1 Cloud energy storage for residential and 2 small commercial consumers: a business case 3 study

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11

12 **Abstract:**

13 Energy storage is extensively recognized as a significant potential resource for balancing
14 generation and load in future power systems. Although small residential and commercial
15 consumers of electrical energy can now purchase energy storage systems, many factors, such as
16 cost, policy and control efficiency, limit the spread of distributed energy storage (DES). This paper
17 proposes a new type of DES—cloud energy storage (CES)—that is capable of providing energy
18 storage services at a substantially lower cost. This grid-based storage service enables ubiquitous
19 and on-demand access to a shared pool of grid-scale energy storage resources. It provides users
20 the ability to store and withdraw electrical energy to and from centralized batteries. This paper
21 describes the concept of CES and the control and communication technologies that are required
22 for its implementation and its operating mechanism, as well as its business model. Simulation
23 results that are based on actual power system operating data demonstrate the feasibility and
24 economic benefit of CES.

25

26 **Keywords:** energy storage, energy Internet, cloud, business model, distributed energy storage,
27 sharing economy, economies of scale

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1 Introduction

Power systems around the world are transitioning from fossil fuels to renewable energy sources, with variable renewable energy (VRE) sources, such as wind and photovoltaic (PV), increasing from 181.57 GW of worldwide installed capacity in 2009 to 549.24 GW in 2014 [1], and generating 2.7% of the electrical energy consumed globally [2]. By 2050, wind power and PV are estimated to provide more than half of the electricity demand in China and more than 40% of the electricity demand in the U.S. [3], [4]. However, statistics about installed capacity and energy production do not reveal the entire story. Maintaining the stability of the power system requires real-time balancing of the energy that is consumed and produced. The integration of VRE replaces controllable power-generating plants with an uncertain and intermittent energy source that complicates the task of satisfying the demand at all times [5]. In countries where electrical energy is traded on a competitive market, the intermittency and variability of renewable energy sources will also increase the volatility of electricity prices [6].

Energy storage can significantly facilitate VRE integration [7] because it can store electrical energy when VRE sources produce more power than can be used and release this energy when needed. Energy storage can smooth the intermittency of VRE sources to better follow the variation of the load demand [8]. Several energy storage technologies are in various stages of development: pumped hydro, compressed air (CAES), super capacitor, flywheel, and various types of flow batteries or solid batteries [9]. Although the cost of these energy storage technologies remains high compared with the price of electricity [10], [11], recent advances in battery technologies, especially in lithium-ion chemistries, suggest that their cost may be substantially declining [12]. In parallel, electricity markets are evolving toward a model in which a larger number of consumers will be exposed to real-time prices [13]. As VRE sources cause the volatility of real-time prices to increase, these consumers will want to control their instantaneous demand using an individual energy storage system [14]. Consumers who have installed solar panels may also want to use this storage to reduce their dependence on electricity purchased from the grid. These factors are likely to lead to the development and deployment of distributed energy storage (DES) [15]. Commercial products aimed at this market are already available [16].

Although the technology to support DES is available and the economics of DES are evolving favorably, some regulatory barriers and technical limitations may hinder its development. In particular, in many countries, customers receive little or no compensation for electrical energy that they inject back into the power grid. This lack of compensation provides little incentive for DES to react to variations in electricity prices [17]. DESs, particularly those installed at the residential level, are unlikely to be equipped with the smart control and communication systems that enable them to optimally self-schedule based on price forecasts and the total need for system real-time balancing. To circumvent these problems, centralized management approaches have been proposed to better utilize DES resources [18], [19]. There are also emerging commercial attempts of DES. Green2store is a project which uses the energy storage units in a local network together as one large storage facility [20]. Sonnenbatterie, a Germany based company, aims at providing an energy storage solution to residential users, including software

1 and energy storage units [21]. SENEC.IES utilizes DES to provide users a lower electricity price [22].
2 Some other companies aggregate users' DES to participate ancillary services market [23], [24].

3

4 In this paper, we describe an alternative technique that we refer to as cloud energy storage (CES).
5 This technique supports both the needs of residential DES and the optimal operation of storage
6 resources. The CES concept is inspired by cloud services [25] and the sharing economy [26], [27],
7 [28]. As locating shared computing resources in "the cloud" enhances their utilization and
8 cost-effectiveness, CES is dependent on the power grid to optimize the use of energy storage
9 resources [29]. In the remainder of this paper, we describe how the cloud energy storage concept
10 can be realized using state-of-art technology. We also demonstrate how CES can provide the
11 same quality of service as DES at a substantially lower cost via sharing storage resources and
12 taking advantage of the economies of scale. The gains in social welfare and profitability are
13 illustrated using actual residential load data and electricity prices.

