iScience

CellPress
OPEN ACCESS

Perspective

Business Models and Profitability of Energy Storage

Felix Baumgarte,[1] Gunther Glenk,[2,*] and Alexander Rieger[3]

SUMMARY

Rapid growth of intermittent renewable power generation makes the identification of investment opportunities in energy storage and the establishment of their profitability indispensable. Here we first present a conceptual framework to characterize business models of energy storage and systematically differentiate investment opportunities. We then use the framework to examine which storage technologies can perform the identified business models and review the recent literature regarding the profitability of individual combinations of business models and technologies. Our analysis shows that a set of commercially available technologies can serve all identified business models. We also find that certain combinations appear to have approached a tipping point toward profitability. Yet, this conclusion only holds for combinations examined most recently or stacking several business models. Many technologically feasible combinations have been neglected, indicating a need for further research to provide a detailed and conclusive understanding about the profitability of energy storage.

INTRODUCTION

As the reliance on renewable energy sources rises, intermittency and limited dispatchability of wind and solar power generation evolve as crucial challenges in the transition toward sustainable energy systems (Olauson et al., 2016; Davis et al., 2018; Ferrara et al., 2019). Since electricity storage is widely recognized as a potential buffer to these challenges (Fares and Webber, 2017; Kittner et al., 2017; Davies et al., 2019), the number of advancements in energy storage technology and the amount of deployed capacity have rapidly grown in recent years (Schmidt et al., 2017; Comello et al., 2018; Sutherland, 2019; Blanc et al., 2020). The profitability of investment opportunities for storage overall, however, has remained ambiguous, partially due to an incomplete identification of such opportunities in modern power systems (Argyrou et al., 2018; Albertus et al., 2020) and contradicting conclusions about the profitability of individual opportunities (Braff et al., 2016; Kaschub et al., 2016; Fares and Webber, 2017; Metz and Saraiva, 2018; Comello and Reichelstein, 2019).

Numerous recent studies in the energy literature have explored the applicability and economic viability of storage technologies. Many have studied the profitability of specific investment opportunities, such as the use of lithium-ion batteries for residential consumers to increase the utilization of electricity generated by their rooftop solar panels (Hoppmann et al., 2014; Stephan et al., 2016; van der Stelt et al., 2018). Others have reviewed the range of potential applications of storage technologies, that is, the services that storage facilities can perform in power systems (Koohi-Kamali et al., 2013; Kousksou et al., 2014; Palizban and Kauhaniemi, 2016). Building upon both strands of work, we propose to characterize business models of energy storage as the combination of an application of storage with the revenue stream earned from the operation and the market role of the investor. Such business models can then be used to systematically differentiate investment opportunities, to assess which storage technologies are capable of serving a business model, and to review the profitability of individual combinations of business models and technologies.

This paper presents a conceptual framework to describe business models of energy storage. Using the framework, we identify 28 distinct business models applicable to modern power systems. We match the identified business models with storage technologies via overlaps in operational requirements of a business model and operational capabilities of a technology. The matching shows that all business models can be served by a set of commercially available technologies. Reviewing the results of previous studies on the profitability of individual matches, we find that they are largely found to be unprofitable. Yet,

[1] FIM Research Center, University of Bayreuth, Project Group Business & Information Systems Engineering, Fraunhofer FIT, Bayreuth 95444, Germany

[2] Business School, University of Mannheim, MIT CEEPR, Massachusetts Institute of Technology, Mannheim 68131, Germany

[3] Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg, Luxembourg 1855, Luxembourg

*Correspondence: glenk@uni-mannheim.de

https://doi.org/10.1016/j.isci.2020.101554

Application	Description
1) Provide frequency containment	Storage can stabilize the frequency and voltage of power supply providing either frequency containment, short- and long-term frequency restoration (The European Commission, 2017), or reactive energy for voltage control
2) Provide short-/long-term frequency restoration	
3) Provide voltage control	
4) Provide black start energy	Storage can support black starts of the electricity grid after a power outage and provide backup energy to bridge a power outage
5) Provide backup energy	
6) Meet selling/buying forecast	Storage can help meeting committed forecasts, adding power supply/demand when needed, for instance, during periods of unforeseen changes to the demand/generation profile
7) Shave supply/demand peaks	Storage can smooth out supply/demand curves and shave peaks
8) Sell at high/buy at low prices	Storage can improve power trades by buying at low and selling at high prices, including the utilization of surplus power from an onsite renewable energy source

Table 1. Applications for Energy Storage

matches assessed since 2017 or comprising multiple business models served by one storage facility appear to have approached a tipping point toward profitability. Overall, our review reveals many technologically feasible matches that have been neglected so far. Their examination over the coming years will be essential to reach a detailed and conclusive evaluation of the profitability of energy storage. To conclude, we summarize the main research directions recommended in the reviewed literature to foster widespread profitability of storage.

RESULTS

Business Models

We propose to characterize a ''business model'' for storage by three parameters: the application of a storage facility, the market role of a potential investor, and the revenue stream obtained from its operation (Massa et al., 2017). An application represents the activity that an energy storage facility would perform to address a particular need for storing electricity over time in modern power systems. A market role of potential investors refers to their assumed position in the electricity value chain. The revenue stream describes the type of income a storage facility can generate from its operation.

Table 1 provides a list and description of eight distinct applications derived from previous reviews on potential applications for energy storage (Castillo and Gayme, 2014; Kousksou et al., 2014; Palizban and Kauhaniemi, 2016). In the first three applications (i.e., provide frequency containment, short-/long-term frequency restoration, and voltage control), a storage facility would provide either power supply or power demand for certain periods of time to support the stable operation of the power grid. The following two applications in Table 1 (i.e., provide black start energy and backup energy) would support the availability of electricity at all times through the provision of power supply during blackouts either to reboot grid operations or to bridge the power outage for an electricity consumer. These five applications are frequently referred to as applications for ancillary services (Fuchs et al., 2012; Richter, 2013).

The remaining three applications in Table 1 can be referred to as applications for load shifting as they focus on shifting electricity across time. In application (6) of Table 1, an energy storage facility would help meeting a committed selling/buying forecast, for instance, by compensating unforeseen changes in a demand or generation profile. In application (7), energy storage would shave supply/demand peaks and, for instance, avoid the expansion of transmission lines by reducing the peak of supply/demand in a particular geographic area. In application (8), the owner of a storage facility would seize the opportunity to exploit differences in power prices by selling electricity when prices are high and buying energy when prices are low.

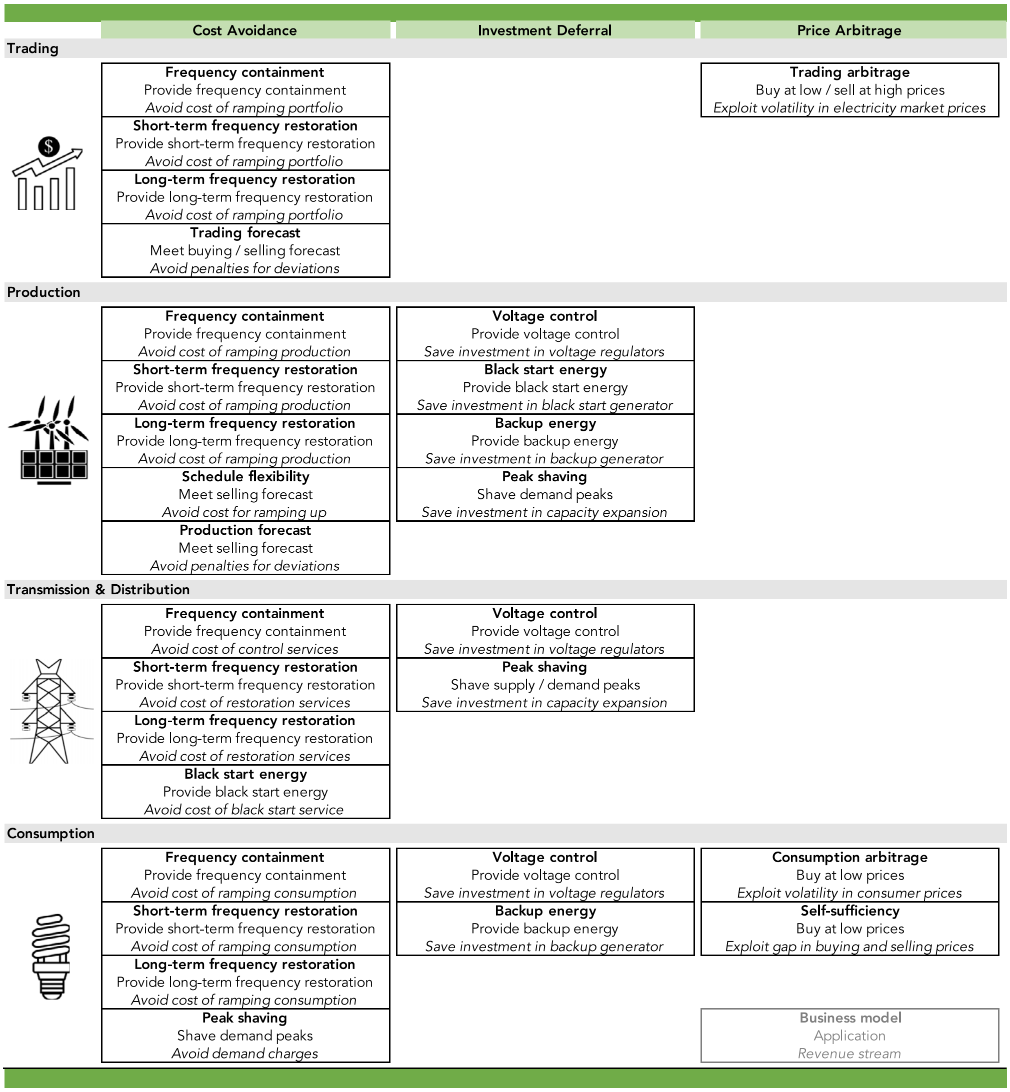
As for the market role, we differentiate between the four main roles in the electricity value chain: trading, production, transmission and distribution (T&D), and consumption (Zucker et al., 2013). In trading, the investor would buy electricity from producers or the market and sell it to consumers or the market. In production, the investor would generate and sell electricity. In T&D, the investor is responsible for the transportation of electricity and the stable operation of the power grid. We aggregate the roles of a transmission and a distribution grid operator, because they appear compatible for the purpose of our study. Finally, an investor in consumption would purchase and consume electricity. We note that our concept of market roles is not equivalent to common descriptions of individual persons or organizations participating in the electricity market, even though they may coincide. An investor, that is, a person or an organization, can obtain multiple different roles or assume one role several times, for instance, by bundling consumers or producers, similar to how utilities and aggregators operate today. The decision to invest in a storage facility remains specific to each market role. Regulation is also often tied to market roles, potentially prohibiting the pursuit of distinct business models, as we review in the Discussion. T&D operators, for instance, are in many jurisdictions not allowed to provide frequency containment or restoration services.

For revenue streams, we delineate three different types, each comprising a range of distinct revenue streams. With "price arbitrage," we refer to the utilization of differentials in electricity prices across markets at one time or across time within one market. The former can result from transaction costs, such as taxes and fees, which add to the market price when electricity is purchased rather than sold. For instance, residential consumers are typically paid less for electricity they produce with their solar panels and feed into the grid than they pay for sourcing electricity from the grid. The latter price differential results from fluctuations in electricity prices over time. "Cost avoidance" describes savings in operating costs, such as the ramping of power generation capacity, or penalties for, say, deviations in electricity production. Cost avoidance also includes savings in operating costs for electricity consumers, such as the ramping of a production facility for an industrial consumer or simply the inconvenience of changing behavior for a residential consumer. Finally, "investment deferral" refers to savings resulting from not investing in alternative generation or grid capacity.

Figure 1 depicts 28 distinct business models for energy storage technologies that we identify based on the combination of the three parameters described above. Each business model, represented by a box in Figure 1, applies storage to solve a particular problem and to generate a distinct revenue stream for a specific market role. We determine the business models to be both mutually exclusive and collectively exhaustive. The former means that the business models are distinct from each other. The latter describes that we seek to record all observable and conceivable business models for a modern power system, recognizing that the identified set may change in the future.

