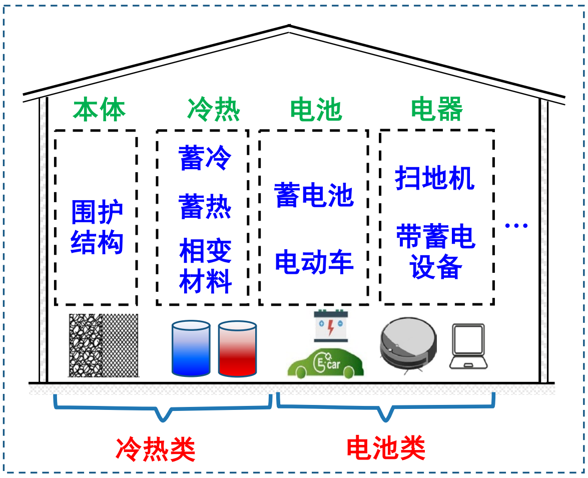


图 9 用户侧储能/等效储能

- **随着电动汽车占比迅速提高，电动汽车以充电桩作为接口，可以为建筑提供可观的储能能力。**如图 10 对于建筑来说其配电容量等效利用小时数较少，存在配电容量的富余，但是要实现建筑的灵活调节，需要较大的储能投入；而对于电动汽车，其日耗电仅占总电池容量 10%，电池容量相对比较富余，但是同时电动汽车需要比较大的充电功率，随着车辆电气化的推进会给电网带来较大负担。因此建筑与电动汽车可以优势互补，建筑可以为电动汽车提供富余的配电容量满足其充电功率需求，而电动汽车可以为建筑提供富余的储能容量，两者可以实现协同配合。

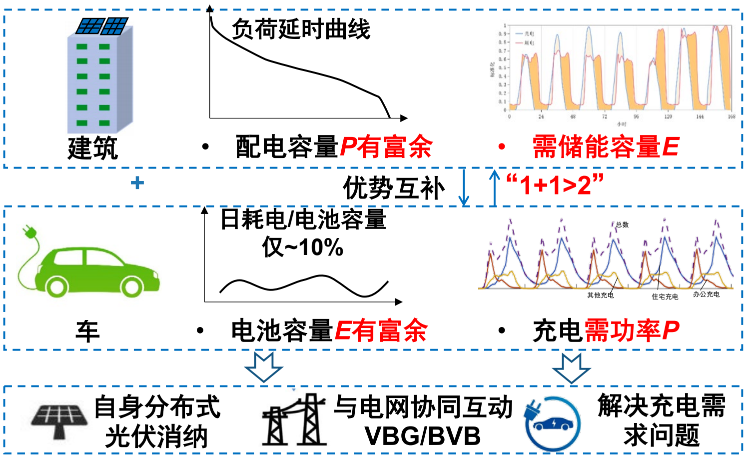


图 10 车与建筑协同优势互补

- **对于暖通空调系统，室内设定参数、室内末端、输配系统和冷热源系统**

等有一定的柔性调节潜力。如图 11 对于室内设定参数，温度、湿度、二氧化碳浓度等都有允许的波动范围，利用其波动特点和建筑本体的惯性，可以实现建筑用能调节；对于输配系统，管网中的冷热水也有一定的蓄能能力；对于冷热源系统，可以为其配套主动的蓄能方式。总体而言，对于供冷工况从分体空调到半集中空调，再到集中空调+蓄冷系统，其可利用柔性调节能力逐渐变强；而对于供暖工况，从对流末端到辐射+对流末端，到辐射末端，再到蓄热系统，其柔性调节能力逐渐变强。

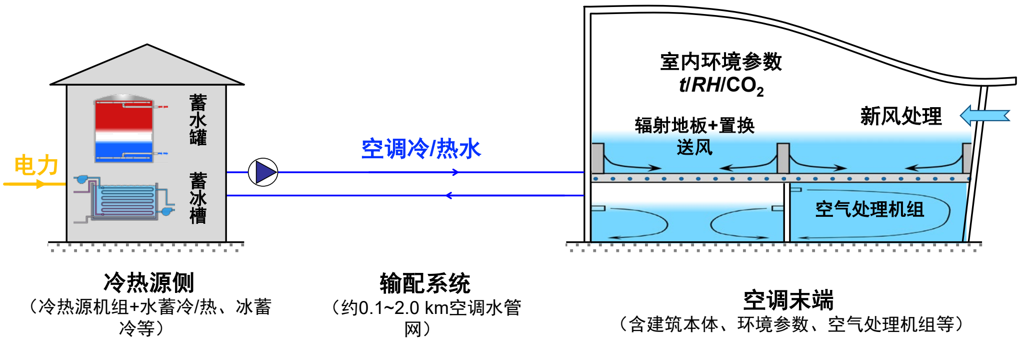
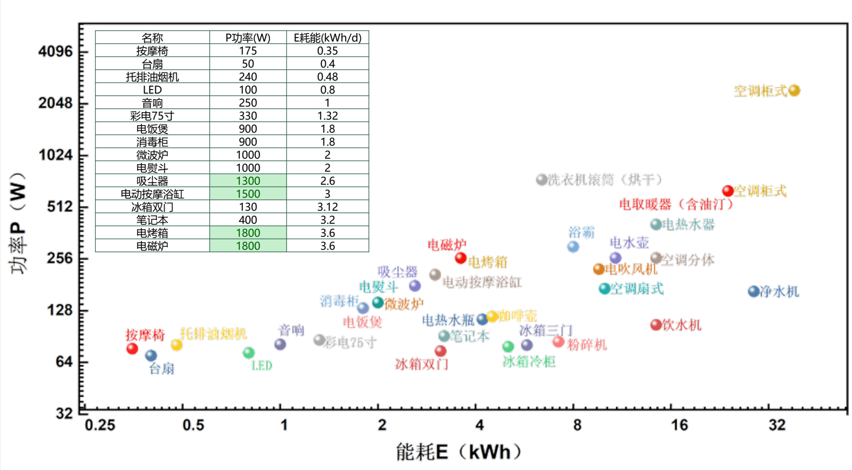


图 11 暖通空调系统各环节等效储能能力

- **各类可储能电器设备也是重要的虚拟储能形式。**全球锂离子电池市场中消费电子产品占比达到了 33%~40%，为主要应用板块。因此电器设备拥有海量的分散式蓄电池资源，对其进行深入研究可以挖掘出巨大的等效储能潜力。图 12 给出了常见电器设备功率、能耗范围。