14

15 The contribution of this paper mainly lies in three aspects: 1) proposing the concept of Cloud
16 Energy Storage which would utilize centralized energy storage facilities to provide distributed
17 storage services for residential and small commercial users; 2) describing the architecture and
18 enabling technologies, operation mechanism that facilitate CES; 3) designing the business model
19 of CES and demonstrating its profitability using real-life residential load and electricity data.

20

21 The rest of the paper is organized as follows. Chapter 2 describes the concept of CES and the
22 associated technology framework and business model. Chapter 3 proposes an economic analysis
23 model which can be used to calculate the benefits of CES. Chapter 4 presents the case study.
24 Chapter 5 concludes.

2 Concept and Business Model

2.1 Concept of Cloud Energy Storage

Figure 1. Framework of cloud energy storage. (CAES: compressed air energy storage).

The demand for DES has very similar characteristics to the demand for distributed computing services [30]. 1) Uniformity: electrical energy is a homogeneous commodity that is similar to computing services, which facilitates the extensive sharing of resources. 2) Transportability: electrical energy can be rapidly and efficiently transmitted through the power grid as data are communicated via the Internet, which enables the use of a real-time remote service that is comparable to a local service. CES can be defined as a grid-based storage service that enables ubiquitous and on-demand access to a shared pool of grid-scale energy storage resources. CES provides users the ability to store and withdraw electrical energy to and from centralized batteries. It relies on the sharing of resources to achieve economies of scale [31]. Figure 1 illustrates the structure of CES, which consists of three main parts: the CES users, the energy storage facilities and the CES operator.

The users of CES can be residential consumers or businesses who want to use energy storage to optimize the profile of their demand for electrical energy or reduce their electricity bill by storing energy when the price of energy is low and releasing the energy that have been stored when the price of energy is high. Instead of purchasing batteries and battery management systems, they rely on energy storage services from the CES, where they can rent a customized amount of both power and energy capacity. CES users can charge or discharge their cloud batteries in the same manner as they would control an actual battery that they would buy, install, operate and

1 maintain.

2

3 The energy storage facility of CES is large-scale and centrally controlled by the CES operator to
4 achieve optimal operation. Because of its size and centralized nature, CES facilities can combine
5 different storage technologies, such as Li-ion batteries, flow batteries or compressed air energy
6 storage, and use each technology as appropriate for current needs.

7

8 The CES operator controls the energy storage devices to satisfy the charging and discharging
9 demands of CES users while maximizing the utilization of the storage resources. The available
10 storage facilities are not only shared by multiple CES users but are also dynamically reallocated
11 based on the demand for charging and discharging. By optimizing schedules and coordinating the
12 control of the energy storage facility, the CES operator can reduce the total investment cost, the
13 cycling losses, the battery space, and the maintenance cost.

14

15 Figure 1 also illustrates the flows of information, energy and money among the various
16 participants. The CES operator bidirectionally communicates with the CES users and the energy
17 storage facilities. CES users do not directly communicate with the energy storage facility. Instead,
18 CES users send their requests for charging and discharging to the CES operator, who can give
19 advice to CES users regarding their use of storage. The energy storage facilities are fully controlled
20 and monitored by the CES operator.

21

22 CES shifts the energy flow that is produced by the charge and discharge from the distribution
23 feeder, where CES users are connected to the feeder that contains the energy storage facilities.
24 When a CES user charges its cloud storage, the energy storage facility charges by absorbing
25 energy from the grid. When CES users discharge their cloud storage for their own use, the
26 energy storage facility releases the energy to the grid to compensate for the corresponding load
27 of the CES users.

28

29 The CES operator oversees the flow of money among the CES users, the owner of the energy
30 storage facility and the electricity market. The CES users pay a service fee that is based on the
31 power and energy capacity of the storage that they have rented. They also transfer the amount of
32 charging fees for their cloud batteries to the CES operator. The owner of the CES facility recovers
33 its investment cost via these fees. The CES operator also pays the market price for the energy that
34 it is not delivered and has to be obtained from the grid.

2.2 Architecture and Enabling Technologies

Figure 2. Architecture of the cloud energy storage system

As Figure 2 illustrates, a CES system involves several functional modules and relies on state-of-the-art technologies, such as data analytics, optimization and communication.