Each of the three parameters is useful to systematically differentiate investment opportunities for energy storage in terms of applicable business models. The application as the central element defines what a storage facility would do in a business model. The application parameter is especially relevant if separate business models exhibit the same market role and the same revenue stream, such as for the business models we named (in bold letters in Figure 1) *Frequency containment, Short-term frequency restoration,* and *Long-term frequency restoration.*

Market roles are crucial for business models where the same application applies to several roles and generates the same revenue stream. All three frequency-related applications help the four market roles avoid costs. Market participants in trading, production, or consumption avoid the respective costs of ramping their portfolio, production, or consumption. Operators of a T&D grid would avoid costs of the control/restoration services offered by other market participants, provided they are allowed to do so by regulation. If an investor, that is a person or an organization, wants to provide one or more frequency-related applications simply for the price paid for this service, the investor would effectively pursue the business model *Trading arbitrage.* As the names suggest, *Trading/Consumption arbitrage* apply to trading and consumption, where energy storage enables the respective investor to sell at high prices and/or buy at low prices to take advantage of temporal fluctuations in electricity market prices. A version of price arbitrage may intuitively be assumed to also apply to producers, but they would then effectively act as traders and pursue the business model *Trading arbitrage.*



	Cost Avoidance	Investment Deferral	Price Arbitrage
Trading			
	Frequency containment Provide frequency containment *Avoid cost of ramping portfolio*		**Trading arbitrage** Buy at low / sell at high prices *Exploit volatility in electricity market prices*
	Short-term frequency restoration Provide short-term frequency restoration *Avoid cost of ramping portfolio*		
	Long-term frequency restoration Provide long-term frequency restoration *Avoid cost of ramping portfolio*		
	Trading forecast Meet buying / selling forecast *Avoid penalties for deviations*		
Production			
	Frequency containment Provide frequency containment *Avoid cost of ramping production*	**Voltage control** Provide voltage control *Save investment in voltage regulators*	
	Short-term frequency restoration Provide short-term frequency restoration *Avoid cost of ramping production*	**Black start energy** Provide black start energy *Save investment in black start generator*	
	Long-term frequency restoration Provide long-term frequency restoration *Avoid cost of ramping production*	**Backup energy** Provide backup energy *Save investment in backup generator*	
	Schedule flexibility Meet selling forecast *Avoid cost for ramping up*	**Peak shaving** Shave demand peaks *Save investment in capacity expansion*	
	Production forecast Meet selling forecast *Avoid penalties for deviations*		
Transmission & Distribution			
	Frequency containment Provide frequency containment *Avoid cost of control services*	**Voltage control** Provide voltage control *Save investment in voltage regulators*	
	Short-term frequency restoration Provide short-term frequency restoration *Avoid cost of restoration services*	**Peak shaving** Shave supply / demand peaks *Save investment in capacity expansion*	
	Long-term frequency restoration Provide long-term frequency restoration *Avoid cost of restoration services*		
	Black start energy Provide black start energy *Avoid cost of black start service*		
Consumption			
	Frequency containment Provide frequency containment *Avoid cost of ramping consumption*	**Voltage control** Provide voltage control *Save investment in voltage regulators*	**Consumption arbitrage** Buy at low prices *Exploit volatility in consumer prices*
	Short-term frequency restoration Provide short-term frequency restoration *Avoid cost of ramping consumption*	**Backup energy** Provide backup energy *Save investment in backup generator*	**Self-sufficiency** Buy at low prices *Exploit gap in buying and selling prices*
	Long-term frequency restoration Provide long-term frequency restoration *Avoid cost of ramping consumption*		
	Peak shaving Shave demand peaks *Avoid demand charges*		**Business model** Application *Revenue stream*

Figure 1. Business Models for Energy Storage

Rows display market roles, columns reflect types of revenue streams, and boxes specify the business model around an application.

The business model *Voltage control* can apply to production, T&D, or consumption (Akhil et al., 2013), where the investment in energy storage would save the investment in a voltage regulator. Need for *Backup energy* typically arises at either the level of production or the level of consumption, where an energy storage facility would replace a conventional backup generator commonly based on diesel fuel. The meeting of forecasts applies to traders, who are obliged to purchase or sell a forecasted and contracted amount of electricity (i.e., *Trading forecast)*, as well as to producers, who have to deliver a contracted amount of power (i.e., *Production forecast*). Investment in energy storage can enable them to meet the contracted amount of electricity more accurately and avoid penalties charged for deviations.

Revenue streams are decisive to distinguish business models when one application applies to the same market role multiple times. *Schedule flexibility* and *Production forecast* both help an investor in production to meet a selling forecast. Yet, the former avoids the cost of ramping the production capacity, whereas the latter avoids penalties charged for deviations from the forecast. Similarly, *Consumption arbitrage* and *Self-sufficiency* allow an investor in consumption to buy more electricity during periods of low prices. The former takes advantage of fluctuations in power prices over time, whereas the latter exploits that selling prices for electricity generated with own renewable sources are at times below the buying prices for electricity sourced from the grid.

Market roles and revenue streams may also jointly differentiate business models. *Black start energy* can be pursued by an investor in production, who seeks to defer the investment in a black start generator with an investment in energy storage. Alternatively, the business model can be pursued by an investor in T&D, who seeks to avoid or lower costs of sourcing black start services through a competitive tender if market regulation permits (Denholm et al., 2010). The business model *Peak shaving* can be pursued by an investor in production, T&D, or consumption. For the former two energy storage can defer the investment in production or transmission capacity, whereas for the latter storage lowers charges by utilities for periodical demand peaks.

The literature on energy storage frequently includes ''renewable integration'' or ''generation firming'' as applications for storage (Eyer and Corey, 2010; Zafirakis et al., 2013; Pellow et al., 2020). Yet, for storage combined with a dispatchable power generator, such as a gas turbine, the terms describe *Schedule flexibility* to avoid the cost of ramping the generator up and down. For storage combined with renewables, the terms may describe the meeting of *Production forecasts* to avoid penalties for underproduction. Alternatively, the terms may describe *Trading arbitrage* if storage is installed to take advantage of excess production from wind and solar power sources, which can without storage be shut down at negligible cost. Similarly, the term ''long-term storage'' is reflected in the business models *Trading arbitrage*, *Black start energy*, *Backup energy*, or *Self-sufficiency*, depending on the actual implementation of the storage facility.

Investors can pursue multiple business models with a single storage capacity if market regulation permits. Applicable examples for business models that are frequently combined include the combination of *Frequency containment* with *Frequency restoration*, the combination of *Consumption arbitrage* with *Self-sufficiency*, or the combination of *Frequency containment* with *Trading arbitrage* (Stephan et al., 2016; Berrada et al., 2017; Yu and Foggo, 2017).

Profitability

We now use the preceding framework to systematically review recent studies on energy storage regarding their findings on the profitability of potential investments. Our goal is to give an overview of the profitability of business models for energy storage, showing which business model performed by a certain technology has been examined and identified as rather profitable or unprofitable. We refrain from attempting to compare specific investments, which depend on regionally distinct economic, operational, and regulatory parameters.

Before providing the profitability overview, we first examine whether a technology has the capability to serve a business model. Each business model entails specific operational requirements through its application, but each technology can only operate within distinct ranges. We match the business models identified above to a set of technologies via overlaps in operational parameters that we extracted from technical reports as well as previous reviews and technology-specific articles in peer-reviewed journals (Schoenung, 2001; EPRI, 2003, 2010; Barton and Infield, 2004; Eyer et al., 2004; McDowall, 2006; Sayer et al., 2007; Chen et al., 2009; Eyer and Corey, 2010; Beaudin et al., 2010; Connolly, 2010; Denholm et al., 2010; Akhil et al., 2013; Koohi-Kamali et al., 2013; Del Rosso and Eckroad, 2014; Palizban and Kauhaniemi, 2016; Eid et al., 2016). We examine the parameters power capacity, discharge duration, and response time. These reflect non-negotiable requirements for business models. Details on the matching and the used parameters are provided in the Supplemental Information.

We focus on a set of common and commercially available technologies for energy storage (see Table S1 for details). These technologies convert electrical energy to various forms of storable energy. For mechanical storage, we focus on flywheels, pumped hydro, and compressed air energy storage (CAES). Thermal storage refers to molten salt technology. Chemical storage technologies include supercapacitors, batteries, and hydrogen. Of the various battery technologies available, we focus on lithium-ion batteries, which have recently exhibited the most rapid cost declines and technological advances (Schmidt et al., 2017).

In comparison, flywheels have a medium power capacity and can respond spontaneously but commonly discharge in less than an hour. Pumped hydro and CAES currently offer the largest power capacity and a

	Business Model	Mechanical									Thermal			Chemical								
		Flywheel			Pumped Hydro			CAES			Thermal			Supercapacit.			Batteries			Hydrogen		
	Trading	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	🟩	⬜	-	🟨	🟩	1	🟨	🟩	1	🟨	⬜	-	🟨	⬜	-	🟩	🟥	1	🟨	⬜	-
	Short-term frequency restoration	🟩	⬜	-	🟨	🟩	1	🟨	🟨	2	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Long-term frequency restoration	🟩	⬜	-	🟩	🟩	1	🟨	🟨	2	🟩	⬜	-	🟨	⬜	-	🟩	🟥	1	🟩	⬜	-
	Trading forecast	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟥	⬜	-	🟩	⬜	-	🟩	⬜	-
PA	Trading arbitrage	🟨	🟥	2	🟩	🟨	9	🟩	🟨	12	🟩	⬜	-	🟨	🟥	2	🟩	🟥	10	🟩	🟥	1
	Production	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	🟩	1	🟨	⬜	-
	Short-term frequency restoration	🟩	🟥	1	🟨	🟨	2	🟨	🟥	1	🟨	⬜	-	🟨	🟥	1	🟩	🟥	1	🟩	⬜	-
	Long-term frequency restoration	🟩	🟥	1	🟩	🟥	1	🟨	🟨	2	🟩	⬜	-	🟨	🟥	1	🟩	🟥	1	🟩	⬜	-
	Production forecast	🟨	⬜	-	🟩	🟥	1	🟩	🟥	3	🟩	⬜	-	🟥	⬜	-	🟩	🟩	1	🟩	⬜	-
	Schedule flexibility	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟩	⬜	-	🟥	⬜	-	🟩	⬜	-	🟩	⬜	-
ID	Voltage control	🟩	⬜	-	🟥	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-
	Backup energy	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟥	⬜	-	🟩	⬜	-	🟩	⬜	-
	Black start energy	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Peak shaving	🟨	⬜	-	🟩	🟩	4	🟩	🟥	1	🟩	⬜	-	🟥	⬜	-	🟩	🟩	1	🟩	⬜	-
	T&D	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	🟩	⬜	-	🟨	⬜	-	🟨	🟨	2	🟨	⬜	-	🟨	⬜	-	🟩	🟥	3	🟨	⬜	-
	Short-term frequency restoration	🟩	⬜	-	🟨	🟥	1	🟨	🟥	3	🟨	⬜	-	🟨	⬜	-	🟩	🟥	3	🟩	⬜	-
	Long-term frequency restoration	🟩	⬜	-	🟩	🟥	1	🟨	🟥	3	🟩	⬜	-	🟨	⬜	-	🟩	🟥	4	🟩	⬜	-
	Black start energy	🟩	⬜	-	🟨	⬜	-	🟨	🟥	1	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
ID	Voltage control	🟩	⬜	-	🟥	🟩	1	🟨	🟩	1	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-
	Peak shaving	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟩	⬜	-	🟥	⬜	-	🟩	🟥	2	🟩	🟥	1
	Consumption	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-
	Short-term frequency restoration	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	🟥	1	🟩	⬜	-
	Long-term frequency restoration	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Peak shaving	🟨	🟩	1	🟨	🟩	1	🟨	🟩	1	🟩	⬜	-	🟨	🟩	1	🟩	🟨	8	🟩	⬜	-
ID	Voltage control	🟩	⬜	-	🟥	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-
	Backup energy	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟥	⬜	-	🟩	🟥	1	🟩	⬜	-
PA	Self-sufficiency	🟨	⬜	-	🟨	🟩	1	🟩	🟩	1	🟩	⬜	-	🟨	⬜	-	🟩	🟥	20	🟩	⬜	-
	Consumption arbitrage	🟨	⬜	-	🟨	🟩	1	🟩	🟩	1	🟩	⬜	-	🟨	⬜	-	🟩	🟥	9	🟩	⬜	-

CA Cost avoidance
ID Investment deferral
PA Price arbitrage

Figure 2. Technology Match and Profitability of Business Models for Energy Storage
The first column (∞) indicates the matching of business models with storage technologies, the second column ($) the profitability, and the third column (#) the number of studies that examine the profitability of a match.

sustained discharge duration but require several minutes to respond as well as appropriate geographic formations. Thermal storage responds within minutes and exhibits a medium power capacity with discharge durations of several hours. Supercapacitors can respond instantly but frequently display the smallest power capacity and discharge duration. Batteries show a medium power capacity range and discharge duration and a short response time. Finally, hydrogen storage can have a relatively large power capacity with a long discharge duration but requires several minutes to respond from a cold start (see Tables S2 and S3 for details).