名称	P功率(W)	E耗能(kWh/d)
按摩椅	175	0.35
台扇	50	0.4
托排油烟机	240	0.48
LED	100	0.8
音响	250	1
彩电75寸	330	1.32
电饭煲	900	1.8
消毒柜	900	1.8
微波炉	1000	2
电熨斗	1000	2
吸尘器	1300	2.6
电动按摩浴缸	1500	3
冰箱双门	130	3.12
笔记本	400	3.2
电烤箱	1800	3.6
电磁炉	1800	3.6

图 12 各类电器设备功率、能耗范围

5. 各柔性用能资源量化描述方法

- **建立“等效电池模型”对广义储能进行统一刻画。**利用等效储能的主要目的是为了减少传统储能的装机容量，因此需要将其纳入传统储能的设计评价体系。给出虚拟储能的“等效电池模型”定义，参数包括折算的等效充电功率、等效放电功率、等效储电量和等效综合效率。图 13 对比了三类建筑区域虚拟储能资源和各类传统储能技术，建筑区域虚拟储能资源

的等效时间常数 T 主要为分钟-天的量级。考虑等效折算系数后各类可利用储能成本的大致范围如图 14，其仍显著低于蓄电池。

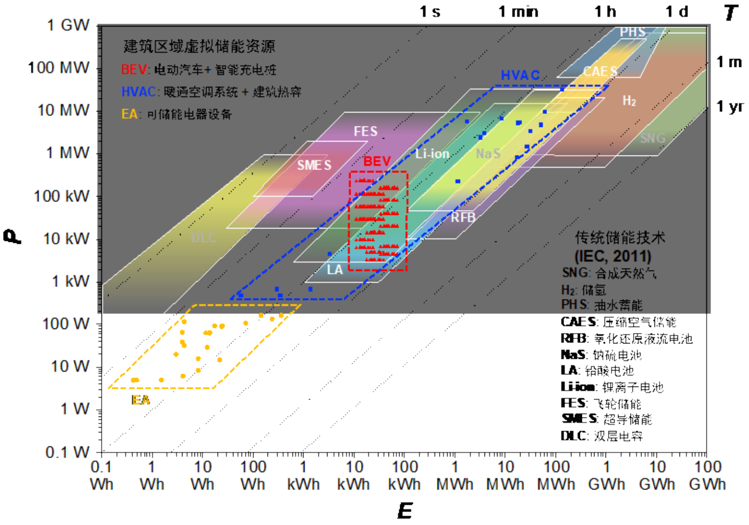


图 13 建筑区域广义储能：传统储能技术与虚拟储能资源

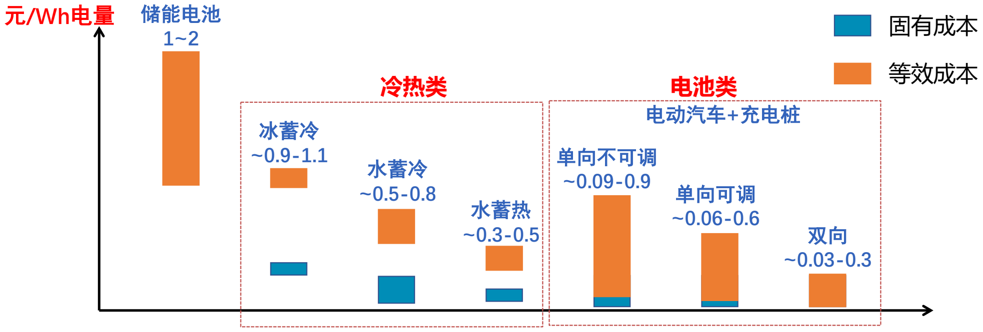
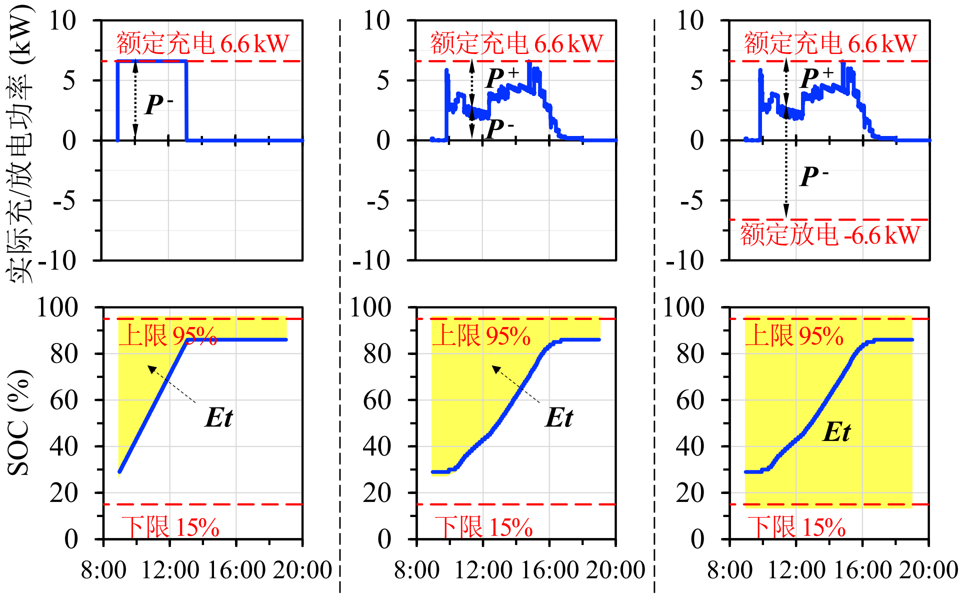


图 14 考虑等效折算系数后各类可利用储能成本的大致范围

- **电动汽车+充电桩的实际可调度虚拟储能能力，受到车辆行为、电池安全、充放电系统功能和策略等的影响。**对于常见的功率不可调单向充电桩，其一连接就以车辆允许的最大功率充电，一般不具有功率上调的能力；其等效储电量为电量可调节的上限值与实际值之差（即图 15(a)中黄区域面积与时长 *t* 的比值）。于功率可调的单向充电桩，其充电功率可根据指令，在 0 至额定功率之间连续调节；与图 15(a)相比相同时长 *t* 内黄区域面积更大，等效储电量更大。对于功率可调的双向充电桩，其功率可降低至放电功率，理论上可在保证电池安全的前提下调度所有的电量；如图 15(c)，黄色区域面积进一步增大，等效储电量折算系数也相应增大。