The communication module of the CES enables the exchange of information among the CES operator and the users, the energy management module and the power grid. The CES operator receives real-time charging and discharging requests from the users. Users should be able to access the CES consumer interface [32] using apps to set their charging and discharging schedules. The CES can also directly interact with smart meters [33] for automated charging and discharging requests. The CES operator can also text or e-mail users to influence their cloud storage usage. Communication between the CES operator and the energy storage facility implements the real-time control and monitoring of the storage facility. Standard industrial network protocols such as Modbus [34] and Profibus [35] can be used to guarantee the security and reliability of these communications. The communication module of the CES also gathers information about electricity prices to support the scheduling of the batteries.

Forecasts of the charging and discharging behaviors of CES users and electricity prices are required. These forecasts support the scheduling of the batteries and increase the revenues of the CES operator. Understanding how consumers use their batteries requires CES operator to forecast the behavior of users. Emerging technologies that are based on behavioral science and big data are able to identify consumers' patterns of electricity usage [36]. They can identify their lifestyle (e.g., whether they work at home, at what time they go to bed) using historical load curves. This information yields more confident forecasts of their load demand. In addition to the load curve, the CES operator also needs to forecast users' charging and discharging demand, which may require techniques that substantially differ from traditional load forecasting [37].

1 The schedule optimization module makes optimal operation decisions for the energy storage
 2 facility based on the forecasted and real charge and discharge demand and electricity prices, as
 3 well as the state of charge of the batteries. The charge and discharge of the storage facility do not
 4 always follow the aggregated charge and discharge demand of all users. The schedule of the
 5 storage facility can be optimized toward a minimum cost of CES while considering its operating
 6 constraints. The optimization of the energy storage facility is essentially a linear programming (LP)
 7 problem that can be efficiently solved using commercial software. Advanced stochastic and
 8 robust optimization techniques can also be used to consider the price and load uncertainties
 9 during decision-making. Decomposition and coordination approaches can be adopted when this
 10 optimization involves too many storage facilities.

11

12 The battery management system [38] controls the charge and discharge of each battery based on
 13 the optimized schedule and monitors the state of charge and the state of health of the batteries.
 14 This system is also responsible for the protection of the battery cells and communication with the
 15 CES operator.

16 2.3 Operation Mechanism

17

18 Figure 3. Operation mechanism of cloud energy storage. (SOC: state of charge, CAES:
 19 compressed air energy storage).

20

21 The users of the CES purchase services from the CES operator for both the electric power
 22 capacity and the energy capacity. To CES users, this virtual storage is similar to actual batteries,
 23 with the exception that they are operated by centralized operators. Their CES capacity has a
 24 virtual discharging rate, efficiency and lifetime. CES users can operate their virtual energy storage

1 in real-time in the same manner that they would operate actual batteries. They can charge and
2 discharge their CES via the consumer interface. In this manner, they can store electricity when
3 the price of electricity is high and release electricity when the price of electricity is low to reduce
4 their electricity bills or store for future use the excess electrical energy that was produced by
5 their PV panels. The CES operator gathers information about the CES users and forecasts their
6 charging and discharging behaviors to determine their total charging and discharging profiles for
7 the next day. The CES operator simultaneously forecasts electricity prices for the next day and
8 collects information about the SOC of each energy storage facility. An optimal charge and
9 discharge schedule for the next day can be established to minimize the operating cost according
10 to this information. The schedule can subsequently be optimally allocated to each storage facility
11 according to the characteristics (energy capacity, operation flexibility, and efficiency) of different
12 storage technologies. In real-time, the CES operator updates the schedule on a rolling basis
13 according to real-time charge/discharge instructions from the users and the real-time prices. The
14 schedule is sent to the management system of each storage facility at regular time intervals.

15
16 Various types of storage with complementary characteristics are available in a CES facility, which
17 enables the facility to fulfill the needs of the users in a cost-effective manner. Storage with high
18 power density, such as super capacitor [39], can be employed to satisfy the peak energy storage
19 needs of users, whereas storage with high energy density, such as flow battery [40], will meet the
20 needs to shift large amounts of energy. The portfolio of energy storage technologies with
21 different levels of cost-effectiveness on unit capacity and energy density, e.g., compressed-air
22 energy storage [41] and Li-ion batteries [42], can reduce the investment cost. In each single
23 storage facility, the battery management system receives the schedule from the CES operator and
24 optimally controls the charge and discharge of different batteries to maximize their life span.

25 2.4 Business Model

26 The business model of CES is similar to that of other cloud-based businesses, such as cloud
27 computing. CES users purchase or rent virtual energy storage capacity from the cloud. The power
28 and energy capacity can be customized according to the needs of users.