To depict the quality of a match, we employ a simple traffic light scheme. We consider a match as "green" if the capabilities of a technology overlap with the requirements of a business model in all three characteristics. Alternatively, a match is "yellow" if the parameters overlap in only two characteristics and "red" if they overlap in one or none. This simple scheme only provides a snapshot of the current development but is helpful to quickly grasp the quality of a match.

Figure 2 shows for each technology in the first column the result of this matching. We find that every business model can be served (i.e., green match) by at least one of the commercially available storage technologies and that most business models can even rely on multiple technologies. The matching confirms the widespread preference of batteries and hydrogen in the sense that these technologies can serve almost all business models. Yet, the matching also highlights many green matches for other technologies, such as flywheels and thermal storage. CAES is green for only a few matches, such as *Self-sufficiency* and *Consumption arbitrage*, noting that the market role also includes large industrial consumers. Pumped hydro is often either too slow to respond (e.g., for frequency containment and short-term restoration) or too large in its minimal power capacity (e.g., for consumption). Supercapacitors often fall below the required power capacity and discharge duration. The matching assumes that business models in Figure 2, which entail the same application, have the same range of operational requirements.

For economic opportunities, we aim at extracting a similar map. Our review is based on 143 profitability estimates for individual business model and technology combinations. The estimates result from a systematic literature review of articles in peer-reviewed journals from 2013 to 2019 with selected keywords. Since our objective is to identify general opportunities for storage rather than evaluating distinct investment cases, we aggregate estimates across valuation methodologies and geographical parameters. To ensure quality, applicability, and comparability, we narrowed down the set of 489 articles initially retrieved from the review to 47 focus papers with several criteria, including the ranking of the journal, the rigor of the analysis, as well as the comparability of the research setting (see the Supplemental Information for details).

We again use the traffic light scheme to illustrate profitability estimates of each match. We consider a match as green if the share of estimates that finds the match to be profitable is above 75%. Similarly, a match is yellow if the share of profitable estimates is between 50% and 75% and red if the share is below 50%. In addition, we label a match as "gray" if our review returned no estimate for the match. More optimistic color thresholds would not change the overall conclusion. A figure with numerical results is provided in Figure S1 in the Supplemental Information. For a sense of confidence in our findings, we also report the number of profitability estimates for the respective finding. Across all matches, the number of estimates also indicates the distribution of research effort.

Figure 2 shows the result of the profitability review in the second and third column of each technology. The main finding is that examined business models for energy storage given in the set of technologies are largely found to be unprofitable or ambiguous. Our finding is corroborated by both the distribution of profitability labels in Figure 2 (31 red, 8 yellow, and 18 green) and the average number of estimates per profitability label (2.7 for red, 4.9 for yellow, and 1.2 for green). This conclusion applies in particular to batteries (13 of 17 examined business models are red), which opposes the image of a promising complement to intermittent renewable power sources. The technology with the highest number of green profitability labels (i.e., 8) is pumped hydro. New installations of pumped hydro, however, are often limited by either the availability of caverns and mountains or public resistance to environmental changes.

Figure 2 also delineates that research on the profitability of energy storage is distributed unevenly across technologies, business models, and matches. The by far most examined technologies are batteries (68 profitability estimates), CAES (37), and pumped hydro (26). The most prominent business models are frequency containment (44 profitability estimates for *Frequency containment* and *Short*- and *Long-term frequency restoration* combined), *Trading arbitrage* (36), and *Self-sufficiency* (22). The most examined matches also result from this pool and comprise batteries for *Self-sufficiency* (20 profitability estimates), and pumped hydro and CAES for *Trading arbitrage* (9 and 12 estimates). This distribution unveils a considerable potential for future research (71 of 139 gray labels have a green label for the technology match), in particular, for flywheels used for ancillary services and thermal and hydrogen storage in general.

Although academic analysis finds that business models for energy storage are largely unprofitable, annual deployment of storage capacity is globally on the rise (IEA, 2020). One reason may be generous subsidy support and non-financial drivers like a first-mover advantage (Wood Mackenzie, 2019). Another reason may be the time lag between the publication of academic articles and the market development. Some storage technologies have exhibited a substantial cost decline in recent years (Kittner et al., 2017; Schmidt et al., 2017; Glenk and Reichelstein, 2019). The cost of battery cells, for instance, decreased from above US$1,100/kWh in 2010 to less than US$156/kWh in 2019 (BNEF, 2019). Repeating our review with papers from 2017 to 2019 only, we find the conclusion to improve markedly, as shown in Figure S2 in the Supplemental Information. Of the 19 examined business models 14 are now green. Batteries contribute 6 green business models, of which 5 have flipped from red to green in comparison with Figure 2. These green business models include *Trading arbitrage, Production forecast,* as well as *Frequency containment/restoration* on a trading and T&D level. The residual green matches comprise pumped hydro and CAES for *Trading Arbitrage, Self-sufficiency,* and *Consumption arbitrage*, as well as pumped hydro for *Short-term restoration* and *Peak shaving* for the production level. Most of the green labels, however, rely on only few studies.

	First Business Model		Second Business Model	Mechanical									Thermal			Chemical								
				Flywheel			Pumped Hydro			CAES			Thermal			Supercapacit.			Batteries			Hydrogen		
	Trading		**Trading**	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Short-term frequency restoration	CA	Long-term frequency restoration	🟩	⬜	-	🟨	🟩	1	🟨	🟨	2	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Short-term frequency restoration	PA	Trading arbitrage	🟨	⬜	-	🟨	🟩	1	🟨	🟨	2	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Long-term frequency restoration		Trading arbitrage	🟨	⬜	-	🟩	🟩	1	🟨	🟨	2	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Trading		**Production**	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
PA	Trading arbitrage	CA	Long-term frequency restoration	🟨	🟥	1	🟩	🟩	1	🟨	🟩	1	🟩	⬜	-	🟨	🟥	1	🟩	🟥	1	🟩	⬜	-
	Trading arbitrage		Production forecast	🟨	⬜	-	🟩	⬜	-	🟩	🟩	2	🟩	⬜	-	🟥	⬜	-	🟩	⬜	-	🟩	⬜	-
	Trading		**T&D**	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
PA	Trading arbitrage	CA	Frequency containment	🟨	⬜	-	🟨	⬜	-	🟨	🟩	2	🟨	⬜	-	🟨	⬜	-	🟩	🟩	1	🟨	⬜	-
	Trading arbitrage		Short-term frequency restoration	🟨	⬜	-	🟨	🟥	1	🟨	🟨	3	🟨	⬜	-	🟨	⬜	-	🟩	🟩	1	🟩	⬜	-
	Trading arbitrage		Long-term frequency restoration	🟨	⬜	-	🟩	🟥	1	🟨	🟨	3	🟩	⬜	-	🟨	⬜	-	🟩	🟨	2	🟩	⬜	-
	Trading		**Consumption**	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
PA	Trading arbitrage	PA	Self-sufficiency	🟨	⬜	-	🟨	🟩	1	🟩	🟩	1	🟩	⬜	-	🟨	⬜	-	🟩	🟥	2	🟩	⬜	-
	T&D		**T&D**	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	CA	Short-term frequency restoration	🟩	⬜	-	🟨	⬜	-	🟨	🟩	2	🟨	⬜	-	🟨	⬜	-	🟩	🟩	2	🟨	⬜	-
	Frequency containment		Long-term frequency restoration	🟩	⬜	-	🟨	⬜	-	🟨	🟩	2	🟨	⬜	-	🟨	⬜	-	🟩	🟩	2	🟨	⬜	-
	Short-term frequency restoration		Long-term frequency restoration	🟩	⬜	-	🟨	🟥	1	🟨	🟨	3	🟨	⬜	-	🟨	⬜	-	🟩	🟩	2	🟩	⬜	-
	Consumption		**Consumption**	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Peak shaving	PA	Self-sufficiency	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	🟩	6	🟩	⬜	-
	Peak shaving		Consumption arbitrage	🟨	🟩	1	🟨	🟩	1	🟨	🟩	1	🟩	⬜	-	🟨	🟩	1	🟩	🟨	3	🟩	⬜	-
PA	Self-sufficiency		Consumption arbitrage	🟨	⬜	-	🟨	🟩	1	🟩	🟩	1	🟩	⬜	-	🟨	⬜	-	🟩	🟥	3	🟩	⬜	-

CA Cost avoidance
ID Investment deferral
PA Price arbitrage

Figure 3. Technology Match and Profitability of Stacked Business Models

The first column (∞) indicates the matching of business models with storage technologies, the second column ($) the profitability, and the third column (#) the number of studies that examine the profitability of a match.

A third reason may be the stacking of business models. Stacking describes the simultaneous serving of two or more business models with the same storage unit (Schmidt et al., 2017). This can allow a storage facility to both diversify its revenue streams and to increase its utilization by bridging idle time in one business model with operation in another. To assess the effect of stacking on profitability, we reviewed the focus papers again and collected the profitability estimates of matches with stacked business models. Figure 3 shows that the stacking of two business models can already improve profitability considerably. Of 39 stacks analyzed in the literature, 23 profitability labels are green, 8 are yellow, and 8 are red. The most frequent stacks are combinations of consumption business models, such as *Self-sufficiency* with *Consumption peak shaving*, combinations of frequency containment/restoration business models with *Trading arbitrage*, or aggregations of multiple frequency containment/restoration business models. The most examined technologies are again CAES (27 profitability estimates), batteries (25), and pumped hydro (10).

Recent deployments of storage capacity confirm the trend for improved investment conditions (U.S. Department of Energy, 2020). For instance, the Imperial Irrigation District in El Centro, California, installed 30 MW of battery storage for *Frequency containment*, *Schedule flexibility*, and *Black start energy* in 2017. The Deepwater Wind in Montauk, New York, built 15 MW of battery storage for *Production forecast* in 2018. The Hornsdale Power Reserve in Jamestown, South Australia, has been using grid-scale battery storage with a capacity of 100 MW for *Frequency containment* and *Peak shaving* since 2017. Nant de Drance in Martigny, Switzerland, is constructing 900 MW of pumped hydro storage for *Peak shaving* and *Production forecast* with a planned start of operations in 2021. A study by RWTH Aaachen has reported more than 120,000 residential PV battery systems in Germany by the end of 2018 with a cumulative capacity of 400 MW used for *Self-sufficiency* and *Consumption arbitrage*. Finally, the HyBalance project located in Hobro, Denmark, installed 2 MW of hydrogen storage for *Frequency restoration* and *Peak shaving* in 2017.