(a) 不可调单向充电桩 (b) 可调单向充电桩 (c) 可调双向充电桩

图 15 “电动汽车+智能充电桩”等效储能潜力示例

- **暖通空调系统一般包含冷热源、输配系统和末端三个环节，各环节均有冷热蓄存能力。**冷热源可配有蓄冷/热水罐、蓄冰槽等冷热蓄存设备；输配系统带有载冷/热的工质，具有一定的热容量；末端能够不同程度地利用建筑热容，室内温湿度参数允许在人员可接受的舒适区内波动，因此末端与建筑热容耦合同样具有调蓄能力。上述各环节的冷热蓄存能力主要分为“冷热源+输配”虚拟储能和“末端+建筑热容”虚拟储能，其可在“暖通空调系统+建筑热容”整体作为虚拟储能的等效放电过程中依次利用，即等效储电量和等效时间常数具有加和性。

- **可储能电器设备是继电动汽车之后锂电池保有量最多的领域。**目前常见的可储能电器设备及充电器主要采用功率不可调单向充电模式，与电动汽车+功率不可调单向充电桩类似。基于已有数据分析，单件可储能电器设备的等效储能容量远小于“电动汽车+智能充电桩”和“暖通空调系统+建筑热容”两类。但是，这类虚拟储能无初投资成本，同时考虑其巨大的数量及智能建筑的高速发展，未来也将具有一定调蓄潜力。利用该虚拟储能的最大瓶颈是如何有效调用海量、高度随机的终端设备。物联网技术可支持在一定范围内控制电器设备的充电过程；利用电力线载波技术在低压配电网中广播需求响应信号，采用号召式参与调节的模式，也是一种具有潜力的方式。

- **“等效电池模型”与既有基于优化计算的模型存在差异。**既有基于优化计算的模型有利于配电网整体的优化调度，但是在设计阶段各类型负荷难以和具体设备系统形成对应，此类模型在工程应用中可能会遇到定量取值的困难。本文提出的“等效电池模型”目的是将建筑机电系统中既有的虚拟储能资源折算并从总储能需求中减去，为建筑机电系统设计中储能电池容量设计提供指导。此模型采用了“最大容量-折算系数”的方式，并

且针对实际具备储能能力的设备系统，目的是方便设计院等工业界单位进行简化计算。此外，基于优化计算的模型可以详细得到各种虚拟储能在特定约束下发挥的真实调度作用，为“等效电池模型”提供更加精确的折算系数。

Executive Summary

1. Rapid Development and Integration Challenges of Distributed Photovoltaics in Buildings

- **Rapid growth of building-integrated distributed photovoltaics.** In recent years, China has witnessed a rapid increase in photovoltaic (PV) installation capacity, with an increasing share being attributed to distributed PV systems. As the primary energy consumer and land occupier, the building sector holds substantial potential for distributed PV integration. However, PV generation inherently exhibits intermittency and periodicity, leading to a temporal mismatch with building electricity demand. To alleviate grid regulation pressures and enhance the utilization of renewable energy sources, there is a pressing need for in-depth research into the utilization patterns of building-integrated PV.

- **Building-integrated PV utilization patterns and demand side flexibility assessment.** With the advancements in PV technology and the significant reduction in PV costs, buildings are increasingly adopting distributed PV systems. As the proportion of distributed PV generation relative to building electricity consumption continues to rise, it becomes essential to explore distinct renewable energy utilization patterns in various building scenarios. Additionally, it is crucial to analyze the roles of energy storage and flexibility regulation within these scenarios. Furthermore, from an overall building perspective, harnessing the synergies with the power system requires a profound understanding of flexible and adjustable resources within buildings. This involves incorporating flexible and adjustable building resources into the conventional energy storage resource characterization framework, considering capacity and power aspects. Such an approach facilitates the unified quantitative assessment of various flexible and adjustable resources and contributes to the development of a design methodology for generalized energy storage resources within building regions.

2. Analysis of the Relationship Between Distributed Photovoltaic Generation and Building Electricity Consumption

- **The seasonal variations in building electricity consumption are influenced by meteorological changes, while the daily and hourly fluctuations are influenced by occupant activity patterns.** As shown in Figure 1, the seasonal analysis reveals that power consumption peaks during the summer, surpassing that during the transitional months of April and October. Regarding the weekly variations, office buildings exhibit lower electricity consumption on weekends compared to weekdays. Figure 2 further illustrates that the peak power consumption in many buildings occurs relatively infrequently. The time during which the power consumption exceeds 95% of the maximum power accounts for less than 1% of the total annual duration. Utilizing the maximum power consumption as a reference point, the equivalent utilization hours of peak power is calculated. Typically, this value falls within the range of 2,000 to

3,500 hours (much less than 8,760 hours). Thus, it is crucial to optimize the efficient utilization of electricity distribution capacity on the building side.

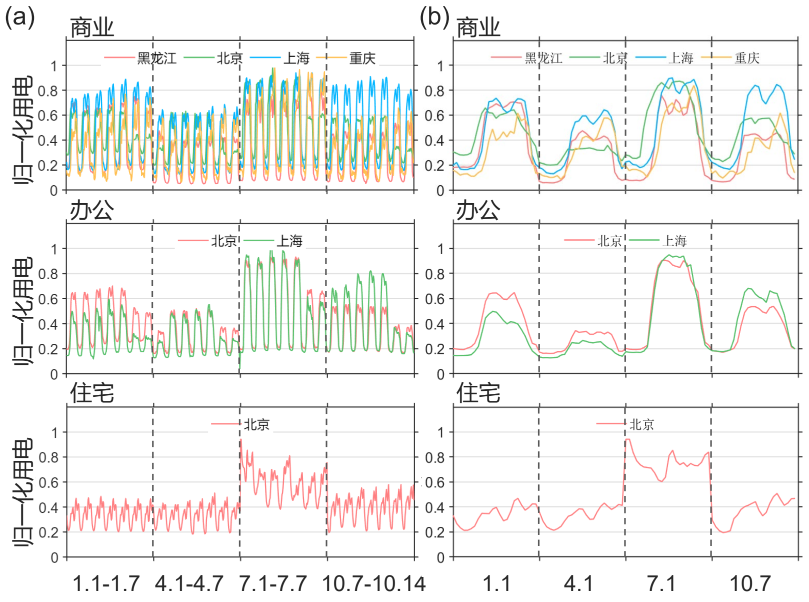


Figure 1 Hourly electricity consumption profiles of typical buildings: representative (a) weekly and (b) daily profiles for different seasons

