Original Research Article

GREENHOUSE GASES SCIENCE AND TECHNOLOGY

On current and future economics of electricity storage

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Abstract: Increasing electricity generation from variable renewable energy sources, such as wind and solar, has led to interest in additional short-term and long-term storage capacities. The core objective of this paper is to investigate the costs and the future market prospects of different electricity storage options, such as short-term battery storage and long-term storage as pumped hydro storage, as well as hydrogen and methane from power-to-gas conversion technologies. The method of approach is based on a formal economic framework with a dynamic component to derive scenarios up to 2040. The major conclusion is that the economic prospects of storage are not very bright. For all market-based storage technologies it will become hard to compete in the wholesale electricity markets and for decentralized (battery) systems it will be hard to compete with the end users' electricity price. The core problem of virtually all categories of storage are low full-load hours (for market-based systems) and low full charge/discharge cycles (for decentralized batteries). However, any new storage capacity should be constructed only in a coordinated way and if there is a clear sign for new excess production, in this case from variable renewables. In addition, for hydrogen and methane there could be better economic prospects in the transport sector due to both, higher energy price levels as well as a general lack of low carbon fuel alternatives. © 2020 The Authors. *Greenhouse Gases: Science and Technology* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: Costs; economics; variable renewables; pumped hydro storage; power-to-gas; battery storage; technological learning

Introduction

The European Commission has set ambitious targets to increase the share of electricity from renewable energy sources (RES). In recent years, especially electricity generation from variable sources, such as wind and solar, has increased remarkably (see Fig. 1). This figure shows that between 1990 and 2018 in the EU-28 'new' renewables, excluding hydro, grew from less than 1% to about 20%, mainly from wind and photovoltaics (PV). As seen in 2018, wind and PV represent more than half of the 'new' RES. To even out demand and supply from variable RES, energy storage could be a key component in the integration of renewable energy. It could play a crucial role in the transition towards a sustainable energy system by enhancing the reliability, flexibility, and security of European energy supply. The potential position of energy storage in the future energy industry could be particularly significant, given the ambitious targets for the development and deployment of renewable energy. Especially, in Germany calls for large new capacities have been launched.[1,2] Already in 2010, the EU addressed this topic and published a corresponding work on storage.[3]

For a broader market penetration of storage most important is their economic performance. As in

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Received December 31, 2019; revised August 25, 2020; accepted September 1, 2020
Published online at Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ghg.2030

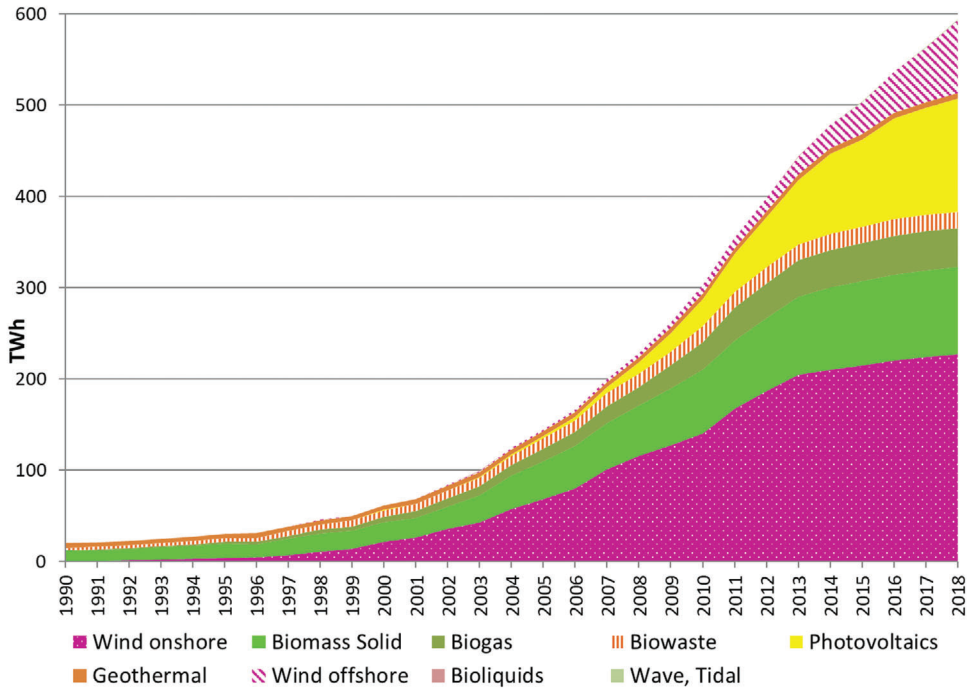

Figure 1. Development of electricity from 'new' renewables (excluding hydro) in EU-28 between 1990 and 2018, in TWh (Source: EUROSTAT, own estimations).

principle many different storage options exist, for example, see Sterner/Stadler,[4] the first economic issue is simply the costs of different types of storage compared to each other to identify the most cost-effective storage option(see, e.g., the analysis in Jülch[5] and Schmidt *et al.*).[6]

From an economist's point-of-view, the economic value of a storage results from an opportunity for arbitrage. The idea is to purchase electricity at times it is cheap and to sell it when the price is high. Hence, this so-called price spread along with the full-load hours (FLH) are the major criteria for economics.[7,9]

Aside from the above-mentioned arbitrage approach, there might also be the opportunity of own use of the stored electricity 'behind the meter', for example in a household, at a farm, in a super market, or in an office building.[8] In this case, storage costs compete with the end users' electricity price and show a positive economic performance if storage costs are lower than electricity costs including all fees and taxes but excluding fixed costs.

As mentioned above, storage is basically one opportunity to balance different generation and demand profiles, see Fig. 2. In this context it is important to note that balancing supply and demand has been a major challenge since the beginning of the electricity system. For example, systems with nuclear power need storage because of the obvious difference between supply and demand profiles. Since variability exists over longer periods (e.g., months, years, see Fig. 3) the need for long-term-electricity storage options is of special interest.[28]

Currently, of specific interest is how to integrate larger amounts of variable RES into the electricity system. The economics of electrical storage for variable renewable energy sources is analyzed by Zerrahn *et al.*[10] They question whether storage will limit the expansion of RES and find that storage needs are considerably lower than often argued in literature. They conclude that electrical storage is unlikely to limit the transition to renewable energy.

In addition, in smart and sustainable energy systems of the future there will be greater opportunities to place storage than in the conventional system of the past.[11,8,36] A major reason is that in future the one-way system of the past will be replaced by kind of a bidirectional system where more flexibility options in the whole electricity system will be used including prosumers and prosumagers as well.[8]

In addition, it has to be stated that storage is not the only flexibility option. It is in competition with grid extension, load management and other options.[8] In

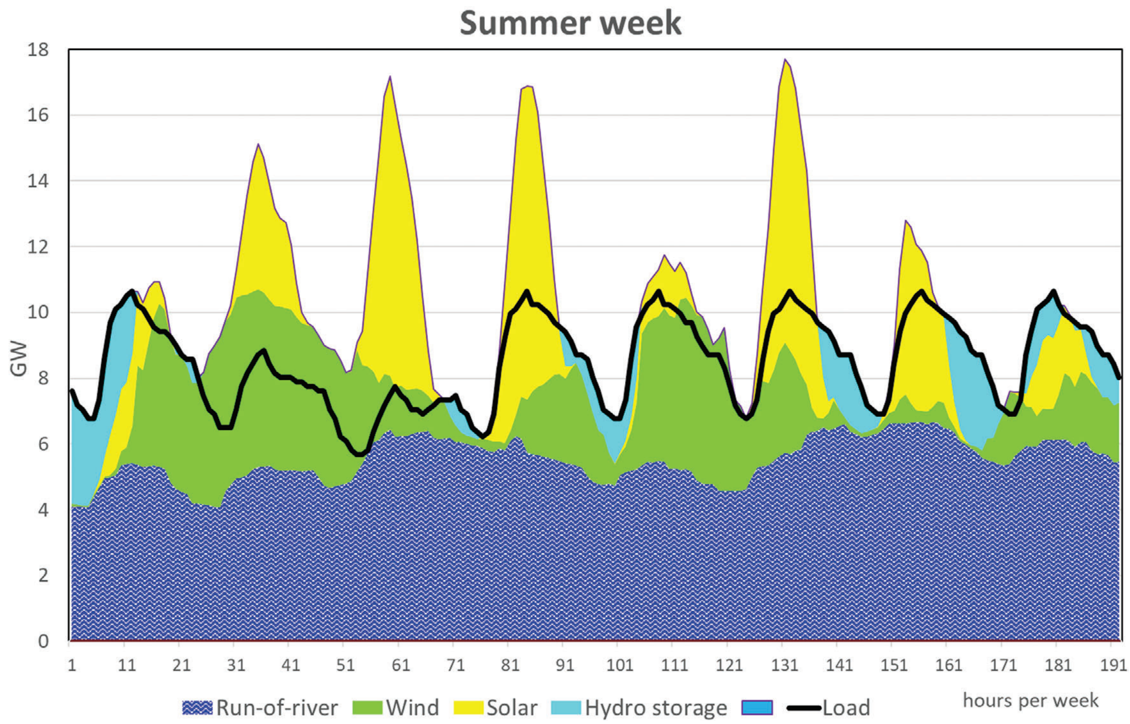

Figure 2. Electricity generation from variable RES and load over a week (modeling example for Austria 2030).

addition, natural gas as storage and natural gas fired turbines for short-term generation are an alternative for flexibility, however, not a fully carbon-free one. Hence, from a long-term economic assessment point of view the possible storage options have to be considered simultaneously with other flexibility options.