DISCUSSION

Although electricity storage technologies could provide useful flexibility to modern power systems with substantial shares of power generation from intermittent renewables, investment opportunities and their profitability have remained ambiguous. Here we first present a conceptual framework to characterize business models of energy storage and, thereby, systematically differentiate investment opportunities. Our framework identifies 28 distinct business models based on the integrated assessment of an application for storage with the market role of the potential investor and the achievable revenue stream from the storage operation. We then use our framework to match storage technologies with the identified business models and to review findings of previous studies on the profitability of individual matches. Our review shows that a set of commercially available technologies is sufficient to perform all identified business models. We also find that matches appear to have approached a tipping point toward profitability. Yet, this conclusion only holds for matches that either have been examined since 2017 or entail multiple business models. Overall, many feasible matches have been ignored, indicating research gaps that need to be filled for a detailed and conclusive understanding of the profitability of energy storage.

Widespread profitability of storage will also require continued work on incremental improvements in both technological and regulatory parameters of storage. Our focus papers highlight, in particular, the need for a reduction of the overall costs of storage technologies and the removal of revenue barriers in a business model. Since the overall costs of storage installations are largely upfront investment, continued declines in the acquisition cost of storage technology are of paramount importance (Madlener and Latz, 2013; Dufo-López and Bernal-Agustín, 2015; de Sisternes et al., 2016; Kaschub et al., 2016; Yu and Foggo, 2017; Hartmann et al., 2018). Reductions may primarily come from technological advancements, such as the use of cheaper materials, improved component architectures, or economies of scale in manufacturing (Comello and Reichelstein, 2019). An improved round-trip efficiency, cycle capacity, and lifetime can further reduce the overall costs (Madlener and Latz, 2013; Dufo-López and Bernal-Agustín, 2015; Lai and McCulloch, 2017; Yu and Foggo, 2017; Chazarra et al., 2018). These characteristics increase the degree of utilization and reduce the amount of costly capacity required for a storage project.

Revenue gains can result from the creation of innovative support schemes and the removal of regulatory barriers. Such support schemes could ensure effectiveness by using our conceptual framework and its parameters. With the market role as one crucial parameter, multiple vested interests could be addressed. One example of how this could be achieved is the public tender for the later Hornsdale Power Reserve. The tender combined interests of the T&D operator by including a certain capacity that was to be contracted to save investments in capacity expansion and interests of an investor by embracing a trading role to use the remaining capacity for exploitation of volatility of market prices (Australian Energy Market Operator, 2018). The revenue stream parameter allows one to differentiate the type of support mechanisms. Where a profitable application of energy storage requires saving of costs or deferral of investments, direct mechanisms, such as subsidies and rebates, will be effective. For applications dependent on price arbitrage, the existence and access to variable market prices are essential.

Prominent regulatory barriers include limited market access for energy storage (Castagneto Gissey, Dodds and Radcliffe, 2018), bans on stacking business models (Stephan et al., 2016), and regulatory markups on electricity prices (Reuter et al., 2012; Mulder et al., 2013; Bradbury et al., 2014; Khalilpour and Vassallo, 2016; Shafiee et al., 2016; Berrada et al., 2017; Lin and Wu, 2017). The recent FERC Order 841 in the Unites States, for instance, reflects one of the first regulatory changes that entitle storage solutions to participate in wholesale power markets, which they are able to serve from a technical point of view (FERC, 2018). The order opens wholesale markets to smaller actors, compelling system operators to modify access requirements where possible and to include energy storage, for instance, through a smaller minimum capacity size.

Another area for policy reform is the stacking of business models, which is still banned in many jurisdictions (Stephan et al., 2016). The California Public Utilities Commission (CPUC) took a first step and published a framework of eleven rules prescribing when energy storage is allowed to provide multiple services. The framework delineates which combinations are permitted and how business models should be prioritized (American Public Power Association, 2018). Bolder approaches could include the design of special electricity tariffs for investors in a consumer role that unlock the ability of energy storage to mitigate unexpected demand peaks (*Peak Shaving*) and balance conventional demand patterns (*Consumption Arbitrage*) (Fridgen et al., 2018).

Moreover, regulators could revisit markups on wholesale electricity prices, such as taxes and fees, that may impede storage investments through the curtailment of available revenue streams in a jurisdiction. For instance, before the modification of the Renewable Energy Act in 2017, storage facilities in Germany were considered as final consumers and, consequently, paid all regulatory price markups for the electricity used for charging (EEG, 2017; Glenk and Reichelstein, 2020).

Limitations of the Study

The identified business models are a snapshot of present economic opportunities in the energy sector and could change over the years coming. Especially with regard to future changes within modern power systems, the identified business models may no longer be mutually exclusive and collectively exhaustive. Moreover, we reviewed only a representative sample of the available literature to extract the profitability of business models applicable to modern power systems. Thus, some matches may not have received a profitability validation that reflects their present profitability. We hope, nevertheless, that our approach may be a foundation for future economic analyses and fosters comparability for future findings about economic opportunities of energy storage.

METHODS

All methods can be found in the accompanying Transparent Methods supplemental file.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.isci.2020.101554.

ACKNOWLEDGMENTS

We gratefully acknowledge financial support through the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation)—Project-ID 403041268—TRR 266. This research was also supported by the Joachim Herz Stiftung and the Hanns-Seidel-Stiftung with funds from the Federal Ministry of Education and Research of Germany. Helpful comments were provided by Stefanie Burgahn, Céleste Chevalier, Stefan Reichelstein, Christian Stoll, and two anonymous reviewers. We also thank Henri Humpert for substantial assistance with the data collection and the initial review.

AUTHOR CONTRIBUTIONS

The authors jointly developed the business model framework. F.B. and A.R. led the literature review and data collection. G.G. proposed the research question and led the empirical analysis. All authors contributed substantially to the writing of the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

Akhil, A.A., Huff, G., Currier, A.B., Kaun, B.C., Rastler, D.M., Chen, S.B., Cotter, A.L., Bradshaw, D.T., and Gauntlett, W.D. (2013). DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA (Sandia National Laboratories).

Albertus, P., Manser, J.S., and Litzelman, S. (2020). Long-duration electricity storage applications, economics, and technologies. Joule *4* (1), 21–32.

American Public Power Association (2018). California PUC Adopts Multi-Use Energy Storage Rules. https://www.publicpower.org/periodical/article/california-puc-adopts-multi-use-energy-storage-rules.

Argyrou, M.C., Christodoulides, P., and Kalogirou, S.A. (2018). Energy storage for electricity generation and related processes: technologies appraisal and grid scale applications. Renew. Sustainable Energy Rev. *94*, 804–821.

Australian Energy Market Operator (2018). Initial Operation of the Hornsdale Power Reserve Battery Energy Storage System. https://doi.org/10.1111/fcre.12333.

Barton, J.P., and Infield, D.G. (2004). Energy storage and its use with intermittent renewable energy. IEEE Trans. Energy Convers. *19* (2), 441–448.

Beaudin, M., Zareipour, H., Schellenberglabe, A., and Rosehart, W. (2010). Energy storage for mitigating the variability of renewable electricity sources: an updated review. Energy Sustainable Develop. *14* (4), 302–314, https://doi.org/10.1016/j.esd.2010.09.007.

Berrada, A., Loudiyi, K., and Zorkani, I. (2017). Profitability, risk, and financial modeling of energy storage in residential and large scale applications. Energy *119*, 94–109.

Blanc, L.E., Kundu, D., and Nazar, L.F. (2020). Scientific challenges for the implementation of Zn-ion batteries. Joule *4* (4), 771–799.

BNEF (2019). Battery Pack Prices Fall as Market Ramps up with Market Average at $156/kWh in 2019. https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/.

Bradbury, K., Pratson, L., and Patiño-Echeverri, D. (2014). Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets. Appl. Energy *114*, 512–519.

Braff, W.A., Mueller, J.M., and Trancik, J.E. (2016). Value of storage technologies for wind and solar energy. Nat. Clim. Change *6* (10), 964–969.

Castagneto Gissey, G., Dodds, P.E., and Radcliffe, J. (2018). Market and regulatory barriers to electrical energy storage innovation. Renew. Sustainable Energy Rev. *82*, 781–790.

Castillo, A., and Gayme, D.F. (2014). Grid-scale energy storage applications in renewable energy integration: a survey. Energy Convers. Management *87*, 885–894.

Chazarra, M., Pérez-Díaz, J.I., García-González, J., and Praus, R. (2018). Economic viability of pumped-storage power plants participating in the secondary regulation service. Appl. Energy *216*, 224–233, https://doi.org/10.1016/j.apenergy.2018.02.025.

Chen, H., Cong, T.N., Yang, W., Tan, C., Li, Y., and Ding, Y. (2009). Progress in electrical energy storage system: a critical review. Prog. Nat. Sci. *19* (3), 291–312, https://doi.org/10.1016/j.pnsc.2008.07.014.

Comello, S., and Reichelstein, S. (2019). The emergence of cost effective battery storage. Nat. Commun. *10* (1), 2038.

Comello, S., Reichelstein, S., and Sahoo, A. (2018). The road ahead for solar PV power. Renew. Sustainable Energy Rev. *92*, 744–756.

Connolly, D. (2010). A Review of Energy Storage Technologies.

Davies, D.M., Verde, M.G., Mnyshenko, O., Chen, Y.R., Rajeev, R., Meng, M.S., and Elliott, G. (2019). Combined economic and technological evaluation of battery energy storage for grid applications. Nat. Energy *4* (1), 42–50, https://doi.org/10.1038/s41560-018-0290-1.

Davis, S.J., Lewis, N.S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I.L., Benson, S.M., Bradley, T., Brouwer, J., Chiang, Y.M., et al. (2018). Net-zero emissions energy systems. Science *360*, eaas9793, https://doi.org/10.1126/science.aas9793.

de Sisternes, F.J., Jenkins, J.D., and Botterud, A. (2016). The value of energy storage in decarbonizing the electricity sector. Appl. Energy *175*, 368–379.

Del Rosso, A.D., and Eckroad, S.W. (2014). Energy storage for relief of transmission congestion. IEEE Trans. Smart Grid *5* (2), 1138–1146.

Denholm, P., Ela, E., Kirby, B., and Milligan, M. (2010). The Role of Energy Storage with Renewable Electricity Generation (National Renewable Energy Laboratory).

Dufo-López, R., and Bernal-Agustín, J.L. (2015). Techno-economic analysis of grid-connected battery storage. Energy Convers. Management *91*, 394–404.

EEG (2017). Gesetz für den Ausbau erneuerbarer Energien.

Eid, C., Codani, P., Perez, Y., Reneses, J., and Hakvoort, R. (2016). Managing electric flexibility from Distributed Energy Resources: a review of incentives for market design. Renew. Sustainable Energy Rev. *64*, 237–247, https://doi.org/10.1016/j.rser.2016.06.008.

EPRI (2003). EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications.

EPRI (2010). Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs and Benefits.

Eyer, J., and Corey, G. (2010). Energy Storage for the Electricity Grid : Benefits and Market Potential Assessment Guide, SAND2010-0815.

Eyer, J.M., Iannucci, J.J., and Corey, G.P. (2004). Energy Storage Benefits and Market Analysis Handbook - A Study for the DOE Energy Storage Systems Program.

Fares, R.L., and Webber, M.E. (2017). The impacts of storing solar energy in the home to reduce reliance on the utility. Nat. Energy *2* (2), 17001.

FERC (2018). FERC Order 841.

Ferrara, M., Chiang, Y.-M., and Deutch, J. (2019). Demonstrating electricity generation from renewables and storage. Joule, 1–4, https://doi.org/10.1016/j.joule.2019.08.007.

Fridgen, G., Kahlen, M., Ketter, W., Rieger, A., and Thimmel, M. (2018). One rate does not fit all: an empirical analysis of electricity tariffs for residential microgrids. Appl. Energy *210*, 800–814.

Fuchs, G., Lunz, B., Leuthold, M., and Sauer, D.U. (2012). Technology Overview on Electricity Storage - Overview on the Potential and on the Deployment Perspectives of Energy Storage Technologies (iSETA RWTH Aachen).

Glenk, G., and Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. Nat. Energy *4*, 216–222.

Glenk, G., and Reichelstein, S. (2020). Synergistic value in vertically integrated power-to-gas energy systems. Prod. Operations Management *29* (3), 526–546.

Hartmann, B., Divényi, D., and Vokony, I. (2018). Evaluation of business possibilities of energy storage at commercial and industrial consumers – a case study. Appl. Energy *222*, 59–66.