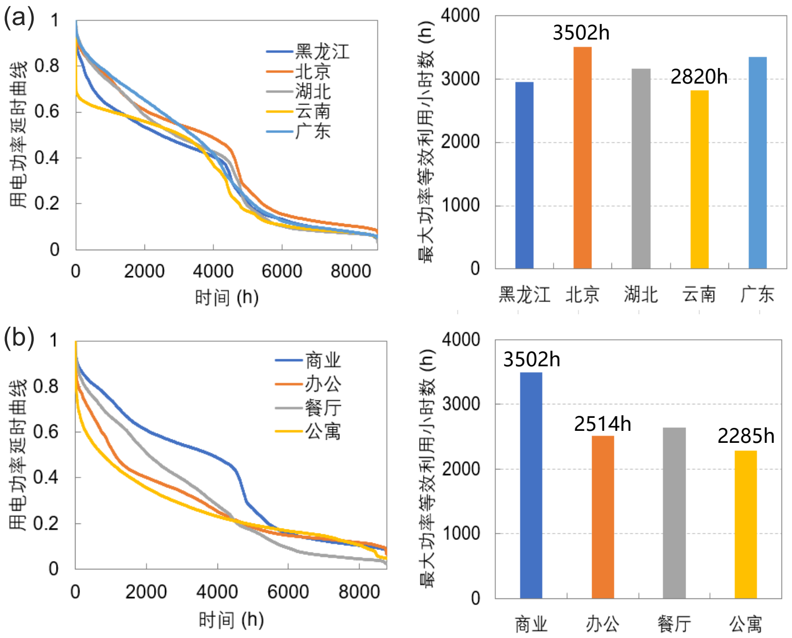


Figure 2 Yearly load duration profiles and equivalent utilization hours of peak power for typical buildings: (a) commercial buildings in different climatic zones; and (b) different building types in Beijing

- **The mismatch between PV generation and building electricity consumption is primarily dominated by diurnal mismatch.** To characterize the disparities in the shapes of PV generation and building electricity consumption profiles, mismatch coefficients are employed. Initially, both generation and consumption profiles are normalized by dividing them by their respective averages. The non-guaranteed electricity consumption portion, obtained by subtracting the normalized generation profile from the normalized consumption profile, is subjected to a moving average decomposition, yielding mismatch coefficients at three different time scales: diurnal, weekly, and seasonal. Given that both PV generation and building electricity consumption exhibit noticeable daily cyclic fluctuations, the dominant component in the mismatch coefficients for various building types is the diurnal mismatch coefficient. As shown in Figure 3, the annual mismatch coefficients for commercial buildings in different climate zones are similar, although there are slight variations in the proportions of the decomposed components at different time scales. Buildings with predominant daytime electricity usage, such as offices and commercial structures, tend to have smaller mismatch coefficients, whereas apartments with nighttime electricity usage as the primary pattern exhibit the highest level of mismatch.

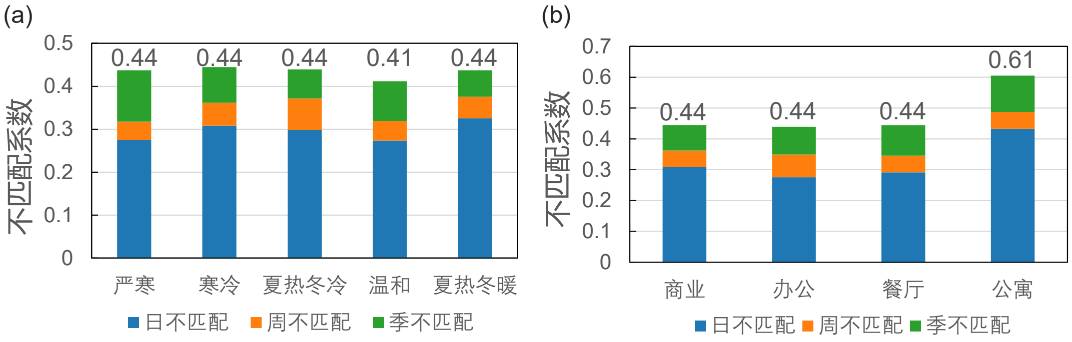


Figure 3 Mismatch coefficients at different time scales for typical buildings: (a) commercial buildings in different climate zones; and (b) different building types in Beijing

- **The matching relationship between supply and demand in terms of both time and size is depicted using an energy matching chart composed of self-consumption rate and self-sufficiency rate.** The self-consumption rate represents the proportion of PV generation that is consumed within the building, while the self-sufficiency rate signifies the proportion of building's total electricity demand met by PV generation.

- When examining the hourly relationship between PV generation and building electricity demand, a value of 100% on the horizontal axis implies that PV generation can be entirely consumed within the building, corresponding to the 'nearly-complete consumer'. On the vertical axis, 100% indicates that PV generation can completely fulfill the building's electricity demand, representing the 'self-sufficient building'. When both axes read 100%, it signifies that PV can fully power the entire electricity load of the building while the building also consumes all generated electricity, characterizing the 'standalone building'. For bidirectional-interaction buildings, adjustments such as adopting energy storage or flexible regulation have minimal impact on the PV generation proportion, assuming negligible losses. Consequently, the status point tends to move towards the upper right corner along the line connecting it to the origin.

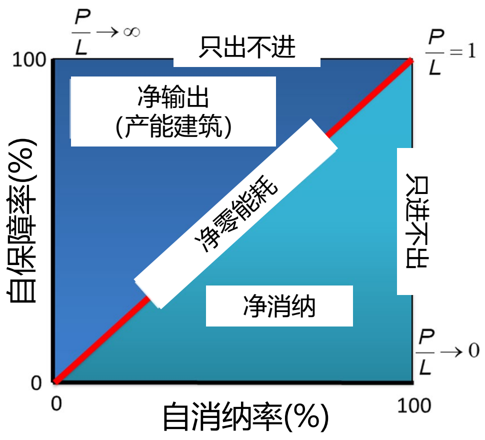


Figure 4 Energy matching chart reflecting the matching relationship between generation and load using self-consumption rate and self-sufficiency rate

3. Classification Study of Distributed Photovoltaic Integration Patterns

- **Different proportions of PV generation result in varying energy storage requirements to reach the matching limit.** Figure 5(a) demonstrates that increasing energy storage or employing flexible regulation can enable buildings to achieve unidirectional interaction with the grid or become islanded buildings. Figure 5(b) illustrates the variation in matching status points for commercial buildings with increased energy storage, where standardized energy storage capacity is the actual energy storage capacity divided by the annual average power consumption. When the PV generation proportion is less than 1, the limit of PV consumption is complete self-consumption. Since commercial buildings have higher daytime power consumption, adding a small amount of energy storage can approach the nearly-complete consumer. However, when the PV generation exceeds 1, the consumption limit is self-sufficient building. As PV generation only occurs during the day, achieving self-sufficient building requires a larger energy storage capacity.