Since the beginning of electricity systems, pumped hydro storage has played the largest role in balancing supply and demand. Currently, about 99% of all electricity storage is pumped hydro storage.[8,12,13] Although Deane[12] is already a 10-year old reference, it is important because it provides the best survey on pumped hydro plants in the literature. Fu *et al.*[13] is a more recent work focusing on batteries.

The core objective of this paper is to analyze the costs and to investigate the current and future market prospects of storage for electricity. We consider short-term battery storage as well as long-term storage options, such as pumped hydro storages, and power-to-gas (PtG) technologies, such as hydrogen (H_2) and methane (CH_4), from an economic point of view. A derived goal is to compare the costs of different storage types depending on likely FLH, storage efficiency, and electricity prices.

In general, economic research on electricity storage is still very limited. However, it has increased in recent years.[14–22]

The major new contributions of this paper are as follows: (i) It serves as a primer on the economics of storage; (ii) it provides a very comprehensive survey and literature review; (iii) it considers all different economic perspectives of central and decentralized storage; (iv) it analyzes all relevant storage technologies; (v) in addition, we also analyze the economic future perspectives for these technologies considering the long-term learning effects regarding the investment costs of the investigated technologies.

In this work, we focus on batteries and long-term storage technologies such as pumped hydro storage, as well as PtG-hydrogen and PtG-methane as chemical storage (see Fig. 4). This figure also shows typical storage and discharge times of the storage technologies investigated as a function of installed storage capacity.

This paper is organized as follows. In the next section, the method of approach for calculating the costs of storing electricity is documented. The third section describes the economic analysis. In the fourth section, the future prospects are investigated. Conclusions complete the analysis.

Greenhouse Gas Sci Technol. **10**:1176–1192 (2020); DOI: 10.1002/ghg.2030

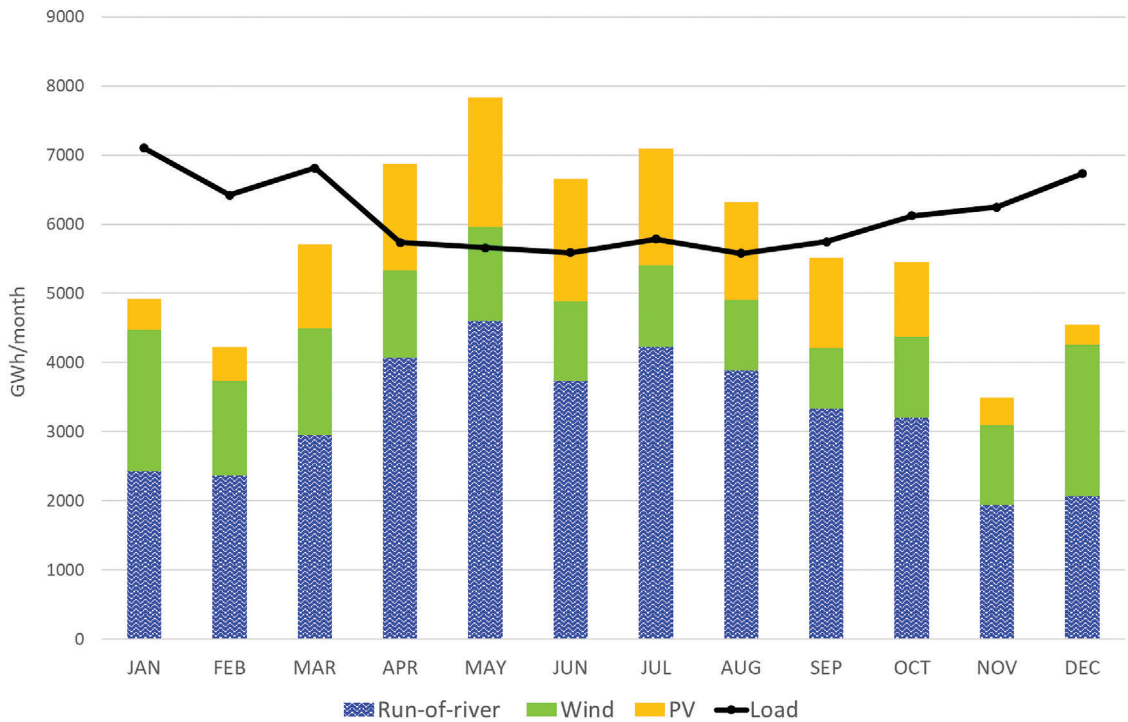

Figure 3. Distribution of electricity generation from variable RES as PV, wind and run-of-river hydro power as well as load (demand) over the months of an average year for Austria.[8]

Method of approach: the costs of storing electricity

Our method of approach is based on cost calculation of different electricity storage technologies.[8,23,25,26] In the following equation, it is described how the storage cost C_{STO} is calculated:

$$C_{STO} = \frac{\frac{IC \times C.R.F + C_{OM}}{T} + C_E}{\eta_{STO}} \quad (€\,kWh^{-1}) \qquad (1)$$

where:

C_{STO} = cost of storing a kWh of electricity in a pumped hydro storage or a battery (€ kWh^{-1}),
IC = investment costs of a storage (€ kW^{-1}),
C.R.F. = capital recovery factor (1 $year^{-1}$),
C_{OM} = operation and maintenance costs (€ $(kW\,year)^{-1}$),
T = full-load hours (hours per year),
C_E = costs of electricity (€ kWh^{-1}),
η_{STO} = efficiency of storage.

Equation (1) shows the cost of storing one kWh. Whether a market-oriented storage is economically feasible decides the so-called price spread in the electricity market and the number of overall operating hours, the FLH. The importance of FLH for the economic feasibility of storage facilities has already been discussed.[8,25–28] Along with the issue of the price spread, the FLHs are the alpha and omega in every discussion on the future prospects of centralized storage as a market-based option from an economic point of view.

Equation (2) shows the definition of the C.R.F. and it is calculated depending on the depreciation time (see Table 2) and the interest rate (assumed 5%).

$$C.R.F. = \frac{z(1+z)^n}{(1+z)^n - 1} \quad (1\ year^{-1}) \qquad (2)$$

where:

n = depreciation time (years),
z = Interest rate (in decimal points, e.g., 0.05).