Hoppmann, J., Volland, J., Schmidt, T., and Hoffmann, V. (2014). The economic viability of battery storage for residential solar photovoltaic systems – A review and a simulation model. Renew. Sustainable Energy Rev. *39*, 1101–1118, https://doi.org/10.1016/j.rser.2014.07.068.

IEA (2020). Tracking Energy Integration. https://www.iea.org/reports/tracking-energy-integration/energy-storage.

Kaschub, T., Jochem, P., and Fichtner, W. (2016). Solar energy storage in German households: profitability, load changes and flexibility. Energy Policy *98*, 520–532.

Khalilpour, K.R., and Vassallo, A. (2016). Technoeconomic parametric analysis of PV-battery systems. Renew. Energy *97*, 757–768.

Kittner, N., Lill, F., and Kammen, D.M. (2017). Energy storage deployment and innovation for the clean energy transition. Nat. Energy *2* (9), 1–6.

Koohi-Kamali, S., Tyagi, V.V., Rahim, N.A., Panwar, N.L., and Mokhlis, H. (2013). Emergence of energy storage technologies as the solution for reliable operation of smart power systems: a review. Renew. Sustainable Energy Rev. *25*, 135–165, https://doi.org/10.1016/j.rser.2013.03.056.

Kousksou, T., Bruel, P., Jamil, A., El Rhafiki, T., and Zeraouli, Y. (2014). Energy storage: applications and challenges. Solar Energy Mater. Solar Cells *120*, 59–80, https://doi.org/10.1016/j.solmat.2013.08.015.

Lai, C.S., and McCulloch, M.D. (2017). Levelized cost of electricity for solar photovoltaic and electrical energy storage. Appl. Energy *190*, 191–203.

Lin, B., and Wu, W. (2017). Economic viability of battery energy storage and grid strategy: a special case of China electricity market. Energy *124*, 423–434.

Madlener, R., and Latz, J. (2013). Economics of centralized and decentralized compressed air energy storage for enhanced grid integration of wind power. Appl. Energy *101*, 299–309.

Massa, L., Tucci, C.L., and Afuah, A. (2017). A critical assessment of business model research. Acad. Management Ann. *11* (1), 73–104.

McDowall, J. (2006). Integrating energy storage with wind power in weak electricity grids. J. Power Sourc. *162*, 959–964.

Metz, D., and Saraiva, J.T. (2018). Simultaneous co-integration of multiple electrical storage applications in a consumer setting. Energy *143*, 202–211.

Mulder, G., Six, D., Claessens, B., Broes, T., Omar, N., and Mierlo, J.V. (2013). The dimensioning of PV-battery systems depending on the incentive and selling price conditions. Appl. Energy *111*, 1126–1135, https://doi.org/10.1016/j.apenergy.2013.03.059.

Olauson, J., Ayob, M.N., Bergkvist, M., Carpman, N., Castellucci, V., Goude, A., Lingfors, D., Waters, R., and Widén, J. (2016). Net load variability in the Nordic countries with a highly or fully renewable power system. Nat. Energy *1*, 1–14, https://doi.org/10.1038/nenergy.2016.175.

Palizban, O., and Kauhaniemi, K. (2016). Energy storage systems in modern grids - matrix of technologies and applications. J. Energy Storage *6*, 248–259.

Pellow, M.A., Ambrose, H., Mulvaney, D., Betita, R., and Shaw, S. (2020). Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: end-of-life options and other issues. Sustainable Materials and Technologies *23*, https://doi.org/10.1016/j.susmat.2019.e00120.

Reuter, W.H., Fuss, S., Szolgayová, J., and Obersteiner, M. (2012). Investment in wind power and pumped storage in a real options model. Renew. Sustainable Energy Rev. *16* (4), 2242–2248, https://doi.org/10.1016/j.rser.2012.01.025.

Richter, M. (2013). Business model innovation for sustainable energy: German utilities and renewable energy. Energy Policy *62*, 1226–1237.

Sayer, J.H., Eyer, J., and Brown, R.S. (2007). Guide to Estimating Benefits and Market Potential for Electricity Storage in New York.

Schmidt, O., Hawkes, A., Gambhir, A., and Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. Nat. Energy *6*, 17110, https://doi.org/10.1038/nenergy.2017.110.

Schoenung, S. (2001). Characteristics and Technologies for Long- vs. Short-Term Energy Storage. https://doi.org/10.2172/780306.

Shafiee, S., Zamani-Dehkordi, P., Zareipour, H., and Knight, A.M. (2016). Economic assessment of a price-maker energy storage facility in the Alberta electricity market. Energy *111*, 537–547, https://doi.org/10.1016/j.energy.2016.05.086.

Stephan, A., Battke, B., Beuse, M.D., Clausdeinken, J.H., and Schmidt, T. (2016). Limiting the public cost of stationary battery deployment by combining applications. Nat. Energy *1* (7), 16079, https://doi.org/10.1038/nenergy.2016.79.

Sutherland, B.R. (2019). Charging up stationary energy storage. Joule *3* (1), 1–3.

The European Commission (2017). Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing. Official J. Eur. Union *2017*, 312/6–312/53.

U.S. Department of Energy (2020). DOE Global Energy Storage Database. https://www.sandia.gov/ess-ssl/global-energy-storage-database/.

van der Stelt, S., AlSkaif, T., and van Sark, W. (2018). Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances. Appl. Energy *209*, 266–276.

Wood, Mackenzie (2019). US Energy Storage Monitor 2018 Year in Review.

Yu, N., and Foggo, B. (2017). Stochastic valuation of energy storage in wholesale power markets. Energy Econ. *64*, 177–185.

Zafirakis, D., Chalvatzis, K.J., Baiocchi, G., and Daskalakis, G. (2013). Modeling of financial incentives for investments in energy storage systems that promote the large-scale integration of wind energy. Appl. Energy *105*, 138–154, https://doi.org/10.1016/j.apenergy.2012.11.073.

Zucker, A., Hinchliffe, T., and Spisto, A. (2013). Assessing Storage Value in Electricity Markets a Literature Review. https://doi.org/10.2790/89242.

iScience, Volume *23*

Supplemental Information

Business Models and Profitability of Energy Storage

Felix Baumgarte, Gunther Glenk, and Alexander Rieger

Transparent Methods

Matching

To match the described business models with a set of commercially available technologies, we look for an overlap in three operational parameters. Power capacity indicates the peak amount of power (in megawatt) a storage device should be able to absorb or provide at any time. Discharge duration (in hours) denotes the time a storage device should provide electricity at peak power capacity and effectively reflects the amount of stored energy. Response time (in seconds) measures the speed with which a storage technology should react to a charging or discharging request.

Some studies also use the cycle capacity, round-trip efficiency, and self-discharge of storage technologies for matching (Aneke and Wang, 2016; Palizban and Kauhaniemi, 2016). Cycle capacity describes the number of full charging and discharging cycles a storage device can perform until it reaches a specified degradation level. Round-trip efficiency defines the amount of energy recoverable from a storage device relative to the amount initially absorbed. Self-discharge labels the amount of charged energy lost during inactivity. Contrary to these studies, we discourage the use of these parameters for the matching of functionality, as in serving a business model they rather affect a technology's cost efficiency.

For each combination, the capability of a technology T must match with the requirements of a business model BM. First, the storage technology's power capacity range must overlap with the required power capacity range of the business model. In particular, the storage technology must have a maximum power capacity C_T^{max} greater than or equal to the minimum required capacity C_{BM}^{min} of the respective business model. At the same time, the technology's minimal possible storage capacity C_T^{min} must be less than or equal to the maximum required capacity C_{BM}^{max} of the business model:

$$C_T^{max} \geq C_{BM}^{min} \qquad \text{and} \qquad C_T^{min} \leq C_{BM}^{max} \tag{1}$$

The storage technology must also have a maximum discharge duration D_T^{max} that is longer than or equal to the shortest required discharge duration D_{BM}^{min} of the business model:

$$D_T^{max} \geq D_{BM}^{min} \tag{2}$$

Further, the storage technology must have a minimum response time R_T^{min} that is smaller than or equal to the slowest required response time R_{BM}^{max} of the business model:

$$R_T^{min} \leq R_{BM}^{max} \tag{3}$$

Our analysis focuses on a set of commercially available technologies. Supplemental Table S1 provides a list and description of these technologies. Supplemental Tables S2-S3 outline the operational requirements of business models and operational capabilities of storage technologies used for the matching. The parameters were collected from various sources as indicated for each parameter.

Profitability Review

We systematically reviewed scientific articles in peer-reviewed journals and frequently cited grey literature such as reports by reputable agencies, consultancies, and industry analysts. We found the initial set of articles by searching the databases ScienceDirect, IEEE, EBSCOhost, and Google Scholar with a combination of various keywords including specific energy storage technologies (e.g. "flywheel"), business models (e.g. "frequency containment"), general keywords (e.g. "energy storage"), and keywords related to profitability assessment (e.g. "valuation"). We then traced citations in the set of articles backward or citations to the set of articles forward to maximize the coverage of relevant articles.

We retrieved 489 articles and reports, which we narrowed down through the application of several criteria to control for quality and fit. We first excluded all reports as well as articles published before 2012 or in journals with a rank below 1.0 in the Scimago Journal and Country Rank to ensure quality and timeliness of our analysis. We then filtered the remaining papers for individual and stacked profitability analyses based on their title and abstract. This resulted in a set of 47 focus papers, most of which were published in the last three years.

For every focus paper we first extracted general information (i.e. technology and market setting), as well as the applications and business models that were analyzed. We then examined all focus papers regarding their findings on single and stacked profitability and the assumptions made. Finally, we collected what the authors have identified as the main opportunities and barriers for the emergence of profitable business models for storage, including their suggestions for policy changes. A table of our focus papers is provided in Supplemental Table S4. Supplemental Figure S1 shows the result of the technology matching and the profitability review in numbers, on which the colored labels of Figure 2 of the main body are based. Supplemental Figure S2 shows the result of the profitability review based on studies from 2017-2019.

Supplemental Tables

Supplemental Table S1, Related to Figure 2 and Figure 3.

List and description of energy storage technologies.

Technology	Storage medium	Charging and discharging process
Flywheels	Rotating mass	Charging: an electric motor accelerates a rotatable mass that is held in place by magnets to minimize friction. Discharging: the rotating mass drives a generator.
Pumped hydro	Water reservoir at higher altitude	Charging: water is pumped uphill into a reservoir. Discharging: water flows back down and drives hydroelectric turbines.
CAES	Compressed air in tank or cavern	Charging: ambient air is pumped into storage tanks or cavernous rock formations. Discharging: pressurized air is released through a turbine.
Thermal	Heat stored as molten salt	Charging: heat pump heats tank with a solid salt that, once molten, is stored in a hot tank. Discharging: the molten, hot salt drives a steam turbine and flows back to the cold tank.
Supercapacitors	Separated charges	Charging: electric current creates a double layer of oppositely charged molecules of electrolyte on either side of an insulator. Discharging: electrons flow from one side of the insulator to the other and balance the charge gradient.
Batteries	Separated ions	Charging: electric current ionizes neutral molecules, which move to oppositely charged electrodes separated by an insulator. Discharging: electrons flow from the negative to the positive electrode, de-ionize molecules and balance the charge gradient.
Hydrogen	Hydrogen in tank, cavern or pipeline	Charging: electric current splits water molecules into oxygen and hydrogen. Discharging: hydrogen is burnt in gas turbines or recombined with oxygen in a (reversible) fuel cell.

Supplemental Table S2, Related to Figure 2 and Figure 3.

Operational requirements of business models.