29
30 CES users rent their cloud-based storage capacities. When CES users charge their virtual storage,
31 they pay the market price for electricity. Accordingly, they do not need to pay for the electricity
32 that is discharged from virtual storage.

33
34 The CES operator invests the centralized energy storage and serves as an agent for all users to
35 store electricity from the grid when the price of electricity is low. The CES operator does not
36 necessarily have to own all storage capacity that they rent to CES users. When CES users store or
37 withdraw energy beyond the total capacity of the CES, the operator can purchase or sell energy in
38 real-time from the electricity market to satisfy the users' demand. Although the CES operator
39 collects revenue by selling the storage capacity to the users, the profit of the CES operator is
40 fundamentally derived from the extra social benefit that is received by employing the centralized
41 storage to provide a distributed storage service.

1
2 CES provides four types of social benefits. First, CES leverages the diversity in the users' demand
3 for storage. Peak storage capacity demands do not simultaneously occur for all users. Thus, the
4 demand for storage can be smoothed, which enables energy storage to be shared among
5 different users. In this manner, CES enhances the utilization of the energy storage devices.

6
7 Second, CES is able to better schedule the battery because its operator has access to more
8 information. Individual users may not be able to optimally control their batteries because they
9 have limited information about the state of the power system and its uncertain evolution. Instead
10 of decentralized decisions by each user, the CES operator is able to make more strategic decisions
11 that are based on more comprehensive information about the future balance between supply
12 and demand and the patterns of the electricity usage of users.

13
14 Third, CES can achieve an economy of scale that reduces the unit investment cost per kW and
15 kWh of storage. It can also reduce the maintenance that is required of all users. Furthermore, the
16 power and energy capacity of CES can be adjusted as the number of users increases.

17
18 Last, CES is able to coordinate multiple storage technologies to satisfy the requirements of users.
19 The portfolio of different storage technologies that are employed by the CES operator can reduce
20 investment and operation costs.

21
22 The total social benefits that are gained through the business model of CES can be shared by the
23 CES operator and CES users via appropriate pricing of CES products. The benefit shared by each
24 participant is determined by CES service fees and rents.

25
26 In addition, it is worth comparing CES business model with some similar international cases. The
27 common point of them is that these business models all help users better utilize energy storage
28 to integrate renewable energy and reduce electricity bills. However, there are also some major
29 differences. Sonnenbatterie [21] installs real energy storage entities at each user's home, while
30 CES provides users virtual energy storage capacities and there are no storage entities at users'
31 places. Green2store [20] gathers a number of distributed energy storage units from users to form
32 a large storage facility on the cloud to provide service for energy storage users. However, CES
33 uses centralized energy storage facilities, which are owned by CES operator, to provide
34 decentralized energy storage services, which makes the service provider easier to take charge of
35 energy storage facilities and to take advantages of the economies of scale. In addition, since CES
36 has a nature of centralized dispatching, the real charging and discharging power curves of CES
37 storage facilities could be different from the aggregated virtual charging and discharging curves of
38 users.

3 Economic Analysis

3.1 Flow of the Economic Analysis Model

3

4 Figure 4. Flow chart of the economic analysis model.

5

6 Figure 4 illustrates the flow of the model that is used to evaluate the benefits and profitability of
7 CES. First, the load profile of each user is assessed to determine whether it could benefit from

DES, using the storage investment and operation model for each user (refer to Support Information for a detailed formulation). Users that would benefit from DES are assumed to purchase CES services. Second, the storage investment and operation model of CES is run considering the charging and discharging behaviors of each user. Last, the total benefit is calculated by comparing the social benefit for all users between the use of DES (the DES case) and the use of CES (the CES case). In both cases, the social cost is calculated as the sum of the annual equivalent investment cost of storage and the annual bill for electricity purchased from the grid. The capacity of DES and CES are optimized by minimizing the cost of users and the CES operator.

3.2 User Side Model

In the original case, when no storage is used, the annual cost to each user C_i^{Original} is defined as the annual electricity bill that each user pays to purchase power from the grid

$$C_i^{\text{Original}} = \sum_{t \in T} \lambda_t d_{i,t} \Delta t \quad (1)$$

where λ_t is the retail rate of electricity at time t , $d_{i,t}$ is the load of user i at time t , and Δt is the time interval.