The total costs of storing electricity for different storage technologies (as of 2018) in new plants or devices and the amounts of capital costs, operation and maintenance (O&M) costs, and energy costs, are depicted in Fig. 5. It can be clearly seen that there is a huge range of total costs – between 0.08 € kWh^{-1} and almost 1 € kWh^{-1} and in addition, quite different shares of capital, energy, and O&M costs. Figure 6 depicts the sensitivity of the capital costs on FLH per

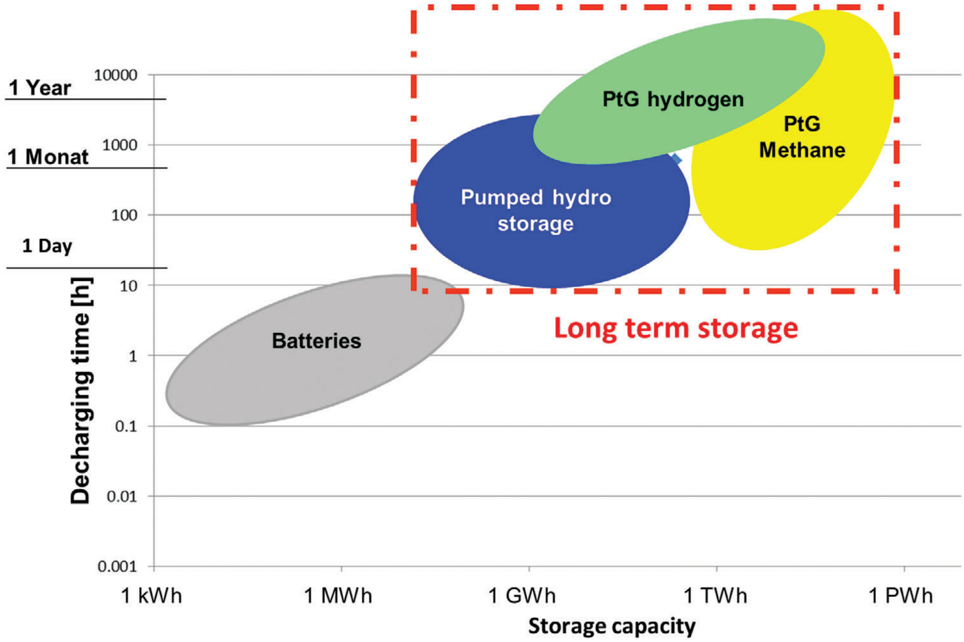

Figure 4. Typical storage times of various storage technologies as a function of installed storage capacity.[8,23,24]

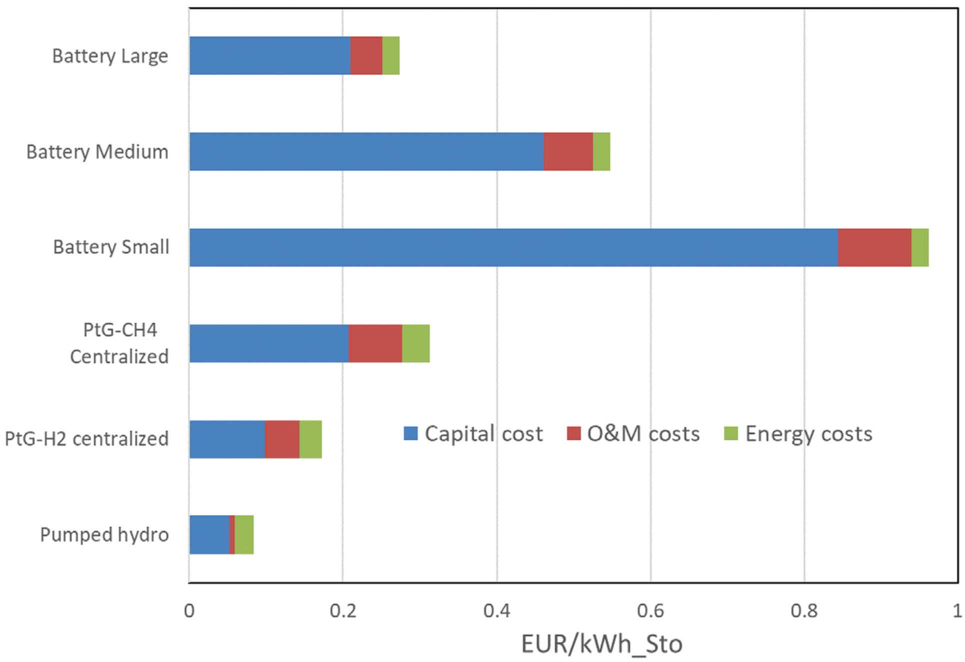

Figure 5. Costs of storing electricity for different technologies (as of 2018) for newly constructed plants including storage efficiency and the corresponding amounts of capital costs, O&M costs, and energy costs.

year. For example, at 500 FLH per year capital costs are four times higher than at 2000 hour year^{-1}. Table 1 provides a summary of the assumptions for the technical parameters used in the following investigations, and Table 2 documents the numbers applied in the economic analysis.

The most important results of our investigations are as follows: the first major problem of the economics of

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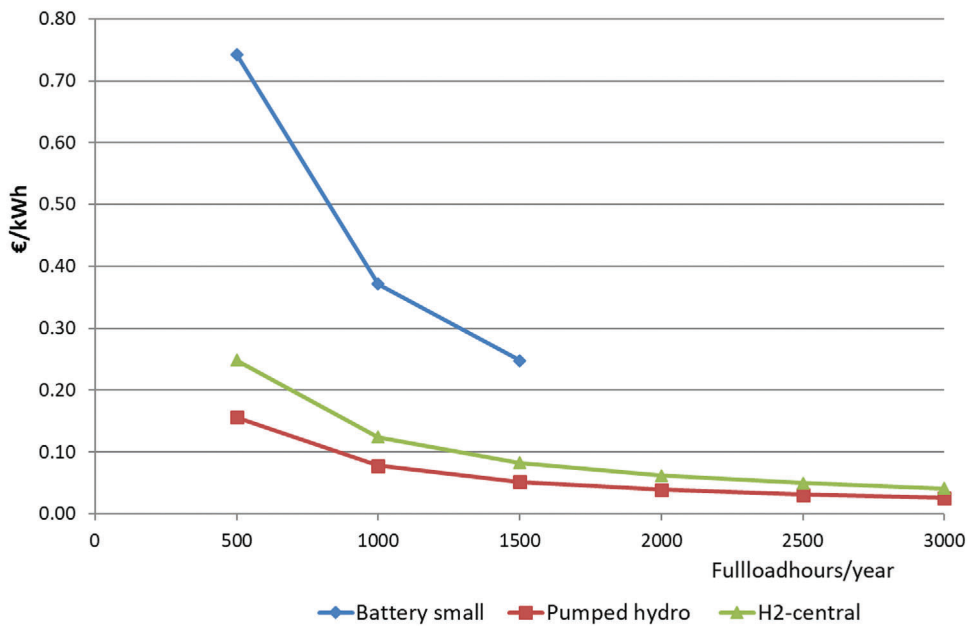

Figure 6. Costs of storing electricity for selected technologies depending on the full-load hours per year.

Table 1. Summary of assumptions for the technical parameters (Source: all numbers are from own investigations, based on the year 2018 for efficiencies).

Type of storage	Capacity (MW)	(kWh)	Efficiency	Full-load hours (hour year^{-1})
PHS	350		0.82	2000
PtG-H2 centralized	10		0.7	2000
PtG-CH4 centralized	10		0.56	2000
Battery small	0.0025	5	0.88	500
Battery medium	0.015	30	0.9	700
Battery large	0.5	1000	0.92	900

storages is low FLH (see Fig. 6). Currently, about 2000 hours per year is considered to be the minimum to operate the storage facilities economically.

As Fig. 6 shows costs at current price spreads of about 0.03–0.06 € kWh^{-1} in the Western European day-ahead markets (range between 2010 and 2020) for 2000 FLH no new plant for any type of storage is economically attractive.

A second reason for limited attractiveness of long-term storages are competition with demand response options, demand-side management, and grid extension. Moreover, decentralized battery storages might also compete. The costs of the latter will not decline significantly faster but they will compete on end-user price level, which is (and will remain) remarkably higher.

An additional reason for the unfavorable economic conditions of long-term storage is the self-cannibalism of storages in electricity markets. This means that every additional storage has lower FLH then the one before and, in addition reduces the price spread and, thus, its own economic performance.[9]

Aspects of the economics of storage

In this section, we analyze the economics of storage more in detail. In the introduction and in the second section, we explained the range of technologies investigated in this paper. In this section, we provide the economic analysis focusing on three technologies as examples: pumped hydro storage, hydrogen as

Table 2. Summary of assumptions for the economic analysis (Source: All costs of 2018, own investigations).

Type of storage	Investment costs (€ kW^{-1})	(€/kWh)	O&M costs (€/kW year)	Depreciation time (years)
Pumped hydro storage	1200		5	30
PtG-H2-centralized	1550		25	20
PtG-CH4 centralized	2600		35	20
Battery small	(2400)$^{+}$	1200	20	12
Battery medium	(1880)$^{+}$	940	15	12
Battery large	(1120)$^{+}$	560	10	12

$^{+}$calculated from (€ kWh^{-1}) assuming 0.5 kW kWh^{-1}.

market-based systems, and batteries as example for own use.

As already explained above from the storage operators point-of-view in a market, the objective is to maximize profit, that is to say the difference between revenues and costs. While the revenues simply result from the sum of the products 'price times quantity sold', the costs are more complex and encompass all terms of Eqn (1).

From a battery storage operator's point-of-view, the objective is also to maximize profit, but it will now be calculated in a different way: The profit is defined as the difference between revenues and costs. The revenues are simply the product of own-used electricity times the end user's electricity price, the costs encompass the capital as well as the operation and maintenance costs.