Business Model	**Power capacity [MW]**			**Discharge duration [h]**			**Response time [sec]**		
	min	max	source	min	max	source	min	max	source
Trading									
Frequency containment	1	100	[1]	0.25	1	[3]	0.001	15	[4]
Short-term frequency restoration	1	100	[1]	0.25	1	[3]	10	30	[3]
Long-term frequency restoration	1	100	[1]	1	2	[5]	30	60	[3]
Trading forecast	1	10	-	2	2	[6]	60	600	[9]
Trading arbitrage	40	400	[2]	1	10	[4]	60	3600	[10]
Production									
Frequency containment	1	100	[1]	0.25	1	[3]	0.001	15	[4]
Short-term frequency restoration	1	100	[1]	0.25	1	[3]	10	30	[3]
Long-term frequency restoration	1	100	[1]	1	2	[5]	30	60	[3]
Production forecast	1	100	[3]	2	4	[5]	60	3600	[10]
Schedule flexibility	1	500	[4]	2	8	[7]	60	1800	[4]
Voltage control	0.1	10	[4]	0.25	1	[5]	0.001	0.1	[4]
Backup energy	1	10	[4]	4	10	[1]	10	60	[4]
Black start energy	5	50	[3]	1	5	[8]	1	60	[10]
Peak shaving	1	500	[3]	4	8	[5]	60	1800	[4]
T&D									
Frequency containment	1	100	[3]	0.25	1	[3]	0.001	15	[4]
Short-term frequency restoration	1	100	[3]	0.25	1	[3]	10	30	[3]
Long-term frequency restoration	1	100	[1]	1	2	[5]	30	60	[3]
Black start energy	5	50	[3]	1	5	[1]	1	60	[10]
Voltage control	0.1	10	[4]	0.25	1	[5]	0.001	0.1	[4]
Peak shaving	1	100	[3]	2	6	[1]	60	3600	[10]
Consumption									
Frequency containment	1	100	[1]	0.25	1	[3]	0.001	15	[4]
Short-term frequency restoration	1	100	[1]	0.25	1	[3]	10	30	[3]
Long-term frequency restoration	1	100	[1]	1	2	[5]	30	60	[3]
Peak shaving	0.05	10	[5]	5	11	[5]	1	60	[11]
Voltage control	0.1	10	[4]	0.003	0.25	[5]	0.01	0.2	[4]
Backup energy	1	10	[4]	4	10	[1]	10	60	[4]
Self-sufficiency	0.001	1	[3]	2	6	[1]	60	3600	[10]
Consumption arbitrage	0.05	10	[5]	5	11	[5]	60	3600	[10]

Sources:

[1] (EPRI, 2010)
[2] (Koohi-Kamali *et al.*, 2013)
[3] (Akhil *et al.*, 2013)
[4] (Palizban and Kauhaniemi, 2016)
[5] (Eyer and Corey, 2010)
[6] (Barton and Infield, 2004)
[7] (Sayer, Eyer and Brown, 2007)
[8] (Eyer, Iannucci and Corey, 2004)
[9] (Beaudin *et al.*, 2010)
[10] (Denholm *et al.*, 2010)
[11] (Schoenung, 2001)

Supplemental Table S3, Related to Figure 2 and Figure 3.

Operational capabilities of storage technologies.

Technology	**Power capacity [MW]**			**Discharge duration [h]**			**Response time [sec]**		
	min	max	source	min	max	source	min	max	source
Flywheels	0.001	20	[1]	0.1	1	[6]	0.01	1	[2]
Pumped hydro	100	5000	[2]	6	24	[1]	60	180	[2]
CAES	1	400	[3]	1	24	[2]	180	600	[7]
Thermal	0.1	300	[3]	1	24	[3]	60	600	[1]
Supercapacitors	0.001	0.3	[4]	0.0027	1	[2]	0.001	0.1	[1]
Batteries	0.1	50	[2]	0.1	5	[3]	0.003	0.1	[7]
Hydrogen	0.1	50	[5]	1	24	[2]	30	300	[8]

Sources:

[1] (Palizban and Kauhaniemi, 2016)
[2] (Gallo *et al.*, 2016)
[3] (Ferreira *et al.*, 2013)
[4] (Chen *et al.*, 2009)
[5] (Aneke and Wang, 2016)
[6] (Cho, Jeong and Kim, 2015)
[7] (Fuchs *et al.*, 2012)
[8] (Bertuccioli *et al.*, 2014)

Supplemental Table S4, Related to Figure 2 and Figure 3. List and analysis of the focus papers.

Articles	Technology	Application	Business Model	Profitability	Stacking
(Arabkoohsar *et al.*, 2015)	CAES	Meet selling forecast (production); Sell at high prices (trading); Buy at low prices (trading);	Production forecast; Trading arbitrage	yes	yes
(Battke and Schmidt, 2015)	Batteries	Buy at low prices (consumption); Sell at high prices (trading); Buy at low prices (trading); Provide frequency containment (T&D); Provide short-term frequency restoration (T&D); Provide long-term frequency restoration (T&D); Provide backup energy (consumption)	Consumption arbitrage; Trading arbitrage; Frequency containment; Short-term frequency restoration; Long-term frequency restoration; Backup energy; Self-sufficiency	no	No
(Berrada and Loudiyi, 2016)	Pumped Hydro; Batteries; Flywheel; Supercaps; CAES	Sell at high prices (trading); Buy at low prices (trading); Provide frequency containment (production); Provide short-term frequency restoration (production); Provide long-term frequency restoration (production)	Trading arbitrage; Frequency containment; Short-term frequency restoration; Long-term frequency restoration	no	yes
(Berrada, Loudiyi and Zorkani, 2016)	Pumped Hydro; CAES; Gravity Storage	Provide frequency containment (trading); Provide short-term frequency restoration (trading); Provide long-term frequency restoration (trading); Provide voltage control (T&D); Sell at high prices (trading); Buy at low prices (trading)	Frequency containment; Short-term frequency restoration; Long-term frequency restoration; Voltage control; Trading arbitrage	yes	yes
(Berrada, Loudiyi and Zorkani, 2017)	Gravity Storage; CAES; Pumped Hydro; Batteries	Buy at low prices (consumption); Sell at high prices (trading); Buy at low prices (trading);	Consumption arbitrage; Trading arbitrage; Self-sufficiency	yes	yes
(Bortolini, Gamberi and Graziani, 2014)	Batteries	Buy at low prices (consumption)	Self-sufficiency	yes	no
(Bradbury, Pratson and Patiño-Echeverri, 2014)	Batteries; Supercaps; Pumped Hydro; CAES; Flywheel	Sell at high prices (trading); Buy at low prices (trading)	Trading arbitrage	yes	no
(Braff, Mueller and Trancik, 2016)	CAES; Pumped Hydro; Batteries	Sell at high prices (trading); Buy at low prices (trading)	Trading arbitrage	yes	no
(Broneske and Wozabal, 2016)	Batteries	Provide short-term frequency restoration (consumption)	Short-term frequency restoration	no	no
(Chazarra *et al.*, 2018)	Pumped Hydro	Provide short-term frequency restoration (production); Shave demand peaks (production)	Short-term frequency restoration; Peak shaving	yes	yes
(Comello and Reichelstein, 2019)	Batteries	Buy at low prices (consumption)	Self-sufficiency	yes	no
(Das, Krishnan and McCalley, 2015)	CAES	Provide frequency containment (T&D); Provide short-term frequency restoration (T&D); Provide long-term frequency restoration (T&D); Provide black start energy (T&D); Meet selling forecast (production); Sell at high prices (trading); Buy at low prices (trading)	Frequency containment; Short-term frequency restoration; Long-term frequency restoration; Production forecast; Black start energy; Trading arbitrage	no	yes
(de Bosio and Verda, 2015)	CAES	Buy at low prices (trading); Sell at high prices (trading); Provide frequency containment (T&D); Provide short-term frequency restoration (T&D); Provide long-term frequency restoration (T&D)	Frequency containment; Short-term frequency restoration; Long-term frequency restoration; Trading arbitrage	yes	yes
(de Sisternes, Jenkins and Botterud, 2016)	Pumped Hydro; Batteries	Shave demand peaks (production);	Generation capacity reserve;	yes	no

(Dufo-López and Bernal-Agustín, 2015)	Batteries	Buy at low prices (consumption)	Consumption arbitrage	no	no
(Fares and Webber, 2017)	Batteries	Buy at low prices (consumption)	Self-sufficiency	no	no
(Fleer *et al.*, 2018)	Batteries	Provide frequency containment (trading)	Frequency containment	no	no
(Gough *et al.*, 2017)	Batteries	Provide long-term frequency restoration (trading); Buy at low prices (consumption); Shave demand peaks (consumption)	Long-term frequency restoration; Consumption arbitrage; Self-sufficiency; Peak shaving	yes	yes
(Härtel *et al.*, 2016)	Batteries; Hydrogen	Shave supply / demand peaks (T&D)	Peak shaving	no	no
(Hartmann, Divényi and Vokony, 2018)	Batteries	Shave demand peaks (consumption); Buy at low prices (consumption)	Peak shaving; Consumption arbitrage	no	no
(Hoppmann *et al.*, 2014)	Batteries	Buy at low prices (consumption)	Self-sufficiency	yes	no
(Johnston *et al.*, 2015)	Batteries	Provide frequency containment (production)	Frequency containment	yes	no
(Kaschub, Jochem and Fichtner, 2016)	Batteries	Buy at low prices (consumption); Shave demand peaks (consumption)	Self-sufficiency; Peak shaving	yes	yes
(Khalilpour and Vassallo, 2016)	Batteries	Buy at low prices (consumption)	Self-sufficiency; Consumption arbitrage	no	no
(Kloess and Zach, 2014)	Pumped Hydro; CAES; Hydrogen; Methane	Sell at high prices (trading); Buy at low prices (trading)	Trading arbitrage	no	no
(Lai and McCulloch, 2017)	Batteries	Buy at low prices (consumption)	Self-sufficiency	no	no
(Lin and Wu, 2017)	Batteries	Sell at high prices (trading); Buy at low prices (trading)	Trading arbitrage	yes	no
(Linssen, Stenzel and Fleer, 2017)	Batteries	Buy at low prices (consumption)	Self-sufficiency	yes	no
(Locatelli, Palerma and Mancini, 2015)	Pumped Hydro; CAES	Provide short-term frequency restoration (T&D); Provide long-term frequency restoration (T&D); Sell at high prices (trading); Buy at low prices (trading)	Short-term frequency restoration; Long-term frequency restoration; Trading arbitrage	no	yes
(Loisel, 2012)	CAES	Provide short-term frequency restoration (trading); Provide long-term frequency restoration (trading); Sell at high prices (trading); Buy at low prices (trading)	Frequency Control; Trading arbitrage	no	yes
(Lombardi and Schwabe, 2017)	Batteries	Meet selling forecast (production); Shave demand peaks (consumption); Buy at low prices (consumption)	Production forecast; Peak shaving; Self-sufficiency	yes	yes
(Madlener and Latz, 2013)	CAES	Provide long-term frequency restoration (production); Sell at high prices (trading); Buy at low prices (trading)	Frequency control; Trading arbitrage	yes	yes
(McHenry, 2012)	Batteries	Buy at low prices (consumption)	Self-sufficiency	no	no
(Merei *et al.*, 2016)	Batteries	Buy at low prices (consumption)	Self-sufficiency	no	no
(Mulder *et al.*, 2013)	Batteries	Buy at low prices (consumption)	Self-sufficiency	yes	no
(Papaefthymiou and Papathanassiou, 2014)	Pumped Hydro	Sell at high prices (trading); Buy at low prices (trading); Shave demand peaks (production)	Trading arbitrage; Peak shaving	yes	yes
(Parra and Patel, 2016)	Batteries	Buy at low prices (consumption); Shave demand peaks (consumption)	Self-sufficiency; Peak shaving	no	yes
(Parra *et al.*, 2017)	Batteries	Shave demand peaks (consumption); Buy at low prices (consumption)	Self-sufficiency; Peak shaving; Consumption arbitrage	no	yes
(Reuter *et al.*, 2012)	Pumped Hydro	Sell at high prices (trading); Buy at low prices (trading)	Trading arbitrage	no	no
(Rudolf and Papastergiou, 2013)	Batteries	Sell at high prices (trading); Buy at low prices (trading)	Trading arbitrage	no	no
(Staffell and Rustomji, 2016)	Batteries	Sell at high prices (trading); Buy at low prices (trading); Provide long-term frequency restoration (T&D)	Trading arbitrage; Long-term frequency restoration	no	yes