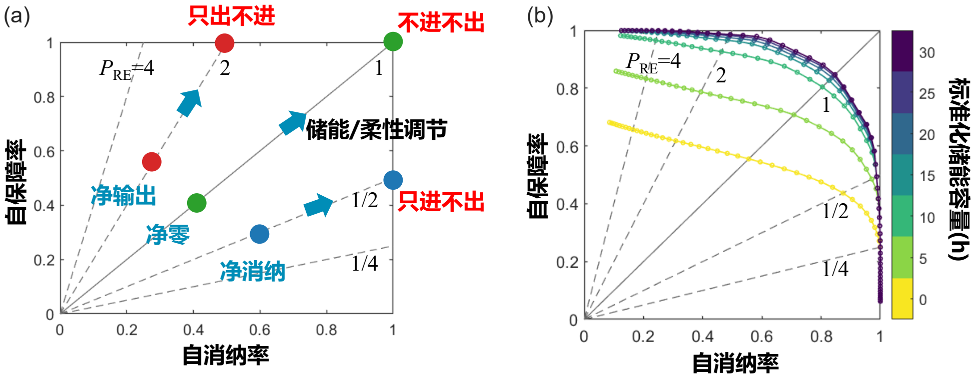


Figure 5 Adopting energy storage/flexible regulation leads to unidirectional interaction with grid or islanded building: (a) schematic; and (b) commercial building case study

- **Urban buildings typically have a low proportion of PV generation, which can be transformed into self-consumption buildings through the adoption of energy storage or flexible regulation.** As illustrated in Figure 6, the left blue line represents the isoline with a self-consumption rate value of one, while the right blue line represents the isoline with a self-sufficiency rate value of one. These isolines categorize distributed PV consumption patterns into four classifications. The upper-left region represents self-consumption buildings, the upper-right region signifies self-sufficient buildings, and the lower region indicates buildings that interact bidirectionally with the grid. The red line segment above represents islanded buildings, which do not require interaction with external grids. For net consumption buildings to achieve the self-consumption status, the required standardized energy storage capacity is positively correlated with the PV generation proportion.

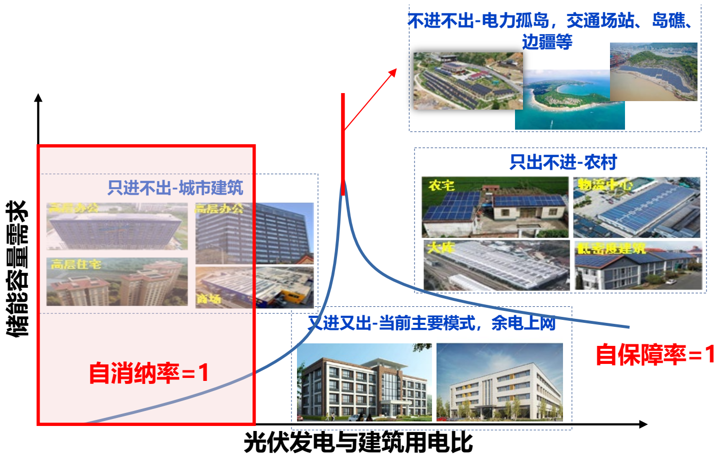


Figure 6 Increasing energy storage/flexible regulation to transform net consumption buildings into self-consumption buildings

- **Buildings with low energy consumption per unit area and fewer floors can be transformed into self-sufficient buildings.** They can serve as stable distributed power sources to provide electricity to the external grid, corresponding to the upper-right region in the schematic diagram shown in Figure 7(a). As illustrated in Figure 7(b), when the PV generation proportion exceeds one, an increase in PV generation reduces the required energy storage capacity for achieving self-sufficient status. However, after reaching a certain point, this reduction rate slows down. Even with a high proportion of PV generation, a certain amount of energy storage is still needed to meet electricity demand during periods with intermittent PV generation, such as nighttime.

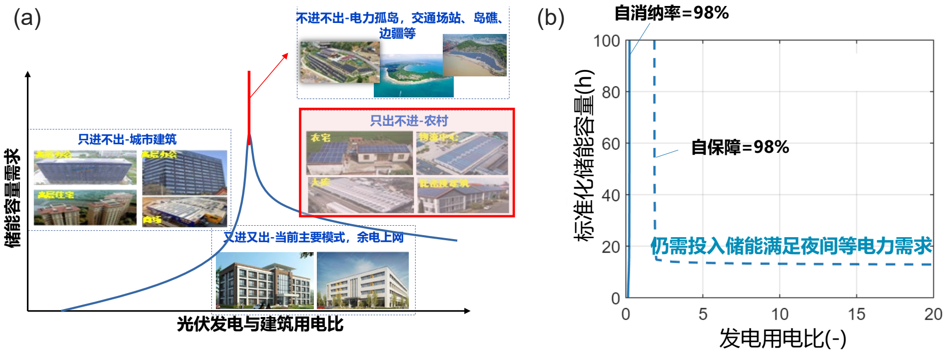


Figure 7 (a) Increasing energy storage/flexible regulation to transform net producer buildings into self-sufficient buildings; (b) required energy storage capacity for achieving 98% self-sufficiency rate with high PV generation proportion

- **To ensure the normal operation of islanded buildings, overcoming the seasonal mismatch between PV generation and building electricity consumption is crucial.** This necessitates the deployment of large-capacity, long-duration energy storage systems. As illustrated in Figure 8(a), when the PV generation proportion approaches one, a building can achieve net-zero carbon emission by increasing its energy storage capacity, resulting in both self-sufficiency and self-reliance becoming 100%. In the case of a building in Hainan with an annual electricity consumption of 18.4 million kWh, Figure 8(b) demonstrates that approximately 200,000 kWh of energy storage capacity is required to establish an islanded power system. This underscores the substantial energy storage capacity needed for such applications. In practical implementations, a flexible approach must be adopted, considering various factors and specific requirements. This includes the selection of suitable energy storage technologies and adaptable electricity consumption strategies to ensure reliable power supply to islanded buildings while maintaining cost-effectiveness.