As seen from Eqn (1), the costs of electricity are an important parameter for calculating the total storage costs. In this context, and also used for the following calculations, Fig. 7 shows the classified frequency of hourly marginal and average prices for electricity in Austria and Germany for the annual average of 2016 and 2017.

The marginal prices represent the actual prices on the day-ahead market, and the average prices show the average of the prices below a certain number of FLH. It can be seen that, for example, the average electricity price is about 0.02 € kWh^{-1} for about 2000 FLH (Fig. 7) used for the further calculations.

Derived from Fig. 7, in Fig. 8 the average costs and also the revenues (average prices of electricity in the wholesale electricity market over a year for the example of the average of 2016 and 2017) in the Austrian–German electricity market are shown, not considering storage losses.

Pumped hydro storage

The most widely used type of storage for electricity is pumped hydro storage (PHS). However, in recent years their economic performance has become challenged due to new market conditions caused mainly by the increases in wind and photovoltaic generation. In addition, a discussion on grid fees has emerged. In some European countries PHS has to pay for using the grid, whereas in others such as Austria they do not. We shortly analyze this issue below.

In Figs 9 and 10 the costs of PHS, depending on the annual FLH with and without a grid fee, are depicted (electricity costs as shown in Fig. 7). It can be seen clearly that only without grid fees they can be operated at reasonable number of FLH per year. Figure 9 shows the possible total profit without grid fees at 2000 FLH per year whereas in Fig. 10 the possible profit is shown for a hypothetical grid fee of 0.015 € kWh^{-1}.

The total costs of new pumped hydro storage without grid fee are shown in Fig. 11 depending on the annual FLH. The major finding from this figure is that if there is no grid fee, these storage could be economically between about 2500 and 4500 FLH. In this range the average revenues from selling electricity from hydro storage are in about the same range as the total costs consisting of the capital, O&M, and the energy costs.

Hydrogen as a storage

Hydrogen can be used as an energy carrier, as well as a storage for excess electricity from RES. It can be produced by electrolyzes and used as long-term electricity storage. Today, mainly small systems with capacities below 500 kW are in operation. However, there are already plans for constructing plants with

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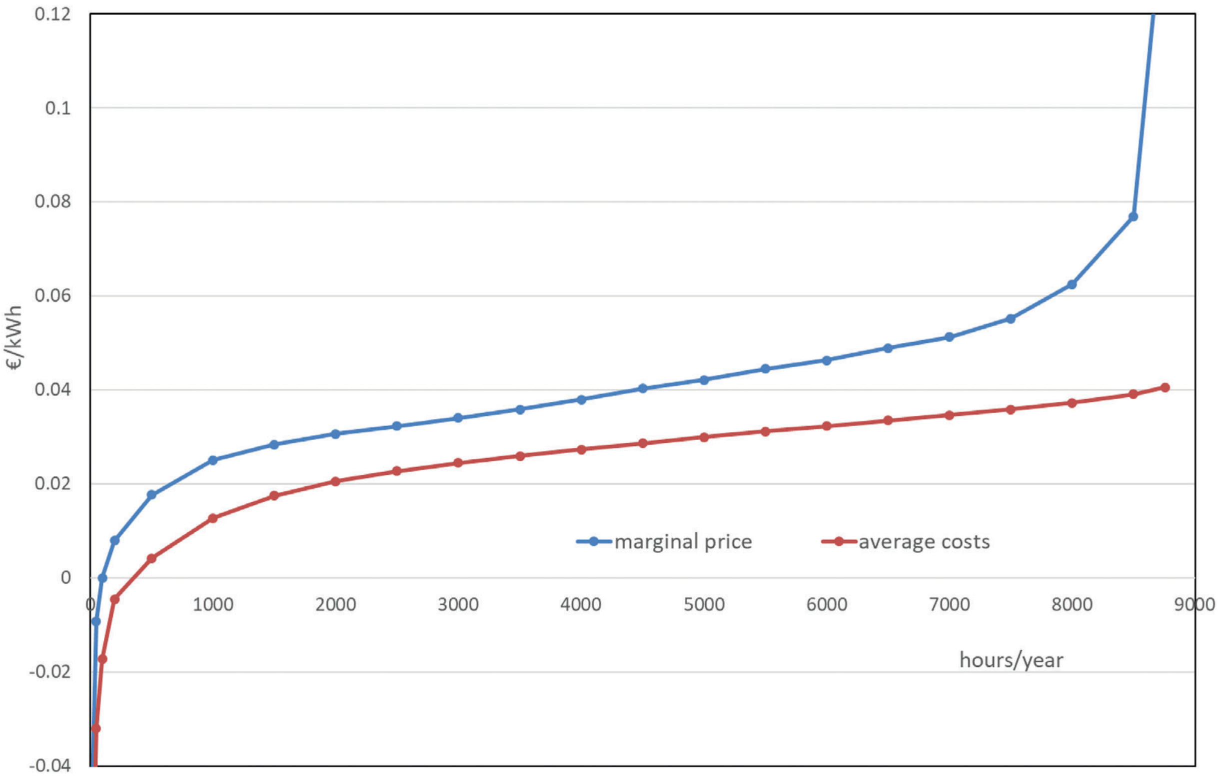

Figure 7. Classified frequency of hourly marginal and average prices of electricity in the joint Austrian-German wholesale electricity market over a year for the example of the average of 2016 and 2017.

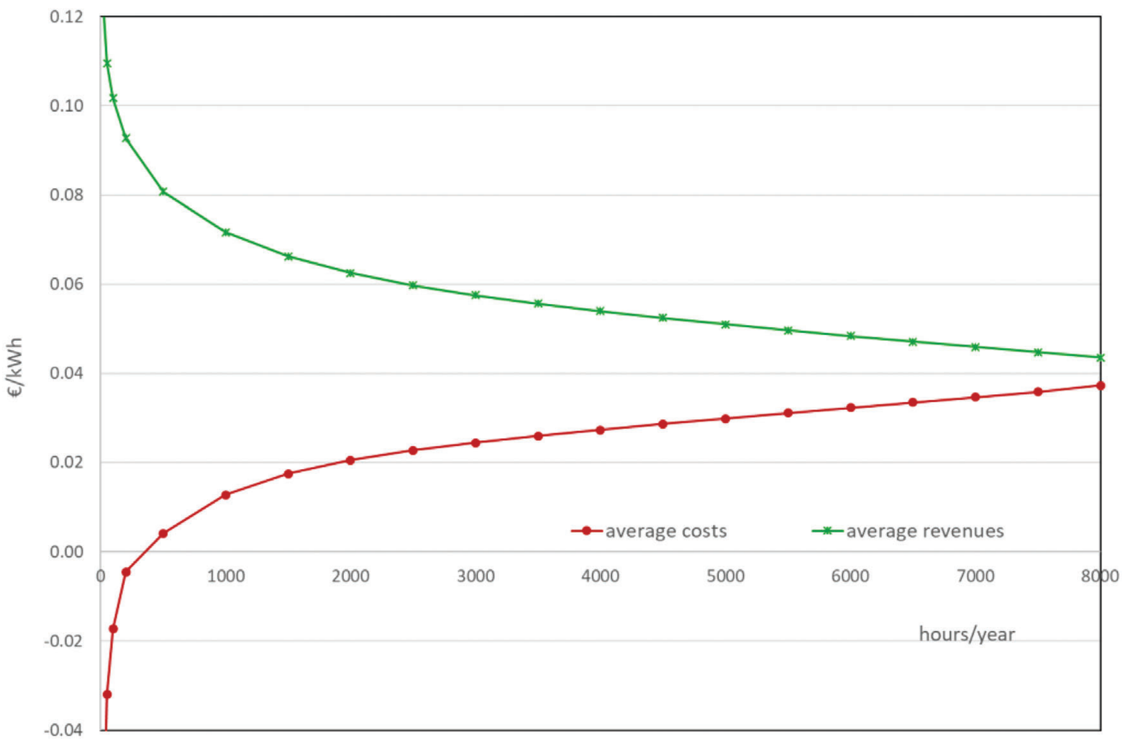

Figure 8. Costs and revenues (average prices of electricity in the joint Austrian–German wholesale electricity market over a year for the example of the average of 2016 and 2017) in an electricity market if there are no storage losses.