(Stephan *et al.*, 2016)	Batteries	Provide frequency containment (T&D); Provide short-term frequency restoration (T&D); Provide long-term frequency restoration (T&D); Shave supply / demand peaks (T&D); Shave demand peaks (consumption); Buy at low prices (consumption)	Frequency containment; Short-term frequency restoration; Long-term frequency restoration; Peak shaving; Peak shaving; Self-sufficiency	no	yes
(van der Stelt, AlSkaif and van Sark, 2018)	Batteries	Buy at low prices (consumption)	Self-sufficiency; Consumption arbitrage	no	no
(Yu and Foggo, 2017)	Batteries	Sell at high prices (trading); Buy at low prices (trading); Provide frequency containment (T&D); Provide short-term frequency restoration (T&D); Provide long-term frequency restoration (T&D)	Trading arbitrage; Frequency containment; Short-term frequency restoration; Long-term frequency restoration	yes	yes
(Zafirakis *et al.*, 2013)	Pumped Hydro; CAES	Meet selling forecast (production); Save generation capacity reserve (production)	Production forecast; Peak shaving	no	yes
(Zheng, Meinrenken and Lackner, 2015)	Batteries; Flywheels; Magnetic Storage; Pumped Hydro; CAES; Capacitors	Shave demand peaks (consumption); Buy at low prices (consumption)	Peak shaving; Consumption arbitrage	yes	yes
(Zucker and Hinchliffe, 2014)	Batteries	Sell at high prices (trading); Buy at low prices (trading); Buy at low prices (consumption)	Trading arbitrage; Self-sufficiency	no	yes

Supplemental Figures

	Business Model	Mechanical									Thermal			Chemical								
		Flywheel			Pumped Hydro			CAES			Thermal			Supercapacit.			Batteries			Hydrogen		
	Trading	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	3	-	-	2	1.0	1	2	1.0	1	2	-	-	2	-	-	3	0.0	1	2	-	-
	Short-term frequency restoration	3	-	-	2	1.0	1	2	0.5	2	2	-	-	2	-	-	3	-	-	3	-	-
	Long-term frequency restoration	3	-	-	3	1.0	1	2	0.5	2	3	-	-	2	-	-	3	0.0	1	3	-	-
	Trading forecast	2	-	-	2	-	-	3	-	-	3	-	-	1	-	-	3	-	-	3	-	-
PA	Trading arbitrage	2	0.0	2	3	0.7	9	3	0.6	12	3	-	-	2	0.0	2	3	0.3	10	3	0.0	1
	Production	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	3	-	-	2	-	-	2	-	-	2	-	-	2	-	-	3	1.0	1	2	-	-
	Short-term frequency restoration	3	0.0	1	2	0.5	2	2	0.0	1	2	-	-	2	0.0	1	3	0.0	1	3	-	-
	Long-term frequency restoration	3	0.0	1	3	0.0	1	2	0.5	2	3	-	-	2	0.0	1	3	0.0	1	3	-	-
	Production forecast	2	-	-	3	0.0	1	3	0.3	3	3	-	-	1	-	-	3	1.0	1	3	-	-
	Schedule flexibility	2	-	-	3	-	-	3	-	-	3	-	-	1	-	-	3	-	-	3	-	-
ID	Voltage control	3	-	-	1	-	-	2	-	-	2	-	-	3	-	-	3	-	-	2	-	-
	Backup energy	2	-	-	2	-	-	2	-	-	3	-	-	1	-	-	3	-	-	3	-	-
	Black start energy	3	-	-	2	-	-	2	-	-	3	-	-	2	-	-	3	-	-	3	-	-
	Peak Shaving	2	-	-	3	0.8	4	3	0.0	1	3	-	-	1	-	-	3	1.0	1	3	-	-
	T&D	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	3	-	-	2	-	-	2	0.5	2	2	-	-	2	-	-	3	0.3	3	2	-	-
	Short-term frequency restoration	3	-	-	2	0.0	1	2	0.3	3	2	-	-	2	-	-	3	0.3	3	3	-	-
	Long-term frequency restoration	3	-	-	3	0.0	1	2	0.3	3	3	-	-	2	-	-	3	0.3	4	3	-	-
	Black start energy	3	-	-	2	-	-	2	0.0	1	3	-	-	2	-	-	3	-	-	3	-	-
ID	Voltage control	3	-	-	1	1.0	1	2	1.0	1	2	-	-	3	-	-	3	-	-	2	-	-
	Peak shaving	2	-	-	3	-	-	3	-	-	3	-	-	1	-	-	3	0.0	2	3	0.0	1
	Consumption	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	3	-	-	2	-	-	2	-	-	2	-	-	2	-	-	3	-	-	2	-	-
	Short-term frequency restoration	3	-	-	2	-	-	2	-	-	2	-	-	2	-	-	3	0.0	1	3	-	-
	Long-term frequency restoration	3	-	-	3	-	-	2	-	-	3	-	-	2	-	-	3	-	-	3	-	-
	Peak shaving	2	1.0	1	2	1.0	1	2	1.0	1	3	-	-	2	1.0	1	3	0.5	8	3	-	-
ID	Voltage control	3	-	-	1	-	-	2	-	-	2	-	-	3	-	-	3	-	-	2	-	-
	Backup energy	2	-	-	2	-	-	2	-	-	3	-	-	1	-	-	3	0.0	1	3	-	-
PA	Self-sufficiency	2	-	-	2	1.0	1	3	1.0	1	3	-	-	2	-	-	3	0.4	20	3	-	-
	Consumption arbitrage	2	-	-	2	1.0	1	3	1.0	1	3	-	-	2	-	-	3	0.2	9	3	-	-

CA	Cost avoidance	ID	Investment deferral	PA	Price arbitrage

Supplemental Figure S1, Related to Figure 2. Technology match and profitability of business models for energy storage. The first column (∞) indicates the matching of business models with storage technologies, the second column ($) the profitability and the third column (#) the number of studies that examine the profitability of a match.

	Business Model	Mechanical									Thermal			Chemical								
		Flywheel			Pumped Hydro			CAES			Thermal			Supercapacit.			Batteries			Hydrogen		
	Trading	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	🟧	1	🟨	⬜	-
	Short-term frequency restoration	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Long-term frequency restoration	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	🟩	1	🟩	⬜	-
	Trading forecast	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟧	⬜	-	🟩	⬜	-	🟩	⬜	-
PA	Trading arbitrage	🟨	⬜	-	🟩	🟩	1	🟩	🟩	1	🟩	⬜	-	🟨	⬜	-	🟩	🟩	3	🟩	⬜	-
	Production	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-
	Short-term frequency restoration	🟩	⬜	-	🟨	🟩	1	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Long-term frequency restoration	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Production forecast	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟩	⬜	-	🟧	⬜	-	🟩	🟩	1	🟩	⬜	-
	Schedule flexibility	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟩	⬜	-	🟧	⬜	-	🟩	⬜	-	🟩	⬜	-
ID	Voltage control	🟩	⬜	-	🟧	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-
	Backup energy	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟧	⬜	-	🟩	⬜	-	🟩	⬜	-
	Black start energy	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Peak shaving	🟨	⬜	-	🟩	🟩	1	🟩	⬜	-	🟩	⬜	-	🟧	⬜	-	🟩	⬜	-	🟩	⬜	-
	T&D	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	🟩	1	🟨	⬜	-
	Short-term frequency restoration	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	🟩	1	🟩	⬜	-
	Long-term frequency restoration	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	🟩	1	🟩	⬜	-
	Black start energy	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
ID	Voltage control	🟩	⬜	-	🟧	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-
	Peak shaving	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟩	⬜	-	🟧	⬜	-	🟩	⬜	-	🟩	⬜	-
	Consumption	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#	∞	$	#
CA	Frequency containment	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-
	Short-term frequency restoration	🟩	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	🟧	1	🟩	⬜	-
	Long-term frequency restoration	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-
	Peak shaving	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟨	⬜	-	🟩	🟨	4	🟩	⬜	-
ID	Voltage control	🟩	⬜	-	🟧	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟩	⬜	-	🟨	⬜	-
	Backup energy	🟨	⬜	-	🟨	⬜	-	🟨	⬜	-	🟩	⬜	-	🟧	⬜	-	🟩	⬜	-	🟩	⬜	-
PA	Self-sufficiency	🟨	⬜	-	🟨	🟩	1	🟩	🟩	1	🟩	⬜	-	🟨	⬜	-	🟩	🟨	8	🟩	⬜	-
	Consumption arbitrage	🟨	⬜	-	🟨	🟩	1	🟩	🟩	1	🟩	⬜	-	🟨	⬜	-	🟩	🟧	5	🟩	⬜	-

CA Cost avoidance   ID Investment deferral   PA Price arbitrage

Supplemental Figure S2, Related to Figure 2. Profitability of business models for energy storage (2017-2019). The first column (∞) indicates the matching of business models with storage technologies, the second column ($) the profitability and the third column (#) the number of studies that examine the profitability of a match.

References

Akhil, A. A. *et al.* (2013) *DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA*. doi: SAND2013-5131.

Aneke, M. and Wang, M. (2016) 'Energy storage technologies and real life applications – A state of the art review', *Applied Energy*. Elsevier Ltd, 179, pp. 350–377. doi: 10.1016/j.apenergy.2016.06.097.

Arabkoohsar, A. *et al.* (2015) 'Thermo-economic analysis and sizing of a PV plant equipped with a compressed air energy storage system', *Renewable Energy*. Elsevier Ltd, 83, pp. 491–509. doi: 10.1016/j.renene.2015.05.005.

Barton, J. P. and Infield, D. G. (2004) 'Energy Storage and Its Use With Intermittent Renewable Energy', *IEEE Transactions on Energy Conversion*, 19(2), pp. 441–448. doi: 10.1109/TEC.2003.822305.

Battke, B. and Schmidt, T. S. (2015) 'Cost-efficient demand-pull policies for multi-purpose technologies - The case of stationary electricity storage', *Applied Energy*, 155, pp. 334–348. doi: 10.1016/j.apenergy.2015.06.010.

Beaudin, M. *et al.* (2010) 'Energy storage for mitigating the variability of renewable electricity sources: An updated review', *Energy for Sustainable Development*, 14(4), pp. 302–314. doi: http://dx.doi.org/10.1016/j.esd.2010.09.007.

Berrada, A. and Loudiyi, K. (2016) 'Operation, sizing, and economic evaluation of storage for solar and wind power plants', *Renewable and Sustainable Energy Reviews*. Elsevier, 59, pp. 1117–1129. doi: 10.1016/j.rser.2016.01.048.

Berrada, A., Loudiyi, K. and Zorkani, I. (2016) 'Valuation of energy storage in energy and regulation markets', *Energy*. Elsevier Ltd, 115, pp. 1109–1118. doi: 10.1016/j.energy.2016.09.093.

Berrada, A., Loudiyi, K. and Zorkani, I. (2017) 'Profitability, risk, and financial modeling of energy storage in residential and large scale applications', *Energy*, 119, pp. 94–109. doi: 10.1016/j.energy.2016.12.066.

Bertuccioli, L. *et al.* (2014) *Study on development of water electrolysis in the EU*, *Fuel Cells and hydrogen Joint Undertaking*.

Bortolini, M., Gamberi, M. and Graziani, A. (2014) 'Technical and economic design of photovoltaic and battery energy storage system', *Energy Conversion and Management*. Elsevier Ltd, 86, pp. 81–92. doi: 10.1016/j.enconman.2014.04.089.

de Bosio, F. and Verda, V. (2015) 'Thermoeconomic analysis of a Compressed Air Energy Storage (CAES) system integrated with a wind power plant in the framework of the IPEX Market', *Applied Energy*. Elsevier Ltd, 152, pp. 173–182. doi: 10.1016/j.apenergy.2015.01.052.

Bradbury, K., Pratson, L. and Patiño-Echeverri, D. (2014) 'Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets', *Applied Energy*. Elsevier Ltd, 114, pp. 512–519. doi: 10.1016/j.apenergy.2013.10.010.