If the user is equipped with DES, its annual cost C_i^{DES} is the annual equivalent investment of DES and its annual electricity bill

$$C_i^{\text{DES}} = I_i^{\text{DES}} + O_i^{\text{User}} \\ = \frac{r}{1 - (1 + r)^{-Y}} (c^{\text{P, DES}} P_i^{\text{Cap}} + c^{\text{E, DES}} E_i^{\text{Cap}}) + \sum_{t \in T} \left[\lambda_t (P_{i,t}^{\text{C}} - P_{i,t}^{\text{D}} + d_{i,t})^+ + \theta_t (P_{i,t}^{\text{C}} - P_{i,t}^{\text{D}} + d_{i,t})^- \right] \Delta t \quad (2)$$

where the I_i^{DES} is the annualized investment cost of DES considering a discount rate r and a return year Y . The investment cost of DES accounts for both its power capacity P_i^{Cap} (kW) and its energy capacity E_i^{Cap} (kWh). $c^{\text{P, DES}}$ and $c^{\text{E, DES}}$ are the unit investment costs of DES for power capacity (\$/kW) and energy capacity (\$/kWh). O_i^{User} denotes the annual cost of electricity. It includes both the cost of the consumed electricity and the cost of the electricity that is sent back to the power grid. $P_{i,t}^{\text{C}}$ and $P_{i,t}^{\text{D}}$ are the charging power of user i and the discharging power of user i , respectively, using DES at the time interval t . θ_t is the price at which the electricity sent back to the grid is purchased from the users. $(\cdot)^+$ and $(\cdot)^-$ denote

the positive part in the brackets and the negative part in the brackets, respectively:

$$(x)^+ = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases}, \quad (x)^- = \begin{cases} x, & x \leq 0 \\ 0, & x > 0 \end{cases} \quad (3)$$

The optimal power capacity and energy capacity of DES are optimized based on the load of each user and the electricity prices. The optimal capacity model also schedules the charge and discharge schedule at each time interval:

$$[P_i^{\text{Cap}}, E_i^{\text{Cap}}, P_{i,t}^{\text{C}}, P_{i,t}^{\text{D}}] = \arg \min_{P_i^{\text{Cap}}, E_i^{\text{Cap}}, P_{i,t}^{\text{C}}, P_{i,t}^{\text{D}}} (C_i^{\text{DES}}) \quad (4)$$

The detailed optimization model is detailed in the support information (SI).

In the CES case, the charge and discharge schedule is assumed to be identical to the DES case. Users purchase the power and energy storage capacity from CES. The user's annual cost in the

CES case, which is regarded as C_i^{CES} , can be calculated as follows:

$$\begin{aligned} C_i^{\text{CES, User}} &= A_i^{\text{CES}} + O_i^{\text{User}} \\ &= (a^{\text{P, CES}} P_i^{\text{Cap}} + a^{\text{E, CES}} E_i^{\text{Cap}}) + \sum_{t \in T} \left[\lambda_t (P_{i,t}^{\text{C}} - P_{i,t}^{\text{D}} + d_{i,t})^+ + \theta_t (P_{i,t}^{\text{C}} - P_{i,t}^{\text{D}} + d_{i,t})^- \right] \Delta t \end{aligned} \quad (5)$$

where A_i^{CES} denotes the annual service fee of CES in terms of its power capacity a^{P} (\$/kW/yr)

and its energy capacity a^{E} (\$/kWh/yr). If the optimal cost in the DES case is less than the

optimal cost in the original case ($\min(C_i^{\text{DES}}) < C_i^{\text{Original}}$), rational users will purchase energy

storage to reduce their electricity bills; otherwise, they will not use DES. A comparison between

(2) and (5) shows that the precondition for users to participate in CES rather than buying DES is

that the annual service fee for CES is less than the annualized investment cost of an energy

storage device. In this case, the users who purchase DES also benefit from CES. We define S^{CES}

as the set of these users.

3.3 Social Cost and CES Model

From the social cost point of view, the total social cost of all users in the set of $C^{\text{DES, Social}}$ is the sum of the cost for all users in the DES case:

$$C^{\text{DES, Social}} = \sum_{i \in S^{\text{CES}}} C_i^{\text{DES}} \quad (6)$$

In the CES case, the social cost is the sum of the investment in the entire storage facility and the

1 electricity bills for all users

$$C^{\text{CES,Social}} = I^{\text{CES}} + O^{\text{CES,Social}}$$

$$2 = \frac{r}{1-(1+r)^{-Y}} (c^{\text{P,CES}} P^{\text{Cap}} + c^{\text{E,CES}} E^{\text{Cap}}) + \sum_{t \in T} \left[\lambda_t \left(P_t^{\text{C}} - P_t^{\text{D}} + \sum_{i \in S^{\text{CES}}} d_{i,t} \right)^+ + \theta_t \left(P_t^{\text{C}} - P_t^{\text{D}} + \sum_{i \in S^{\text{CES}}} d_{i,t} \right)^- \right] \Delta t$$