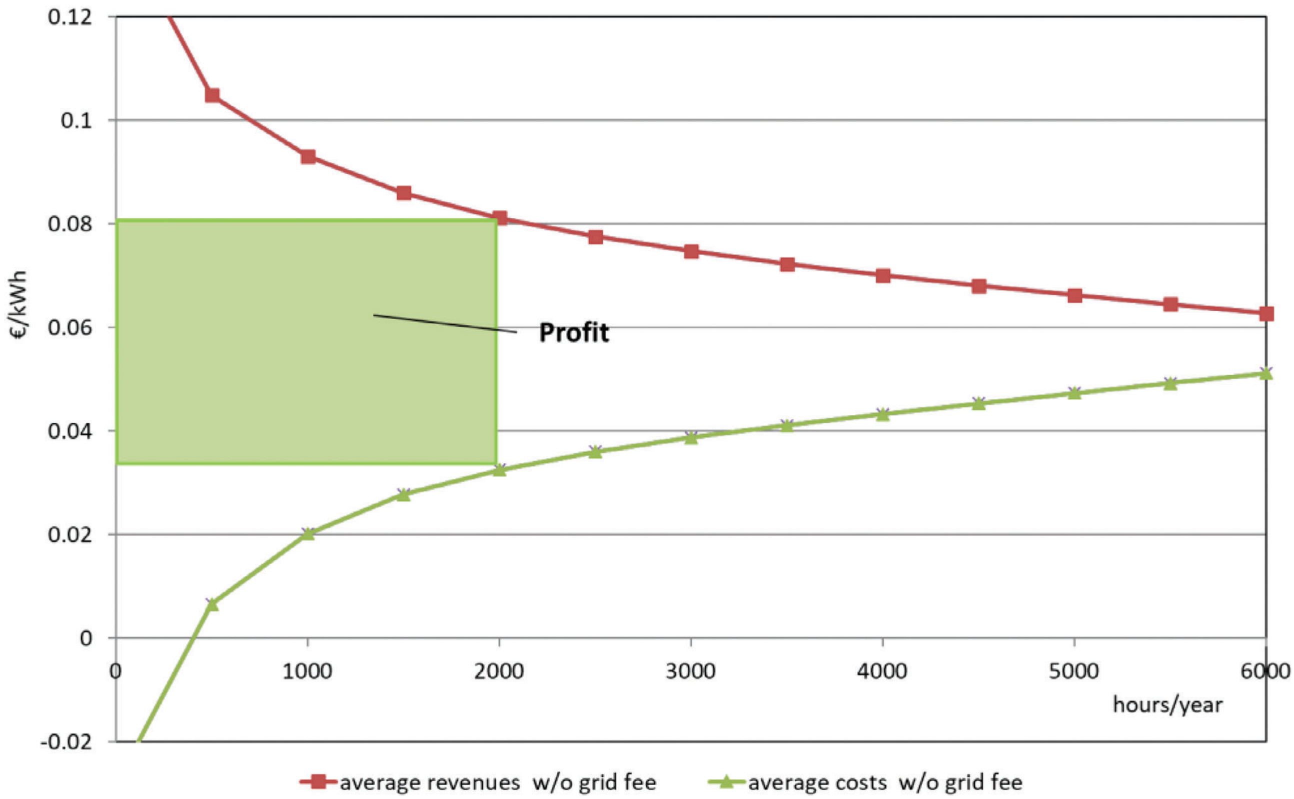

Figure 9. Costs of existing hydro storage depending on the annual full-load hours without a grid fee.

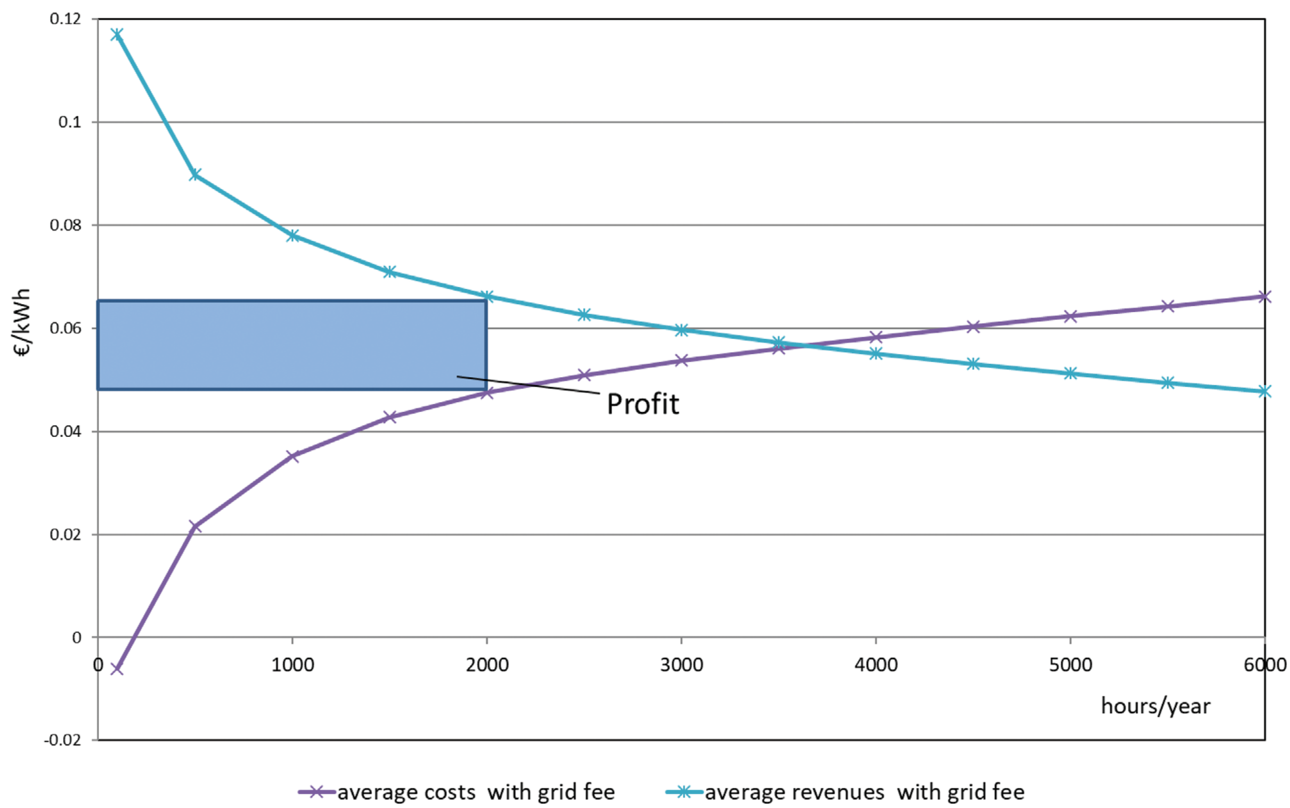

Figure 10. Costs of existing hydro storage depending on yearly full-load hours with a grid fee.

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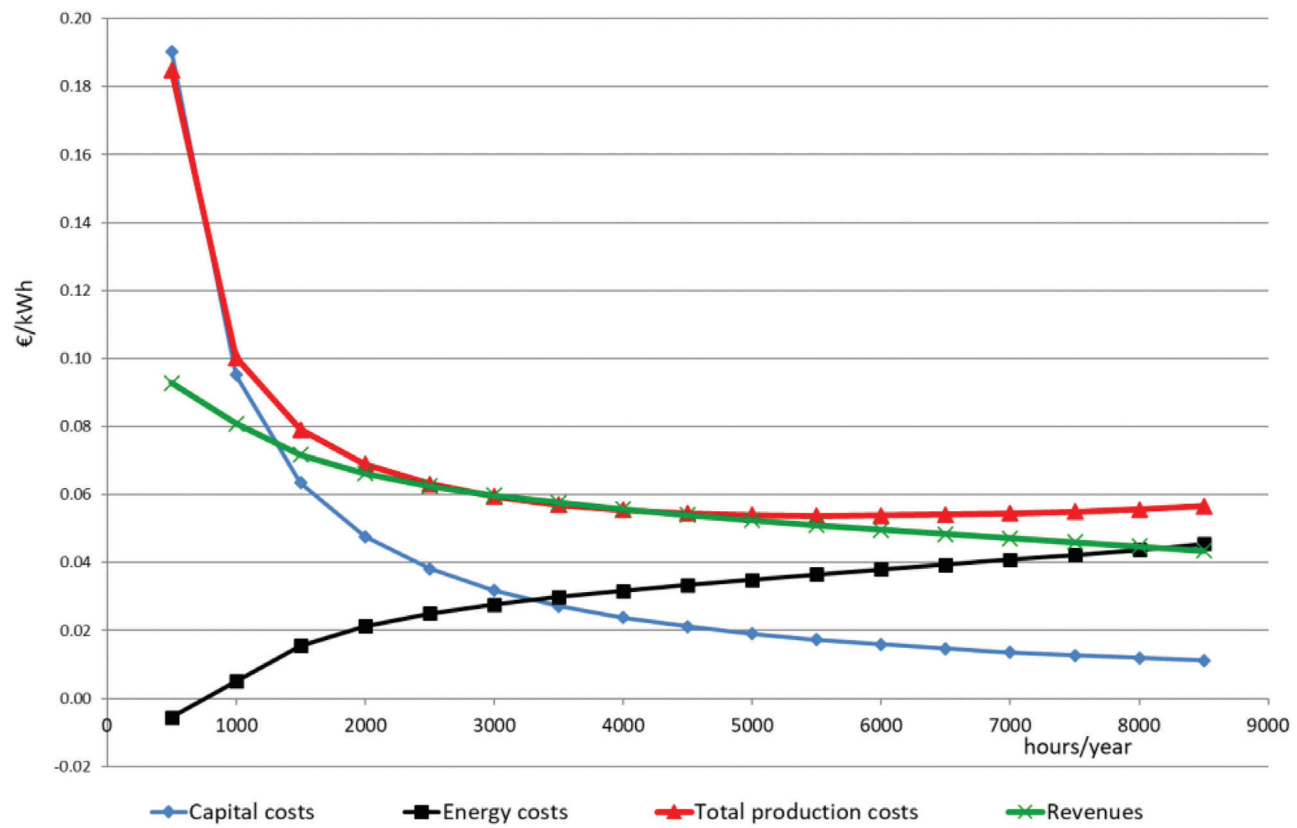