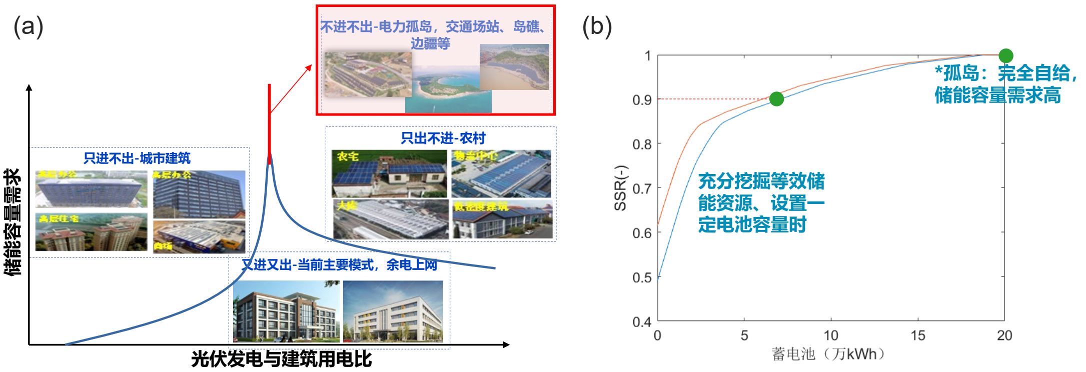


Figure 8 (a) Enabling islanded buildings through increasing energy storage/flexible regulation; (b) required energy storage capacity for achieving islanded operation in a Hainan building with an annual electricity consumption of 18.4 million kWh

4. Survey and Analysis of Flexible Energy Use Resources in Buildings

- **Effectively harnessing the potential of virtual energy storage can significantly reduce traditional energy storage investments, meeting the urgent demand for energy storage in the development of renewable energy.** Existing energy storage technologies each have their advantages and limitations, and no single technology can meet all the energy storage needs. User-side virtual energy storage resources, based on actual terminal usage requirements, are typically divided into electrical energy storage and thermal energy storage, as shown in Figure 9. For electrical energy storage, electric vehicles have surpassed consumer electronics as the primary application sector. Therefore, electric vehicles and various types of energy-storing electrical appliances equipped with intelligent charging and discharging systems represent the most promising terminal electric virtual energy storage solutions. Regarding thermal energy storage, HVAC systems account for 30% to 80% of building operational energy consumption and typically possess thermal storage capabilities. All three categories of virtual energy storage resources are closely related to the planning, design, and operational control of building-area energy systems.

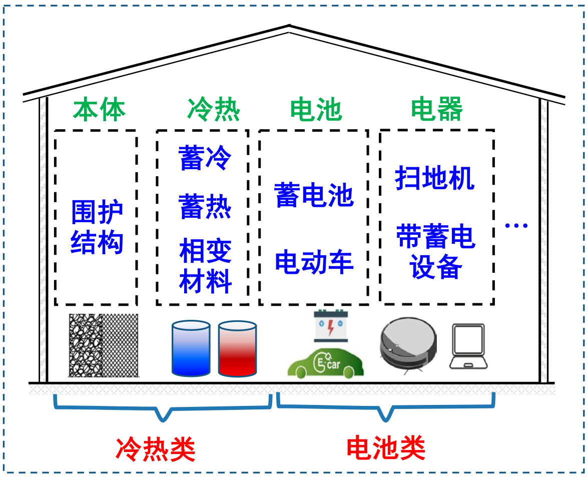


Figure 9 User-Side Energy Storage/Virtual Energy Storage

- **With the rapid increase in the proportion of electric vehicles (EVs), they serve as a valuable source of energy storage for buildings through charging stations.** As depicted in Figure 10, buildings tend to have a surplus of distribution capacity, which requires substantial investment for flexible regulation through energy storage systems. In contrast, electric vehicles generally consume only a small fraction of their total battery capacity on a daily basis, leaving their batteries with significant spare capacity. However, electric vehicles demand relatively high charging power, which can pose a substantial burden on the grid as the electrification of vehicles advances. Consequently, buildings and electric vehicles exhibit complementary advantages: buildings can provide surplus distribution capacity to meet the charging power needs of electric vehicles, while electric vehicles can offer excess energy storage capacity to buildings. This synergy allows for coordinated collaboration between the two, enhancing overall energy efficiency.

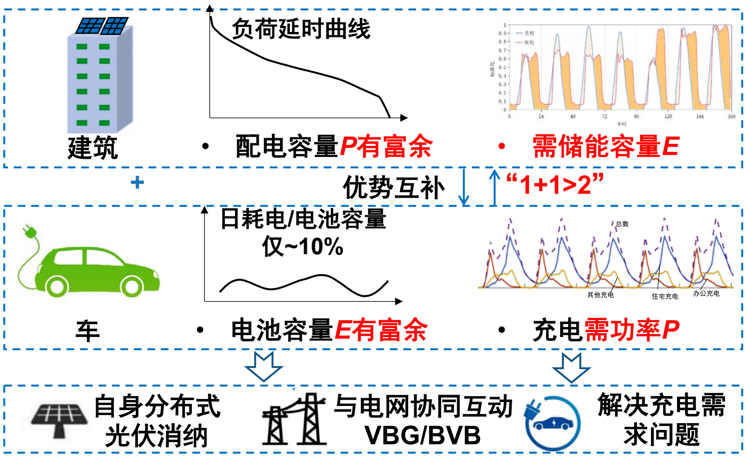


Figure 10 Synergistic Complementarity between Vehicles and Buildings

- **For the HVAC system, there is a certain potential for flexible regulation in indoor settings, terminal units, distribution systems, and cold and heat source systems.** As shown in Figure 11, for indoor setting parameters, temperature, humidity, carbon dioxide concentration, and more have allowable ranges of fluctuation. Utilizing the characteristics of these fluctuations and the inertia of the building itself, energy consumption within the building can be regulated. Concerning distribution systems, there is some energy storage capacity in the pipeline network for hot and cold water. For cold and heat source systems, active energy storage methods can be employed to complement them. In general, the flexible regulation capacity gradually increases for cooling conditions, progressing from split air conditioning to semi-centralized air conditioning, and ultimately to centralized air conditioning combined with cold storage systems. For heating conditions, the flexibility increases from convective terminals to radiative terminals, and then to radiant terminals, eventually reaching the inclusion of thermal storage systems.