3 (7)

4 where I^{CES} is the annualized investment cost of CES considering a discount rate of r and a
 5 return year of Y . The investment cost in CES considers both its power capacity P^{Cap} (kW) and
 6 energy capacity E^{Cap} (kWh). $c^{\text{P,CES}}$ and $c^{\text{E,CES}}$ are the unit investment cost in terms of
 7 the power capacity (\$/kW) and energy capacity (\$/kWh), respectively. $O^{\text{CES,Social}}$ denotes the
 8 annual cost for all users and the CES operator when using CES. P_t^{C} and P_t^{D} are the charge
 9 power and discharge power of CES, respectively, at time interval t .

10

11 Note that the P^{Cap} and E^{Cap} are not always equivalent to the aggregation of P_i^{Cap} and
 12 E_i^{Cap} , respectively, because the charge and discharge requirements of the users may be
 13 complementary. Similarly, P_t^{C} and P_t^{D} are not always equivalent to the aggregation of $P_{i,t}^{\text{C}}$
 14 and $P_{i,t}^{\text{D}}$, respectively. CES can make its own strategic scheduling of the charging and discharging
 15 of the batteries. The objective of the investment and operation decisions of CES is to optimize the
 16 cost from the CES operator's point of view. The total cost for the CES operator is

$$17 \quad C^{\text{CES,Operator}} = I^{\text{CES}} + O^{\text{CES,Operator}} \quad (8)$$

$$= \frac{r}{1-(1+r)^{-Y}} (c^{\text{P,CES}} P^{\text{Cap}} + c^{\text{E,CES}} E^{\text{Cap}}) + \sum_{t \in T} \left[\lambda_t \left(P_t^{\text{C}} - P_t^{\text{D}} + \sum_{i \in S^{\text{CES}}} P_{i,t}^{\text{D}} \right)^+ + \theta_t \left(P_t^{\text{C}} - P_t^{\text{D}} + \sum_{i \in S^{\text{CES}}} P_{i,t}^{\text{D}} \right)^- \right] \Delta t - \sum_{t \in T} \sum_{i \in S^{\text{CES}}} \lambda_t P_{i,t}^{\text{C}} \Delta t$$

18 where $\sum_{t \in T} \sum_{i \in S^{\text{CES}}} \lambda_t P_{i,t}^{\text{C}} \Delta t$ is the annual electricity bill for all users to charge the battery. Equation
 19 (8) shows that the purpose of CES is to serve the aggregated electricity discharge curve for all
 20 users using the centralized battery. The optimal power and energy capacity of CES is optimized
 21 with the charge and discharge decisions according to the aggregated discharge curve of all users
 22 and the electricity price:

$$23 \quad [P^{\text{Cap}}, E^{\text{Cap}}, P_t^{\text{C}}, P_t^{\text{D}}] = \arg \min_{P^{\text{Cap}}, E^{\text{Cap}}, P_t^{\text{C}}, P_t^{\text{D}}} (C^{\text{CES}}) \quad (9)$$

3.4 Benefit and Profitability Indices

The revenue of CES R^{CES} consists of the income from the users' annual service fees

$$R^{\text{CES}} = \sum_{i \in S^{\text{CES}}} A_i^{\text{CES}} \quad (10)$$

where $\sum_{i \in S^{\text{CES}}} A_i^{\text{CES}}$ is the income of selling the service to users. The electricity rate for charging is assumed to be equivalent to the retail rate. If CES exactly follows the aggregated charge and discharge curves of the users, the charging bill will offset the operating cost of CES. Otherwise, CES will purchase extra electricity from the power grid when the battery is empty, if the discharge demand is not satisfied. In this case, the charging bill cannot completely cover the operating cost of CES and the difference must be subtracted from the profit.

We define two indices, the maximum rate of return on investment and the maximum profit margin, to evaluate the benefit and profitability of CES. The maximum rate of return on investment of CES is defined as the ratio of the maximum profit over the investment in CES:

$$\eta = \frac{C^{\text{DES,Social}} - C^{\text{CES,Social}}}{\frac{r}{1 - (1 + r)^{-Y}} (c^{\text{P,CES}} P^{\text{Cap}} + c^{\text{E,CES}} E^{\text{Cap}})} \quad (11)$$

The difference between the total social cost of DES and the total social cost of CES reflects the social welfare that can be improved by CES and the maximum profit that can be obtained by CES. The profit margin of CES is defined as the ratio of the CES profit and revenue:

$$\kappa = \frac{\max R^{\text{CES}} - C^{\text{CES,Operator}}}{\max R^{\text{CES}}} \quad (12)$$

where the $\max R^{\text{CES}} - C^{\text{CES,Operator}}$ denotes the maximum annual profit of CES.

