EKONOMSKA PROCJENA BATERIJA KAO FLEKSIBILNE PODRŠKE ZA SUSTAVE S POVEĆANIM UDJELOM OBNOVLJIVIH IZVORA ELEKTRIČNE ENERGIJE: SLUČAJ REPUBLIKE HRVATSKE

ECONOMIC ASSESSMENT OF BATTERIES FLEXIBLE SUPPORT FOR SYSTEMS WITH INCREASED PENETRATION OF RENEWABLE ELECTRIC ENERGY SOURCES: CROATIAN CASE

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Posljednjih godina može se primijetiti brzo povećanje instaliranih kapaciteta obnovljivih izvora električne energije, posebno u vjetroelektranama i solarnim elektranama. To je bilo moguće zbog brzog razvoja tehnologije i smanjenja troškova izgradnje uz potporu različitih programa subvencija. Njihova obnovljiva priroda dolazi zajedno s primjetnom volatilnošću i nesigurnošću te se stoga nazivaju elektranama koje su neupravljive. Drugim riječima, oni proizvode električnu energiju kada je povezani obnovljivi izvor energije dostupan za razliku od elektrana na fosilna goriva, koje imaju skladištenje goriva ili hidroelektrana s dovoljno velikom akumulacijom i mogu se dispečirati na zahtjev. Također je neizvjesno kako će se razvijati buduće povećanje njihovih instaliranih kapaciteta. Zbog svoje volatilnosti potreban im je neki izvor i određena količina fleksibilne podrške. U ovom radu glavni izvor fleksibilnosti predstavljaju električne baterije. Nedavni razvoj baterija pokazao je brzi pad njihovih povezanih troškova i stoga je upitno na koju će vrijednost konvergirati. Baterije također mogu uštedjeti određenu količinu obnovljive energije koja bi se inače bacila, jer se mogu puniti kada postoji višak obnovljive energije i prazniti kada su obnovljivi izvori nedostupni. U ovom radu ispitat će se nekoliko scenarija za procjenu ekonomske isplativosti fleksibilnih baterijskih sustava. Scenariji pretpostavljaju različite cijene baterija i različitu buduću penetraciju obnovljivih izvora električne energije. Model je razvijen u PLEXOS softveru i temelji se na stvarnom sustavu - hrvatskom elektroenergetskom sustavu. Uključuje sve postojeće elektrane, a razmatra i buduće umirovljenje postojećih elektrana i izgradnju novih koje su u planu. Glavni je cilj utvrditi pod kojim su okolnostima baterije ekonomski isplativ izvor fleksibilne potpore za nestabilne obnovljive izvore električne energije. Glavni ekonomski pokazatelj je nivelirana cijena energije za električne baterije u različitim scenarijima.

Ključne reči: *fleksibilna podrška; obnovljivi izvori električne energije; baterijski sustavi; PLEXOS; LCOE*

Abstract: In recent years rapid increase in installed capacity of renewable electric energy sources can be noticed, especially in wind and solar power plants. It was possible due to rapid technology development and decrease in build cost supported by different subsidy schemes. Its renewable nature comes together with noticeable volatility and uncertainty and therefore they are called undispatchable power plants. In other words, they produce electricity when associated renewable energy source is available in contrast to fossil fueled power plants, that have storage of fuel, or hydro power plants with large enough reservoir and can be dispatched on demand. It is also uncertain how future increase of their installed capacity will evolve. Due to their volatility, they need some source and certain amount of flexible support. In this paper main source of flexibility is introduced by electric batteries. Recent development of batteries has shown rapid decline in their associated cost and there-

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fore it is questionable to which value it will converge. Batteries can also save some amount of renewable energy that would be otherwise thrown away, because they can be charged when excess renewable energy exists and discharged when they are offline. In this paper several scenarios will be examined to assess economic feasibility of flexible battery systems. Scenarios assume different battery prices and different future penetration of renewable electric energy sources. Model is developed in PLEXOS software and is based on real life case - Croatian power system. It includes all existing power plants, and it also considers future retirements of existing power plants and building of new ones that are in plan. Main goal is to identify under which circumstances batteries are economic feasible source of flexible support for volatile renewable electric energy sources. Main economic indicator is levelized cost of energy for electric batteries in different scenarios.

Key words: *flexible support; renewable electric energy sources; battery systems; PLEXOS; LCOE*

1 Introduction

Electricity from the renewable electrical power sources (REPS) has so far been largely subsidized to accelerate the development of new technology that plays a key role in reducing carbon dioxide emissions. Subsidized prices for clean technology attracted many investors in REPS, which caused the accelerated development of electricity generation from REPS plants and thus solar and wind power plants. The accelerated development and production of a large number of electricity generation plants from REPS have led to a decrease in the building cost of plants, increasing efficiency and competitiveness in the electricity market, so that more recently the need for further subsidy of this technology for electricity generation has been increasingly questioned.