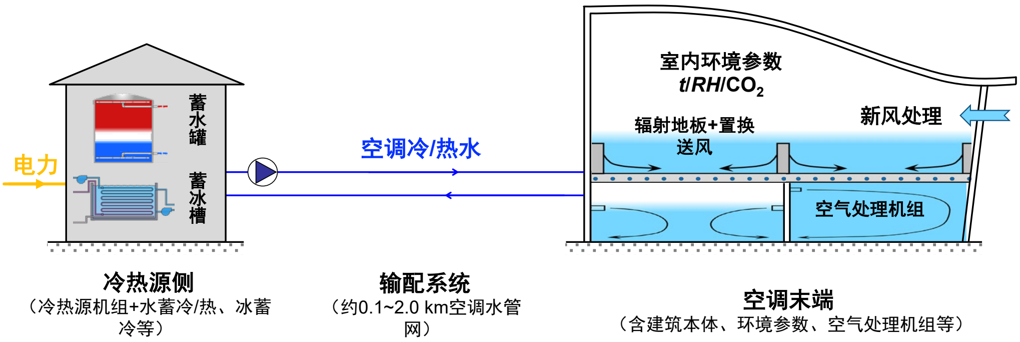
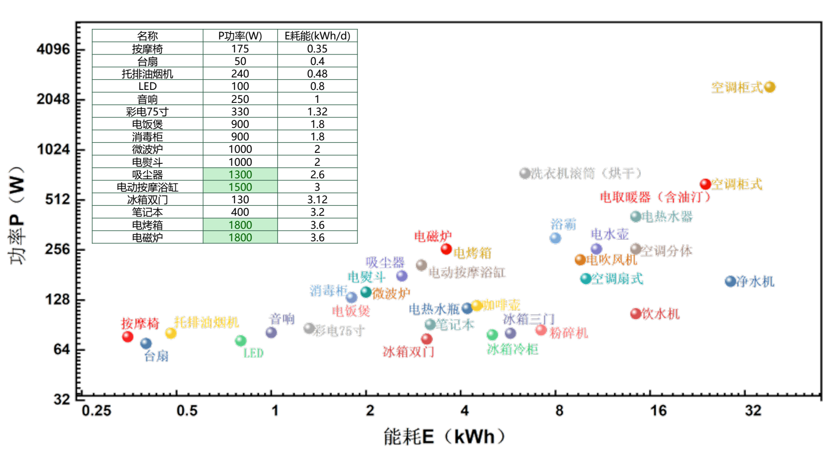


Figure 11 The equivalent energy storage capacity at various components of HVAC systems

- **Various types of energy-storing electrical appliances also serve as important forms of virtual energy storage.** Consumer electronics currently account for 33% to 40% of the global lithium-ion battery market, making them a primary application area. Therefore, electrical appliances represent an extensive network of distributed battery resources, and in-depth research in this area can unlock substantial equivalent energy storage potential. Figure 12 illustrates the power and energy consumption ranges of common electrical appliances.



名称	P功率(W)	E耗能(kWh/d)
按摩椅	175	0.35
台扇	50	0.4
托排油烟机	240	0.48
LED	100	0.8
音响	250	1
彩电75寸	330	1.32
电饭煲	900	1.8
消毒柜	900	1.8
微波炉	1000	2
电熨斗	1000	2
吸尘器	1300	2.6
电动按摩浴缸	1500	3
冰箱双门	130	3.12
笔记本	400	3.2
电烤箱	1800	3.6
电磁炉	1800	3.6

Figure 12 Power and energy consumption ranges for various types of electrical appliances

5. Quantitative Description Methods for Various Flexible Energy Resources

- **Establishing an 'Equivalent Battery Model' for unified characterization of generalized energy storage.** The main purpose of using equivalent energy storage is to reduce the installed capacity of traditional energy storage, hence it needs to be incorporated into the design and evaluation framework of traditional energy storage. We define the 'Equivalent Battery Model' for virtual energy storage, with parameters including equivalent charging power, equivalent discharging power, equivalent storage capacity, and equivalent overall efficiency. Figure 13 compares three categories of virtual energy storage resources in building areas with various traditional energy storage technologies, where the equivalent time constants T for building area virtual energy storage resources are primarily in the range of minutes to days. Considering the equivalent conversion coefficients, the approximate cost range for various utilizable virtual energy storage remains significantly lower than that of batteries, as shown in Figure 14.

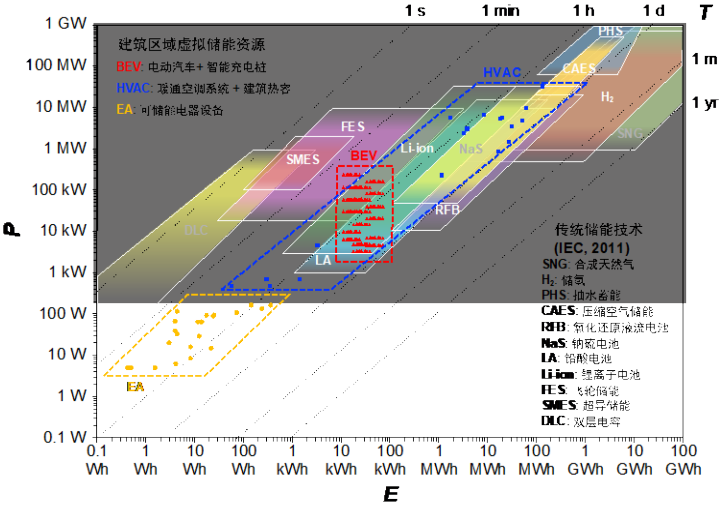


Figure 13 Building area generalized energy storage: traditional energy storage technologies and virtual energy storage resources