Braff, W. A., Mueller, J. M. and Trancik, J. E. (2016) 'Value of storage technologies for wind and solar energy', *Nature Climate Change*, 6(10), pp. 964–969. doi: 10.1038/NCLIMATE3045.

Broneske, G. and Wozabal, D. (2016) 'How Do Contract Parameters Influence the Economics of Vehicle-to-Grid?', *Manufacturing & Service Operations Management*. INFORMS, 19(1), pp. 1–34. doi: 10.1287/msom.2016.0601.

Chazarra, M. *et al.* (2018) 'Economic viability of pumped-storage power plants participating in the secondary regulation service', *Applied Energy*. Elsevier, 216(October 2017), pp. 224–233. doi: 10.1016/j.apenergy.2018.02.025.

Chen, H. *et al.* (2009) 'Progress in electrical energy storage system: A critical review', *Progress in Natural Science*. National Natural Science Foundation of China and Chinese Academy of Sciences, 19(3), pp. 291–312. doi: 10.1016/j.pnsc.2008.07.014.

Cho, J., Jeong, S. and Kim, Y. (2015) 'Commercial and research battery technologies for electrical energy storage applications', *Progress in Energy and Combustion Science*. Elsevier Ltd, 48, pp. 84–101. doi:

10.1016/j.pecs.2015.01.002.

Comello, S. and Reichelstein, S. (2019) 'The emergence of cost effective battery storage', *Nature Communications*. Springer US, 10(1), p. 2038. doi: 10.1038/s41467-019-09988-z.

Das, T., Krishnan, V. and McCalley, J. D. (2015) 'Assessing the benefits and economics of bulk energy storage technologies in the power grid', *Applied Energy*. Elsevier Ltd, 139, pp. 104–118. doi: 10.1016/j.apenergy.2014.11.017.

Denholm, P. *et al.* (2010) *The role of energy storage with renewable electricity generation*.

Dufo-López, R. and Bernal-Agustín, J. L. (2015) 'Techno-economic analysis of grid-connected battery storage', *Energy Conversion and Management*, 91, pp. 394–404. doi: 10.1016/j.enconman.2014.12.038.

EPRI (2010) *Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs and Benefits*.

Eyer, J. and Corey, G. (2010) *Energy Storage for the Electricity Grid : Benefits and Market Potential Assessment Guide*. doi: SAND2010-0815.

Eyer, J. M., Iannucci, J. J. and Corey, G. P. (2004) *Energy Storage Benefits and Market Analysis Handbook - A Study for the DOE Energy Storage Systems Program*.

Fares, R. L. and Webber, M. E. (2017) 'The impacts of storing solar energy in the home to reduce reliance on the utility', *Nature Energy*, 2(2), p. 17001. doi: 10.1038/nenergy.2017.1.

Ferreira, H. L. *et al.* (2013) 'Characterisation of electrical energy storage technologies', *Energy*. Elsevier Ltd, 53, pp. 288–298. doi: 10.1016/j.energy.2013.02.037.

Fleer, J. *et al.* (2018) 'Techno-economic evaluation of battery energy storage systems on the primary control reserve market under consideration of price trends and bidding strategies', *Journal of Energy Storage*. Elsevier Ltd, 17, pp. 345–356. doi: 10.1016/j.est.2018.03.008.

Fuchs, G. *et al.* (2012) *Technology Overview on Electricity Storage - Overview on the potential and on the deployment perspectives of energy storage technologies*.

Gallo, A. B. *et al.* (2016) 'Energy storage in the energy transition context: A technology review', *Renewable and Sustainable Energy Reviews*, 65, pp. 800–822. doi: 10.1016/j.rser.2016.07.028.

Gough, R. *et al.* (2017) 'Vehicle-to-grid feasibility: A techno-economic analysis of EV-based energy storage', *Applied Energy*. Elsevier Ltd, 192, pp. 12–23. doi: 10.1016/j.apenergy.2017.01.102.

Härtel, P. *et al.* (2016) 'Cost assessment of storage options in a region with a high share of network congestions', *Journal of Energy Storage*, 8, pp. 358–367. doi: 10.1016/j.est.2016.05.010.

Hartmann, B., Divényi, D. and Vokony, I. (2018) 'Evaluation of business possibilities of energy storage at commercial and industrial consumers – A case study', *Applied Energy*. Elsevier, 222(March), pp. 59–66. doi: 10.1016/j.apenergy.2018.04.005.

Hoppmann, J. *et al.* (2014) 'The economic viability of battery storage for residential solar photovoltaic systems -- A review and a simulation model', *Renewable and Sustainable Energy Reviews*, 39, pp. 1101–1118. doi: 10.1016/j.rser.2014.07.068.

Johnston, L. *et al.* (2015) 'Methodology for the economic optimisation of energy storage systems for frequency support in wind power plants', *Applied Energy*. Elsevier Ltd, 137, pp. 660–669. doi: 10.1016/j.apenergy.2014.09.031.

Kaschub, T., Jochem, P. and Fichtner, W. (2016) 'Solar energy storage in German households: profitability, load changes and flexibility', *Energy Policy*, 98, pp. 520–532. doi: 10.1016/j.enpol.2016.09.017.

Khalilpour, K. R. and Vassallo, A. (2016) 'Technoeconomic parametric analysis of PV-battery systems', *Renewable Energy*. Elsevier Ltd, 97, pp. 757–768. doi: 10.1016/j.renene.2016.06.010.

Kloess, M. and Zach, K. (2014) 'Bulk electricity storage technologies for load-leveling operation – An economic assessment for the Austrian and German power market', *International Journal of Electrical Power & Energy Systems*, 59, pp. 111–122. doi: http://dx.doi.org/10.1016/j.ijepes.2014.02.002.

Koohi-Kamali, S. *et al.* (2013) 'Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review', *Renewable and Sustainable Energy Reviews*, 25, pp. 135–165. doi: 10.1016/j.rser.2013.03.056.

Lai, C. S. and McCulloch, M. D. (2017) 'Levelized cost of electricity for solar photovoltaic and electrical energy storage', *Applied Energy*. Elsevier Ltd, 190, pp. 191–203. doi: 10.1016/j.apenergy.2016.12.153.

Lin, B. and Wu, W. (2017) 'Economic viability of battery energy storage and grid strategy: A special case of China electricity market', *Energy*. Elsevier Ltd, 124, pp. 423–434. doi: 10.1016/j.energy.2017.02.086.

Linssen, J., Stenzel, P. and Fleer, J. (2017) 'Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles', *Applied Energy*. Elsevier Ltd, 185(2017), pp. 2019–2025. doi: 10.1016/j.apenergy.2015.11.088.

Locatelli, G., Palerma, E. and Mancini, M. (2015) 'Assessing the economics of large Energy Storage Plants with an optimisation methodology', *Energy*. Elsevier Ltd, 83, pp. 15–28. doi: 10.1016/j.energy.2015.01.050.

Loisel, R. (2012) 'Power system flexibility with electricity storage technologies: A technical-economic assessment of a large-scale storage facility', *International Journal of Electrical Power and Energy Systems*. Elsevier Ltd, 42(1), pp. 542–552. doi: 10.1016/j.ijepes.2012.04.058.

Lombardi, P. and Schwabe, F. (2017) 'Sharing economy as a new business model for energy storage systems', *Applied Energy*. Elsevier Ltd, 188, pp. 485–496. doi: 10.1016/j.apenergy.2016.12.016.

Madlener, R. and Latz, J. (2013) 'Economics of centralized and decentralized compressed air energy storage for enhanced grid integration of wind power', *Applied Energy*, 101, pp. 299–309. doi: http://dx.doi.org/10.1016/j.apenergy.2011.09.033.

McHenry, M. P. (2012) 'Are small-scale grid-connected photovoltaic systems a cost-effective policy for lowering electricity bills and reducing carbon emissions? A technical, economic, and carbon emission analysis', *Energy Policy*. Elsevier, 45, pp. 64–72. doi: 10.1016/j.enpol.2012.01.036.

Merei, G. *et al.* (2016) 'Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications', *Applied Energy*. Elsevier Ltd, 168, pp. 171–178. doi: 10.1016/j.apenergy.2016.01.083.

Mulder, G. *et al.* (2013) 'The dimensioning of PV-battery systems depending on the incentive and selling price conditions', *Applied Energy*. Elsevier Ltd, 111, pp. 1126–1135. doi: 10.1016/j.apenergy.2013.03.059.

Palizban, O. and Kauhaniemi, K. (2016) 'Energy storage systems in modern grids - Matrix of technologies and applications', *Journal of Energy Storage*. Elsevier Ltd, 6, pp. 248–259.

Papaefthymiou, S. V. and Papathanassiou, S. A. (2014) 'Optimum sizing of wind-pumped-storage hybrid power stations inisland systems', *Renewable Energy*. Elsevier Ltd, 64, pp. 187–196. doi: 10.1016/j.renene.2013.10.047.

Parra, D. *et al.* (2017) 'Optimum community energy storage for renewable energy and demand load management', *Applied Energy*. Elsevier Ltd, 200, pp. 358–369. doi: 10.1016/j.apenergy.2017.05.048.

Parra, D. and Patel, M. K. (2016) 'Effect of tariffs on the performance and economic benefits of PV-coupled battery systems', *Applied Energy*. Elsevier Ltd, 164(2016), pp. 175–187. doi: 10.1016/j.apenergy.2015.11.037.

Reuter, W. H. *et al.* (2012) 'Investment in wind power and pumped storage in a real options model', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 16(4), pp. 2242–2248. doi: 10.1016/j.rser.2012.01.025.

Rudolf, V. and Papastergiou, K. D. (2013) 'Financial analysis of utility scale photovoltaic plants with battery energy storage', *Energy Policy*, 63, pp. 139–146. doi: http://dx.doi.org/10.1016/j.enpol.2013.08.025.

Sayer, J. H., Eyer, J. and Brown, R. S. (2007) *Guide to Estimating Benefits and Market Potential for Electricity Storage in New York*.

Schoenung, S. (2001) *Characteristics and Technologies for Long- vs. Short-Term Energy Storage*. doi: 10.2172/780306.

de Sisternes, F. J., Jenkins, J. D. and Botterud, A. (2016) 'The value of energy storage in decarbonizing the electricity sector', *Applied Energy*. Elsevier Ltd, 175, pp. 368–379. doi: 10.1016/j.apenergy.2016.05.014.

Staffell, I. and Rustomji, M. (2016) 'Maximising the value of electricity storage', *Journal of Energy Storage*.

Elsevier Ltd, 8, pp. 212–225. doi: 10.1016/j.est.2016.08.010.

van der Stelt, S., AlSkaif, T. and van Sark, W. (2018) 'Techno-economic analysis of household and community energy storage for residential prosumers with smart appliances', *Applied Energy*. Elsevier, 209(October 2017), pp. 266–276. doi: 10.1016/j.apenergy.2017.10.096.

Stephan, A. *et al.* (2016) 'Limiting the public cost of stationary battery deployment by combining applications', *Nature Energy*, 1(7), p. 16079. doi: 10.1038/nenergy.2016.79.

Yu, N. and Foggo, B. (2017) 'Stochastic valuation of energy storage in wholesale power markets', *Energy Economics*. Elsevier B.V., 64, pp. 177–185. doi: 10.1016/j.eneco.2017.03.010.

Zafirakis, D. *et al.* (2013) 'Modeling of financial incentives for investments in energy storage systems that promote the large-scale integration of wind energy', *Applied Energy*, 105, pp. 138–154. doi: 10.1016/j.apenergy.2012.11.073.

Zheng, M., Meinrenken, C. J. and Lackner, K. S. (2015) 'Smart households: Dispatch strategies and economic analysis of distributed energy storage for residential peak shaving', *Applied Energy*. Elsevier Ltd, 147, pp. 246–257. doi: 10.1016/j.apenergy.2015.02.039.

Zucker, A. and Hinchliffe, T. (2014) 'Optimum sizing of PV-attached electricity storage according to power market signals – A case study for Germany and Italy', *Applied Energy*, 127, pp. 141–155. doi: http://dx.doi.org/10.1016/j.apenergy.2014.04.038.