Figure 11. Total costs and revenues of new pumped hydro storage depending on the full-load hours per year.

capacity of 10 MW and beyond.[31] This would reduce the specific hydrogen generation costs remarkably, mainly, because of economies-of-scale.

Finally, it is important to find an optimal balance between investment costs of electrolyzer (depending on the plant size) and possible full-load-hours per year. As an example, Fig. 12 shows the cost of hydrogen generation from a large centralized electrolyzer system (including the costs of hydrogen storage) depending on the full-load-hours and the costs of electricity used, according to Fig. 7 and Table 2. Acceptable low costs of hydrogen of about 0.08–0.09 € kWh^{-1} could be reached only from about 4000 FLH per year upwards.

Battery storage

As already outlined in the previous sections, decentralized battery storage might also play a role in a future electricity system. Their costs will not decline significantly faster than those of long-term storage but they will compete on end-user price level which is (and will remain) remarkably higher.

Different applications naturally require different types of storage. Looking at the worldwide expansion of storage capacity, one thing in particular becomes clear. Lithium-based technologies dominate the storage market, excluding pumped storage technologies. With a share of 88% of worldwide expansion, lithium-based technologies were clearly in the lead.

Basically, there are many different battery types with different cell types, but as it can be seen from Fig. 13, only a few have played an important role in recent years. These technologies are as follows:

- Lithium-based batteries.
- Lead-acid batteries.
- Flow batteries.
- Sodium sulfur batteries.

Most decentralized stationary battery storage systems are either lead-based or lithium-based systems, but lithium-based systems clearly dominate 'behind the meter' as well.

The lead acid battery is one of the most proven and widely used battery in many applications. This battery is known as a classic car battery and most uninterruptible power supply (UPS) systems are still based on this cell type. Lead-acid batteries are

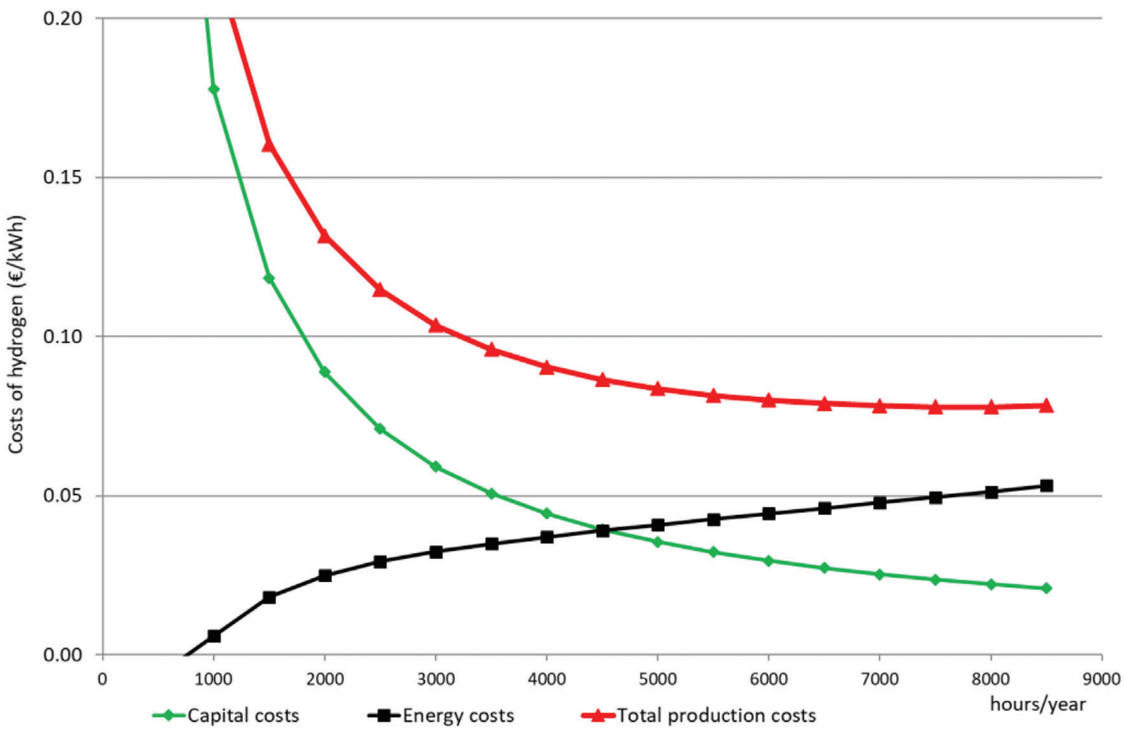

Figure 12. The cost of hydrogen from a large electrolyzer system (10 MW_{Ele}) depending on the number of full-load hours.

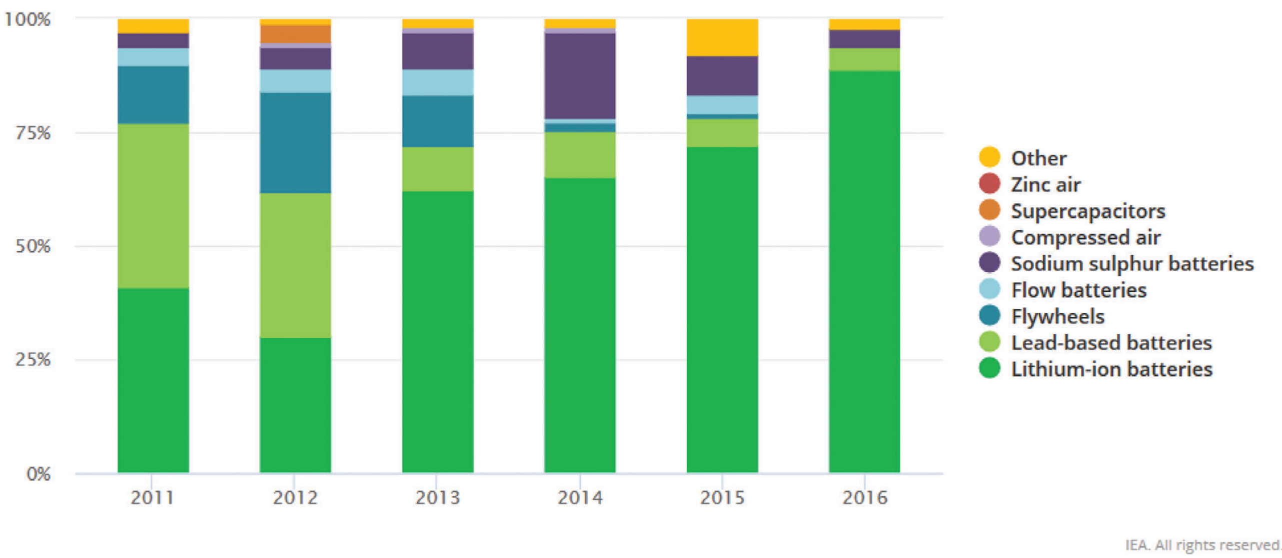

Figure 13. Technology mix in percent in new storage installations per year from 2011 to 2016 excluding pumped hydro. Source: Munuera *et al.*[32]

inexpensive, but also have low cycle stability, especially at high discharge depths. This fact, as well as the fact that lithium-based batteries have significantly higher energy and power densities, has also made them interesting for the prosumer market in recent years.[33]