The increase in electricity consumption is certain in all global and European development policies and it is considered very important to consider the competitiveness of electricity generation from the REPS as well as its role in changing the regulatory and market environment of the power systems. The successful integration of REPS, especially into the electricity system, is a necessary precondition for sustainable long-term satisfaction with the increase in electric energy demand. This future increase in electric energy demand is mainly driven by expected rapid electrification of transport sector [1]. The International Energy Agency, IEA, in the 2016 edition of World Energy Outlook, lists REPS and gas fired power plants as producers that will meet this increase in electric energy demand by 2040. On the domestic front, the strategic energy document Energy Strategy of the Republic of Croatia [2], [3], similar to the Strategy of Low Carbon Development of the Republic of Croatia [4], [5] and Climate neutral scenario of the Republic of Croatia [6] points to the expectation that by 2030 there will be over 1,500 MW of installed power in wind power plants and over 1,000 MW in solar power plants in the Croatian power system.

The European Union (EU) played a key global role in implementing the first legally binding climate change agreement to take place at the United Nations Framework Convention on Climate Change (UNFCCC) in Paris in December 2015. The Paris Agreement is understood by the signatory countries to seek to mitigate climate change and to seed up and reinforce measures and investment needs for a sustainable future that will lead to a reduction in the use of fossil fuels and an increase in the share of renewable sources. The EU also foresees different scenarios for reducing carbon dioxide emissions, ranging from 50 to 80 % by year 2050 (compared to year 1990), which can only be achieved by increasing the generation of electricity from renewable sources as the primary source of energy [7]. Furthermore, EU member states agreed that the share of gross direct energy consumption by 2020 from renewable sources would be at least 20 %. This share should exceed 27% under the EU's plans by year 2030. In that scope, for example Germany adopted the Renewable Energies Act, which entered into force on 1 August 2014, which aims to achieve a share of renewables in total consumption of 40 to 45 % by 2025 and 55% to 60% by 2035 [8]. In short, European and global energy policy must and should balance three partly opposing criteria: energy competitiveness (reasonable prices), climate change (Paris 2015) and energy security.

2 REPS and need for additional flexibility in power systems

The study of scientific literature in the field of renewable energy sources points to the growing competitiveness of REPS, especially wind power plants in electricity generation. The reason for the increase in competitiveness is the significant investment of the world's corporations in the development of technologies for the use of wind energy. The installed power of wind power plants (as well as other REPS, especially solar) is steadily increasing with global energy consumption as the use of fossil fuels declines [9]. Due to the setting of ambitious targets in terms of increasing the REPS until year 2030, key REPS technologies such as wind power plants and solar power plants have seen a significant decrease in total energy production costs. There are some additional costs that increased REPS penetration requires, such as the costs of modernizing and expanding transmission and distribution networks and perhaps the most significant – balancing and flexibility costs in the system. Nevertheless, there are significant additional benefits for human health and environmental protection achieved by REPS penetration. An accelerated increase in the share of REPS can have significant social benefits, such as local economy and the development of poorly developed and rural environments, the creation of new jobs, the alleviation of energy poverty, etc.

A handful of papers assume that the future power systems will surely be based on REPS electricity generation technologies, e.g., 90% penetration by mid-century in Germany [10], penetration of 30% by 2030 in Germany [11], penetration of 70-81% by 2050 globally and 64-97% respectively in the EU [12], etc. It is the potential basis of the future power systems on renewables, in particular wind power plants, that requires a significantly higher level of flexible sources needed for which coverage of fixed costs in the current market-regulatory environment is at least questionable. In addition to balancing with electricity storages, on which the focus is in this work, there are other ways to increase balancing opportunities such as increasing transmission capacities [13] or demand response [10].

Given that the storage technologies of electric energy of significant volume are not yet commercially available, the volatility of solar power plants and wind power plants must still be compensated by conventional units, much of it with a fossil footprint. As customers' expectations for stable delivery of electric energy and the ability of recently invested technologies to provide the desired level of flexibility to guarantee this level of safety are increasingly being countered, there is growing discussion about the missing money problem [14]. The problem is that prices in the electricity market do not fully reflect the value of investments in resources that are necessary for the required level of security under the new conditions.

Paper [15] gives comprehensive review on sources and means of system flexibility. It states that large penetration of solar, wind and also hydro experienced recently significant reduction in investment cost and caused significant increase in their penetration. But their increased penetration brings also new technical and economic issues. Main reason for this is inevitable volatile and unpredictable nature of REPS that makes challenging maintenance of power system stability especially in terms of voltage and frequency control. Therefore [15] states that increase in power system short and long term flexibility is required to counter issues brought by increased penetration of variable REPS. In this way future power systems must greatly evolve from current standpoint.

In past main driver of power system flexibility (without significant REPS penetration) was present in form of traditional flexible generation power plants (e.g., gas turbines). These units can rapidly change output power and can be easily turned off or on. On the other hand, paper [15] states main sources of system flexibility in systems with high REPS penetration: 1) demand side management and demand response, 2) reinforcement of distribution and transmission facilities, 3) energy storage systems (electricity and heat), electric vehicles and 4) flexible generation.

In this paper main source of flexibility in power system is chosen as energy storage in form of electric batteries.