4 Case Study

4.1 Basic Data Setting

We demonstrate the social benefit of CES by comparing the total investment and operating costs of providing the same energy storage service between the use of distributed energy storage (DES) and CES. Our testing is based on actual load profiles from 400 Irish residential consumers in 2009 with a time interval of 30 min [43]. The evaluation is performed using both peak/off-peak prices and real-time prices for Ireland in 2009 [44]. We first assume that each residential consumer is equipped with a DES with optimal capacity and calculate its optimal daily charge and discharge

1 schedule for the entire year using peak/off-peak prices and real-time prices. Investments in DES
2 are conservatively assumed to carry unit prices of 300 USD/kWh and 100 USD/kW (base unit
3 prices). The annual investment cost is calculated assuming a discount rate of 6% and a 10-year
4 asset life. More detailed parameters can be found in Supplementary Table 1 in Supplementary
5 Information. We then calculate the optimal investment and operation of CES that satisfies the
6 aggregated charge and discharge profiles for all consumers. The social benefit of CES is equal to
7 the reduction in the total investment and operating cost relative to the equivalent costs of DES.
8 We evaluate the profitability of CES based on this social benefit.

10 4.2 Simulation Results

11 Figure 5 compares the aggregated charge and discharge power of all consumers and CES for a
12 typical day using both peak/off-peak prices and real-time prices. Negative values in the time
13 series indicate that the storage is discharging. The figure also shows how the electricity prices
14 change over the course of this particular day. The peak value of the CES charging profile is
15 significantly less than the peak value of the aggregated DES charging profile, which suggests that
16 CES is capable of satisfying the requirement of distributed users with a smaller energy storage
17 capacity by sharing the capacity among these users. The CES battery does not exactly follow the
18 charge and discharge curves of the aggregated DES. The optimal schedule of CES usually charges
19 less electricity than the optimal schedule of DES, which indicates that some of the electricity that
20 a consumer discharges from CES is directly purchased from the grid. Although this purchase
21 causes a slight increase in the operating cost for CES, it reduces the total cost over a longer time
22 horizon.

Figure 5 Comparison between the operation of CES and the aggregated operation of individual DES. Figure 5-(a) shows the results using peak/off-peak prices for a typical day, while Fig. 5-(b) shows the results using real-time pricing for the same day. The legend can be applied to both Fig. 5-(a) and Fig. 5-(b).

4.3 Cost Analysis

Figure 6 breaks down the cost and income for CES with 200 users and illustrates how the CES model improves social welfare. The DES unit prices are set as 180 USD/kWh and 60 USD/kW (60% of the base unit prices). To consider the economies of scale, the unit cost of investments for CES is assumed to be 20% less than the unit cost of investments for DES in Fig. 6. The operating cost of CES is based on a simulation of its optimal scheduling with real-time prices. The CES income is derived from the service fees paid by the users and is assumed to be equal to the annualized investment cost of DES. In practice, these services fees would have to be smaller than this cost to render CES attractive to users. The CES income is equivalent to the sum of the CES investment cost, the CES operating cost and the CES model total benefit. The CES operating cost is equal to the CES battery charging fee plus the electricity fees incurred when CES directly purchases electricity from the grid for users when the storage is not enough, and minus battery charging fees that users pay to the CES operator. The total benefits of CES is the residual revenue after covering the investment and operating costs. The results indicate that the profit of CES is derived from the savings of the investment cost achieved by sharing the storage capacity among different users. More detailed results can be found in Supplementary Table 3A in Supplementary

1 Information.

2

3 Figure 6. Breakdown of annual cost and income of CES

4

5 To encourage participation in a CES service, a certain amount of the benefit from the CES model
6 should be returned to the users. Figure 7 shows the annual savings for users when CES is used
7 instead of DES and half of the benefit is returned to the users via a reduction in the paid service
8 fees. The savings of each user is plotted as a function of their electricity consumption. We
9 observe an approximately linear relationship between electricity bill savings and electricity usage
10 because heavy electricity users tend to pay higher service fees to purchase a larger energy
11 storage capacity according to their self-optimal decisions. The results also indicate that the
12 benefit with peak/off-peak electricity pricing is higher than the benefit with real-time pricing.

13

14 Figure 7. Annual benefit for users with different yearly electricity consumption. The
15 blue dots represent users with peak-valley pricing, and the red dots represent users
16 with real-time pricing.