Of specific interest is the development of the storage costs over time. Especially for batteries in the last decade significant cost reductions has been achieved as seen from Fig. 14. Driven by the construction of immense capacities for battery manufacturing facilities

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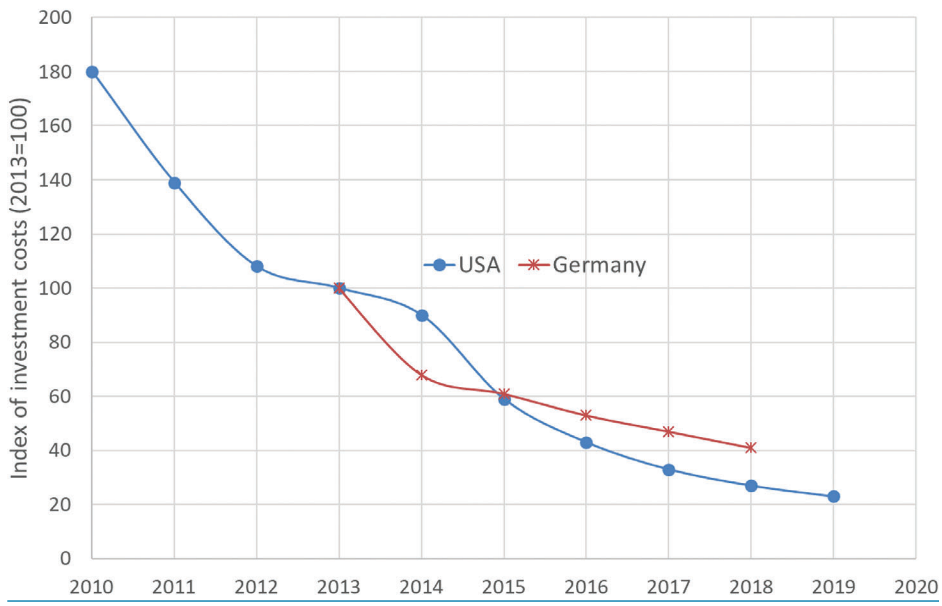

Figure 14. Recent developments of battery investment costs in Germany and the USA (EES 2019 and Bloomberg 2019).

for electric-mobility, prices have fallen significantly, especially for battery modules.

Even if electric mobility can certainly be considered as a major driver or enabler for battery storage systems in general, developments in storage costs in the automotive sector cannot always be transferred one-to-one to stationary operation. It strongly depends on what is directly considered in the costs (cells, packaging, charge control, thermal management, installation, inverter, etc.) and what is left out.[35,44] Looking at the average end-user costs of AC-coupled lithium batteries in recent years for the German/Austrian market, it can clearly be seen – see Fig. 15 – that battery storage costs have fallen significantly, especially in the area of typical sizes for single-family buildings and smaller properties with an energetically optimal battery capacity between 1 and 7 kWh. This is exactly in line with the findings that capacities behind the meter have been expanded in recent years.[32]

This large cost degression in the area of typical household capacities (Fig. 15) can be attributed primarily to the fact that demand in decentralized battery storage systems has increased sharply in recent years and competition has developed between different manufacturers. This is also the area with the most available data points. The demand for storage solutions from 15 kWh upwards is unlikely to be as large, so that the number of system solutions on offer is also no longer as large and therefore the cost degression is hardly noticeable.

Future economic perspectives for storage up to 2040

The current economic performance of all investigated storage options shows that they are hardly competitive, see the situation in 2018 in Fig. 6. However, for most storage technologies – except pumped hydro – in the next decades remarkable reductions in investment costs are expected mainly due to technological learning (TL).

Next we analyze how the prospects of different storage types could be in the next decades up to 2040 based on TL regarding the investment costs. TL can be quantified by so-called experience or learning rates.[45–47] Equation (3) is used to describe such a relationship using a learning rate b:

$$IC_{\mathrm{New}}(x_t) = IC(x_{t_0}) \cdot \left(\frac{x_t}{x_{t_0}}\right)^{-b} \tag{3}$$

where IC_{New} are the investment costs of the new technology at time t, b is a learning index, and IC are the investment costs at time t_0 and x is the cumulated produced quantity of a specific storage type at t and t_0.

Figure 16 depicts the possible development of investment costs of different long-term storage options

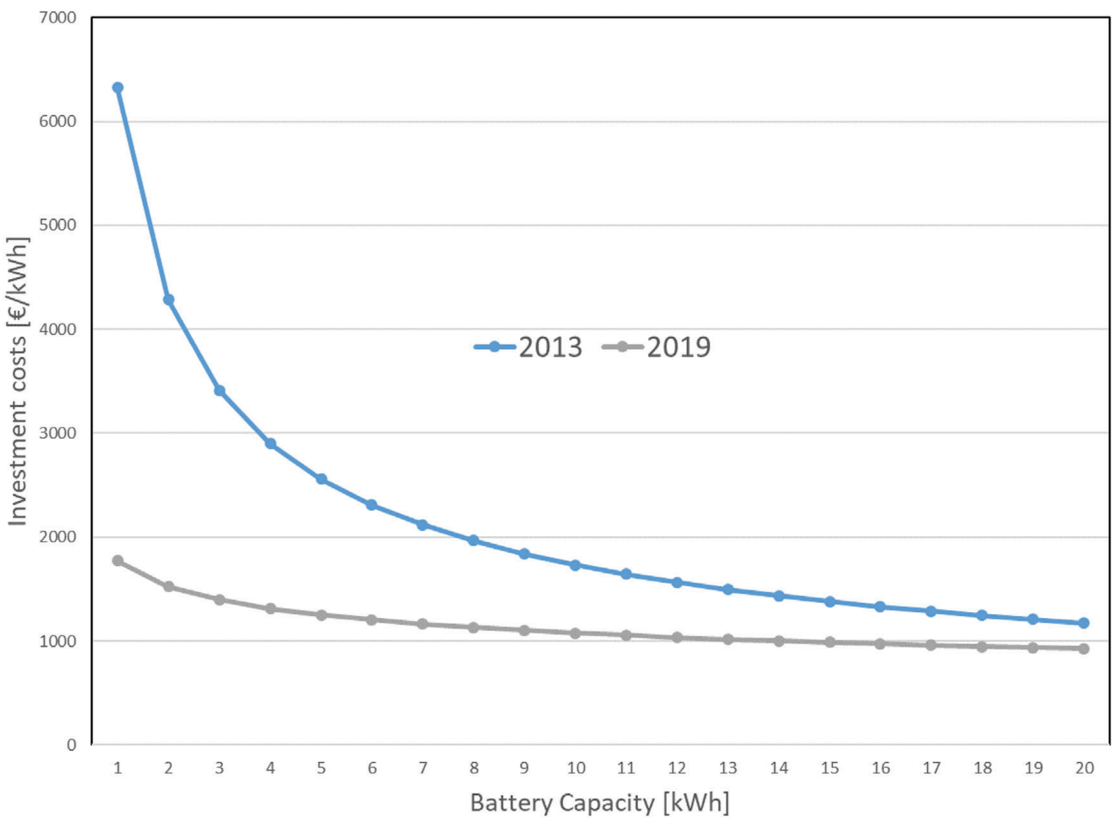

Figure 15. Economies-of-scale of battery storage for 2013 *versus* 2019 (Source: Own calculations, data based on C.A.R.M.E.N[34]).