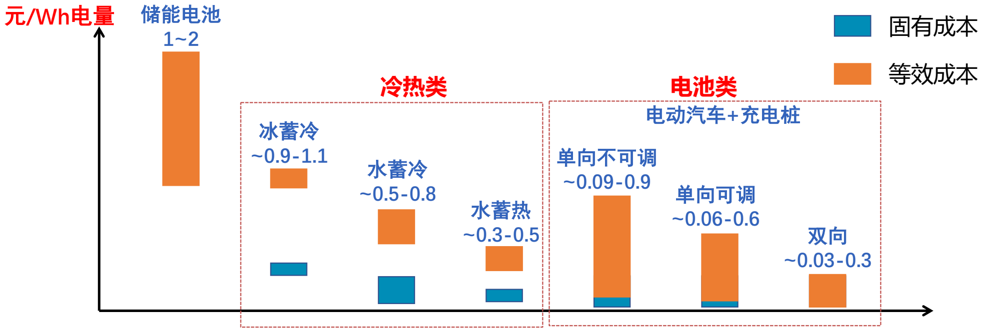
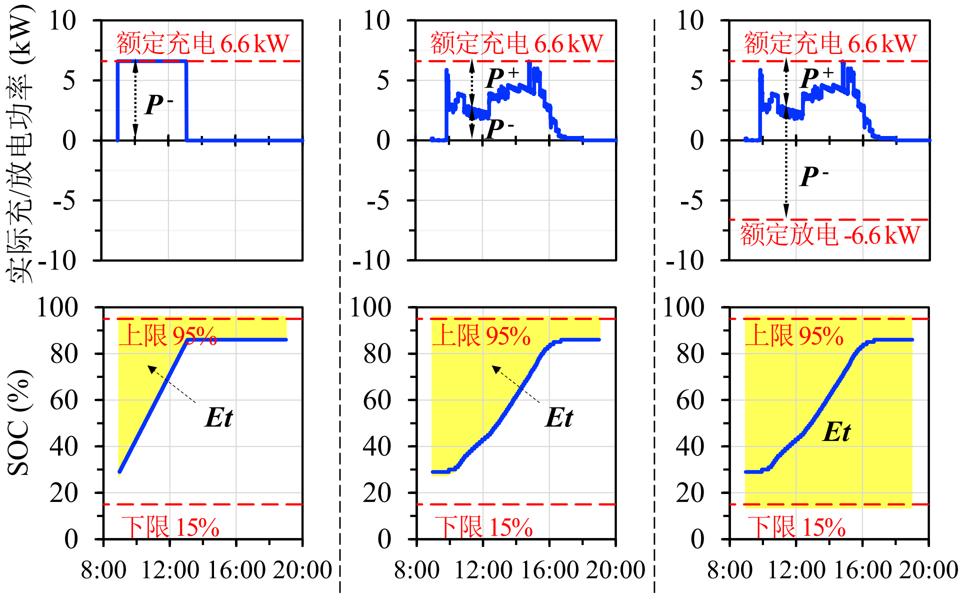


Figure 14 Approximate cost ranges of utilizable energy storage across various types, considering equivalent conversion factors

- **The actual dispatchable virtual energy storage capacity of electric vehicles combined with chargers is influenced by factors such as vehicle behavior, battery safety, charging and discharging system functionality, and strategies.** Commonly, non-adjustable single-direction chargers start charging with the maximum power allowed by the vehicle and generally lack the ability to increase their power output. The equivalent storage capacity is the difference between the upper limit of electricity that can be adjusted and the actual value (as shown by Figure 15(a), expressed as a ratio of the yellow area to time duration *t*). In contrast, power-adjustable single-direction charging stations can continuously adjust their charging power within the range of 0 to the rated power based on instructions. Compared to Figure 15(a), the yellow area within the same time duration *t* is larger in Figure 15(b), resulting in a greater equivalent storage capacity. For power-adjustable bidirectional charging stations, their power can be reduced to discharge power, theoretically allowing the scheduling of all electricity while ensuring battery safety. As shown in Figure 15(c), the yellow area further expands, and the equivalent storage capacity conversion factor also increases accordingly.



(a) 不可调单向充电桩 (b) 可调单向充电桩 (c) 可调双向充电桩

Figure 15 Example of equivalent energy storage potential for 'electric vehicles + smart chargers' system

- **HVAC systems typically consist of three components: heating and cooling sources, distribution systems, and user terminals. Each of these components possesses thermal energy storage capabilities.** The heating and cooling sources can be equipped with devices like thermal storage tanks or ice storage tanks. The distribution system contains heat or cold-carrying fluids with specific heat capacity. The user terminals can exploit the building's thermal mass to varying degrees, allowing indoor temperature and humidity parameters to fluctuate within the range acceptable to occupants. Consequently, the user terminals, coupled with the building's thermal mass, also contribute to the system's energy storage capabilities. The thermal energy storage capacities in these components can be categorized into two main types: 'Source + Distribution' virtual storage and 'User Terminal + Building Thermal Mass' virtual storage. These capacities can be sequentially utilized within the comprehensive virtual energy storage process of the 'HVAC System + Building Thermal Mass.' As a result, the equivalent energy storage capacity and equivalent time constant exhibit additivity.

- **Energy-storing appliances represent one of the largest sectors in lithium battery ownership, following electric vehicles.** Currently, common energy-storing appliances and their chargers primarily employ a fixed-power unidirectional charging mode, akin to electric vehicles paired with fixed-power unidirectional charging stations. Analysis based on existing data indicates that the equivalent energy storage capacity of individual energy-storing appliances is significantly smaller than that of the 'Electric Vehicle + Smart Charger' or 'HVAC System + Building Thermal Mass' categories. Nevertheless, these virtual energy storage resources entail no initial investment costs. Moreover, considering their vast numbers and the rapid development of smart buildings, they are expected to possess significant flexibility in energy modulation in the future. The key challenge in harnessing this virtual energy storage is the effective utilization of an extensive and highly random pool of endpoint devices. Internet of Things (IoT) technologies can support controlling the charging processes of electrical appliances within a certain range. Additionally, using power-line carrier communication in low-voltage distribution networks to broadcast demand response signals and employing an opt-in participation mode represents another potentially promising approach.

- **The 'Equivalent Battery Model' proposed in this study differs from existing optimization-based models.** While existing optimization-based models are advantageous for overall distribution network optimization and scheduling, they may face challenges in associating various types of loads with specific equipment systems during the design phase. These models might encounter difficulties in providing quantitative values for engineering applications. The objective of the 'Equivalent Battery Model' presented in this paper is to convert existing virtual energy storage resources within building electromechanical systems and subtract them from the total energy storage requirement, thereby offering guidance for energy storage battery capacity design in building electromechanical systems. This model adopts a 'maximum capacity - conversion coefficient' approach and is tailored for practical equipment systems with energy storage capabilities, making it convenient for design firms and industrial entities to perform simplified calculations. Furthermore, optimization-based models can provide detailed insights into the actual scheduling impact of various virtual energy storage resources under specific constraints, thus offering the 'Equivalent Battery Model' more precise conversion coefficients.