17

4.4 Sensitivity Analysis

We calculate the annual rate of return on CES investment based on the calculated profit for operation using both peak/off-peak prices and real-time prices. Optimal investment and operation of CES is simulated for investment costs for CES and DES, which range from 20% of the current price to 100%. Figure 8 shows that CES is profitable in all cases, with the exception when the investment cost is 100% or 80% using peak/off-peak prices. As expected, the return on investment of CES increases if the unit cost of energy storage decreases. The economies of scale also improves the profitability of CES and justify its business model. More detailed results can be found in Supplementary Table 2A to 3B-2 in Supplementary Information.

Figure 8. Rate of return on investment for CES for different unit prices of energy storage. Figure 8-(a) is under peak/off-peak pricing, while Fig. 8-(b) is under real-time pricing. The legend can be applied to both Fig. 8-(a) and Fig. 8-(b), which indicates different colors stand for different investment cost savings from economies of scale.

4.5 Discussion

This case study demonstrates the economic feasibility of CES. Under the peak/off-peak prices, 100% and 80% of base energy storage unit price are still prohibitively high, while when energy storage unit price is no more than 60%, users will want to use energy storage and CES would be profitable. However, under the real-time prices, CES will be feasible when the energy storage unit price is 20%-100% of base value. The different results between peak/off-peak prices and real-time prices also indicate that CES is easier to make a profit under real-time prices, because CES can profit when the storage unit price is 80% and 100% of base value and these unit prices are likely to be closer to actual situation in the near future. The trends of rate of return on investment show that the economies of scale will help enhance the profitability of CES significantly and that the changes of storage unit price have smaller influences on the rate of return on investment compared with the economies of scale.

The future development of CES service is driven by two main factors. 1) The need for energy storage. Although DES can arbitrage variations in prices and store excess renewable energy, its benefits are not sufficiently large to justify its deployment. 2) The cost of storage. Currently, the cost of energy storage remains too high compared with its benefit. However, it is substantially decreasing. This case study shows that the rate of return will increase by 45% if the unit cost of energy storage decreases by 30%.

CES does not have to surmount large technological barriers. The deployment of CES can be based on current infrastructures. By sufficiently utilizing all types of available technologies and various resources, CES will be more cost-effective and improve public understanding about energy storage.

The CES business risks include policy risks and public acceptance risks. In contrast to DES, CES is not “behind the meter”. Therefore, future policy is required to support the combination of the electricity meter bill and the cloud battery charging/discharging bill for each CES user. In addition, current price policy, which may establish different prices for download energy and upload energy and significantly reduce the profitability of CES, should be improved for CES to accelerate its development. The public recognition of energy storage as a part of the energy consumption habituation is needed, which is true for both DES and CES; however, with respect to CES, the public needs to understand why and how their batteries can be on the cloud.

5 Conclusion

There is an increasing demand of utilizing distributed energy storage by residential and small commercial users to integrate variable renewable energy and reduce electricity bills. This paper proposes a novel concept, Cloud Energy Storage, to provide the same services to these users at a

lower social cost. The structure of CES consists of three main parts: the CES users, the energy storage facilities and the CES operator. A CES system can employ several state-of-the-art technologies to realize its functions. CES users can use their cloud batteries just like real energy storage devices, while the CES operator will invest and operate centralized energy storage facilities to provide storage services to these users. CES is also demonstrated to be able to gain social benefits through a case study based on actual residential load data and electricity prices. The results indicate that: 1) CES is easier to profit under real-time prices than under peak/off-peak prices; 2) The energy storage unit price decreases brought by technology advance would not have a big influences on the percentages of social welfare improved by CES. However, these unit price decreases will influence the decisions of users on whether using energy storage or not. The result data show that CES is more economic than DES under different prices with the exception when the energy storage unit price is more than 80% of the base unit price under peak/off-peak prices cases; 3) Economies of scale has a significant influence on the economy of CES.

In the future, CES may not only employ a centralized storage facility but also gather fragments of energy storage resources, such as electric vehicles, UPSs, or even residential distributed batteries. The business model of CES will be available to various players in the power system. Both retailers and aggregators can invest in CES to improve their profits and reduce their costs of buying electricity. The business model of CES could also be merged into some current business models as value-added services.

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Author contributions

C.Q.K. conceived the original ideas presented in this paper. J.K.L., N.Z., and D.K. wrote the main manuscript text and figures. J.K.L. completed the data sorting and calculations. D.K. and Q.X. provided theoretical guidance. All authors reviewed the manuscript.

Additional information

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