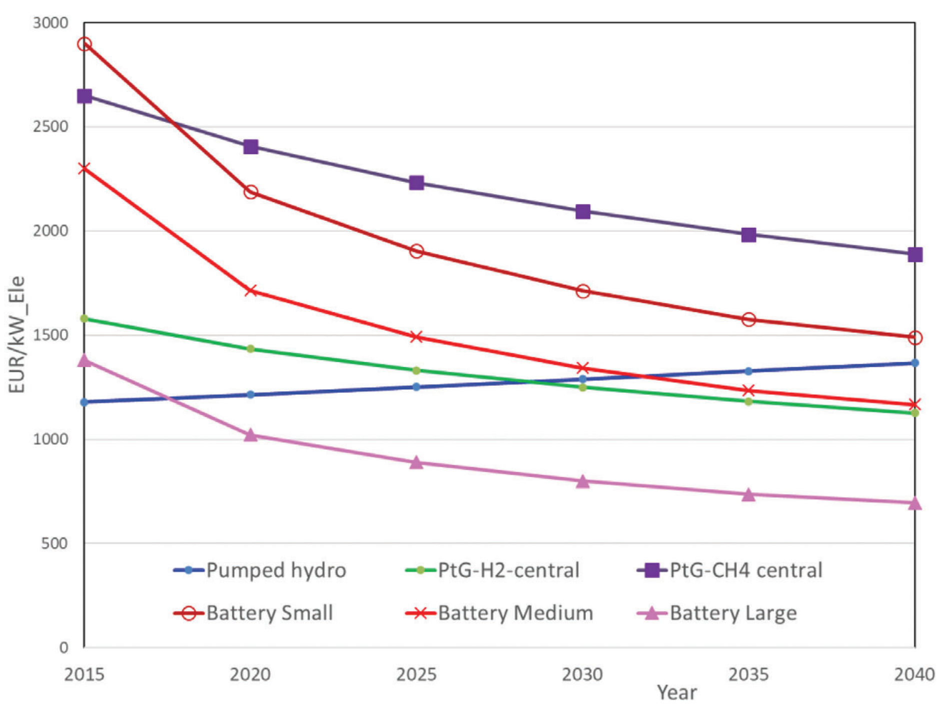

Figure 16. Future perspectives of the investment cost development for different long-term storage types compared to batteries up to 2040 (with learning rates of 20% except for pumped hydro).

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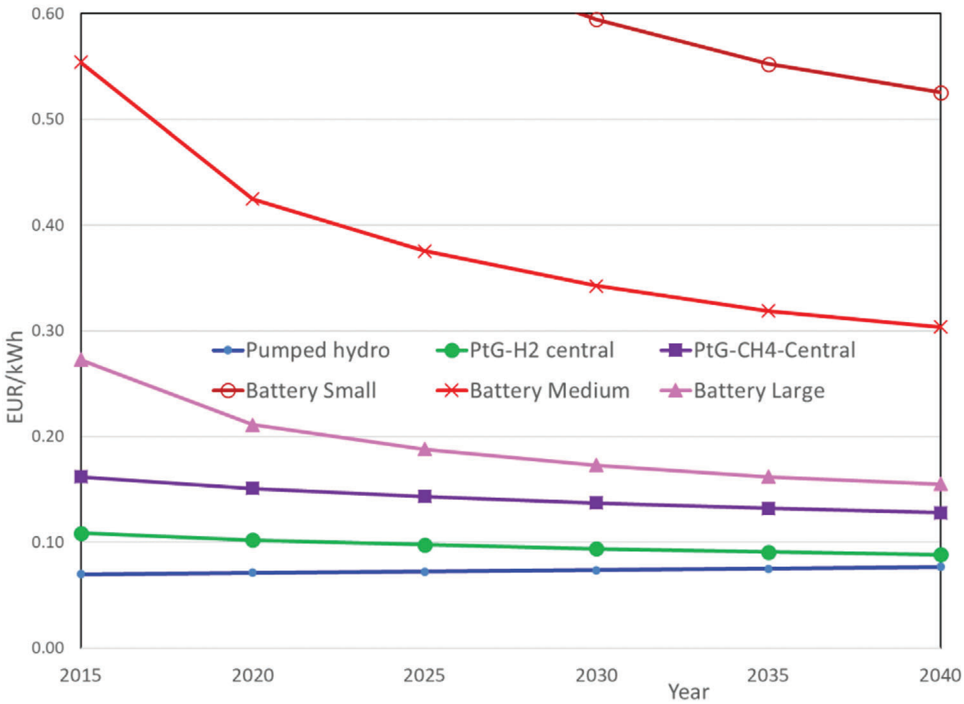

Figure 17. Development of the storage costs of several technologies for long-term storage of electricity vs batteries over time up to 2040 (full-load hours as documented in Table 1).

for electricity compared to batteries, with learning rates of 20%.[36] The quantities for the different technologies are modeled based on work conducted by the International Energy Agency.[37]

As can be seen from Fig. 16 in the period up to 2040 it is to be expected that the investment costs of the PtG technologies will fall, mainly due to learning effects. For pumped hydro storage we do not consider further TL, because their costs are more likely to continue to rise, mainly due to the lack of sites with reasonable costs and increasing lack of acceptance, see Fig. 16.

As an average of learning rates in the literature a value of 20%[37] is depicted. Applying this learning rate to electrolyzers and methane plants their investment costs will decrease by about 30%, applying it to batteries they will even half. The major reason for this difference is that larger quantities x (Eqn (3)) are expected to be deployed for batteries in shorter time frames.

In the last 10 years the price spreads in the Western European day-ahead markets has been between about 0.03 and 0.06 € kWh^{-1} for 2000 FLH per year.

Regarding the storage costs of pumped hydro and batteries respectively the production costs of hydrogen and methane by 2040 under favorable learning conditions (20% learning rates) and the costs of hydrogen and methane for 2000 FLH per year will be between 0.08 € kWh^{-1} and 0.13 € kWh^{-1}. For the same number of FLH the price spread will be at the utmost about 0.10 €/kWh^{-1}. This explains why it will become hard for storage to compete in day-ahead or intraday electricity markets.

Regarding batteries competing with end user prices: as said they compete with end user electricity prices (except the large ones which are likely to be implemented at grid level) which are currently on average about 0.20 € kWh^{-1} in Europe, the highest being in Germany and Denmark with about 0.30 € kWh^{-1}. As seen from Fig. 17, in these cases it will be difficult for batteries to compete.

Conclusions

The major conclusions are:

It has to be stated clearly that the economic prospects of storage are not very bright. The major reason is, that most studies calling for additional storage capacities focus on the technical point of view and neglect the economic performance.

On the one hand, for the economics of market-based storage the price spread is an important incentive for arbitrage and the corresponding FLH. A conclusion is that higher CO_2 prices increasing the electricity market prices at times electricity is scarce could contribute to better economic prospects. In addition, there is the issue of grid fee for storage. While there are arguments that storage is a system component and not a consumer, even in wholesale markets it has to be considered that there are also other flexibility measures than just storage that are possible and exemption of storage from grid fees would lead to biases for other options and, distort this market. In this context Sioshansi[15] stresses the importance of the proper design of market mechanisms that could also improve storage use incentives.

On the other hand, the economics of battery storage highly depends on the number of full load cycles, an equivalent for FLH, and the corresponding end user electricity prices (including taxes). They benefit from the fact that they do not have to compete with the low price margins on the wholesale markets, but with the significantly higher retail prices for electricity (between 0.20 and 0.30 € kWh^{-1} in Western Europe). Of course, in countries like Germany with significantly higher household electricity prices than the European average, the prospects for decentralized storage might be better than in others. However, as battery storage is currently mainly used for complementing PV systems[40] and the energetic performance at least in winter is very low (only very few FLH) this is currently a major economic barrier.

Yet, for the future there are high expectations based on TL. Even in this context the prospects are not purely bright, because: (i) with respect to pumped hydro storage it is important to note that their investment costs in future will not significantly decrease because no remarkable further learning effects are expected and the cheapest site options are already in use; (ii) stationary batteries have the major disadvantage because despite decreasing battery prices in recent years, their very low FLH still lead to a modest economic performance; Anyway, the overall development of batteries remains uncertain, for the future it is clear that battery prices will drop further, however it is not certain to which level; (iii) for PtG-technologies such as hydrogen and methane it will also become very hard to compete in the electricity markets despite a high TL potential. The major reason is the low round-trip efficiency and the resulting high generation costs for electricity after re-electrification of the gases from this process. Yet, for hydrogen and methane there could be better economic prospects in the transport sector due to both, higher energy price levels as well as a general lack of low carbon fuel alternatives.[41–43]

Finally, it has to be stated that storage is not the only flexibility option. It is in competition with grid extension, load management, and other options.[8,38–41] In addition, natural gas as storage and natural gas fired turbines for short-term generation are a flexibility alternative, however, not a fully carbon-free one. Hence, from an economic assessments point of view of electricity storage, the possible competing options have to be considered simultaneously. However, in any case new storages should be constructed only in a coordinated way[44] and if there is a clear sign for new excess production, in this case from variable RES.

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Greenhouse Gas Sci Technol. **10**:1176–1192 (2020); DOI: 10.1002/ghg.2030