3 Electric batteries as source of flexibility in power systems

Electric batteries are one type of energy storage technologies used in power system. Until the mid-1980s, energy storages in the power system were used exclusively for time-shifting energy from high-load periods to low-load periods. Energy storages thus performed the role of peak power plants at peak hours (instead of expensive gas-fired power plants) [16]. The technical and financial advantages of this concept led to the emergence of a large number of pumped storage hydropower plants (more than 22 GW were built in the USA alone from 1920 to 1980). After the 1980s, the increase in the number of pumped storage hydropower plants slowed due to the utilization of the most affordable locations, the increased fight for a clean environment and the initiation of deregulation and re-structuring procedures of the power sector. Consequently, there is increased investment in research into batteries and other energy storage technologies that cannot compete with the large capacities of pumped storage hydropower plants. On the other hand, new technologies are able to react faster and provide services at shorter time intervals, which in particular comes to the fore in power systems with a high share of variable renewable energy sources. However, as stated in [17] the lifespan of the electric batteries varies greatly depending on the charge and discharge cycles and ranges from 10 to 20 years.

Price is a main factor that plays one of the more important roles in the decision to build battery energy storage. Below is a review and price comparison of three technologies that have proven to be the most likely candidates for the construction of a battery tank. Each of these three technologies (sodium sulfur (NaS), lead and lithium-ion) have its pros and cons. Compared to lead and lithium-ion batteries, the NaS is a much more expensive technology, so only a basic overview of price movements is given here. According to [18], today NaS battery prices range between $263 and $735/kWh, but typical installation costs are on average below $400/kWh, but $750/kWh is listed as the average investment cost. Furthermore, NaS batteries have also high maintenance costs ranging between $40 and $70/kW per year according to [19] and between $7 and $15/kW per year according to [18]. The prediction in [19] is that the installation costs of NaS batteries in 2030 will drop to $ 120 to $ 330/kWh. Lead batteries are the oldest of the technologies presented, so it is not surprising that they have reached a low price long ago that other technologies still cannot compete with. Most sources agree that the price of lead batteries has not changed significantly for years where [18] gave a range of $105 to $475/kWh. A 2017 IRENA report [18] predicts that installation costs for lead batteries will drop to $50 - $240/kWh in 2030.

A huge increase in the popularity of lithium-ion batteries owes to the development of the electric automobile industry. Due to the increased demand for batteries, manufacturers increase the efficiency of factories, and the consequences are seen on the prices of final products falling. Falling prices of lithium-ion batteries make them a potential economical solution for stationary application in power grids, thus seeing the positive consequences of economies of scale in the production outside the electric automobile industry. Lithium-ion battery prices have declined multiple times in the last decade. BloombergNEF brings news of the battery price drop to $156/kWh at the end of 2019 and predicts a very likely drop to $100/kWh by 2023 [20]. The same source cites a prediction of a price drop to $61/kWh by 2030. Earlier in 2019, IRENA reported that LCOE, a measure that takes into account both investment and maintenance costs throughout battery life, fell to $187/MWh [18] for lithium-ion technology. Most literature states that lithium-ion batteries have negligible maintenance costs, which is why they are ignored in calculations. The price of lithium-ion batteries depends on the technology chosen. According to [18], the installation cost ranges between $200 and $840/kWh for all technologies except lithium titanate (LTO) whose costs are higher, ranging between $473 and $1,260/kWh. For all lithium-ion technologies, investment costs are projected to fall by 54% to 61% [18] by 2030.

According to information from SYNCRO.GRID project, bilateral project between Croatia and Slovenia, two battery systems were built and integrated in Slovenian power grid. According to available data average build cost is approximated to around 125,000 EUR/MW power installed and 375,000 EUR/MWh capacity installed. Therefore, for batteries with power to capacity ratio equal to 1 average built price is 500,000 EUR/MWh (reduced to battery capacity only). This value is taken as reference price for battery systems in this paper and it is assumed that batteries are used mainly for electricity arbitration from periods with high production of REPS to periods with low production of REPS.

4 Methodology and model

Model of Croatian power system is made in software PLEXOS in similar way as already described in [21]. PLEXOS is worldwide known and accepted software for power system and electricity market modeling problems. It is used both by system experts and also researchers. Model includes all major power plant units in Croatian power system and all other important facilities. Retirements of existing power plants and entries of planned power plants are also included in model. The model is adjusted to the needs of this paper and in accordance to near zero emission scenario [6]. For the purpose of this research battery storage systems of different size are included in model using several scenarios. In order to avoid price arbitrage of batteries market is available only for purchases and not for sales. Namely goal is to identify quantities of energy arbitrage made by batteries for shifting electric energy from periods of high REPS availability to periods of low REPS availability.

Two main scenarios are investigated. The 'Optimistic' scenario assumes increase in both solar and wind power plants installed capacity in accordance with [6]. The 'Pessimistic' scenario assumes significantly lower REPS installed capacity compared to the 'Optimistic' scenario until year 2030 (Fig. 1).

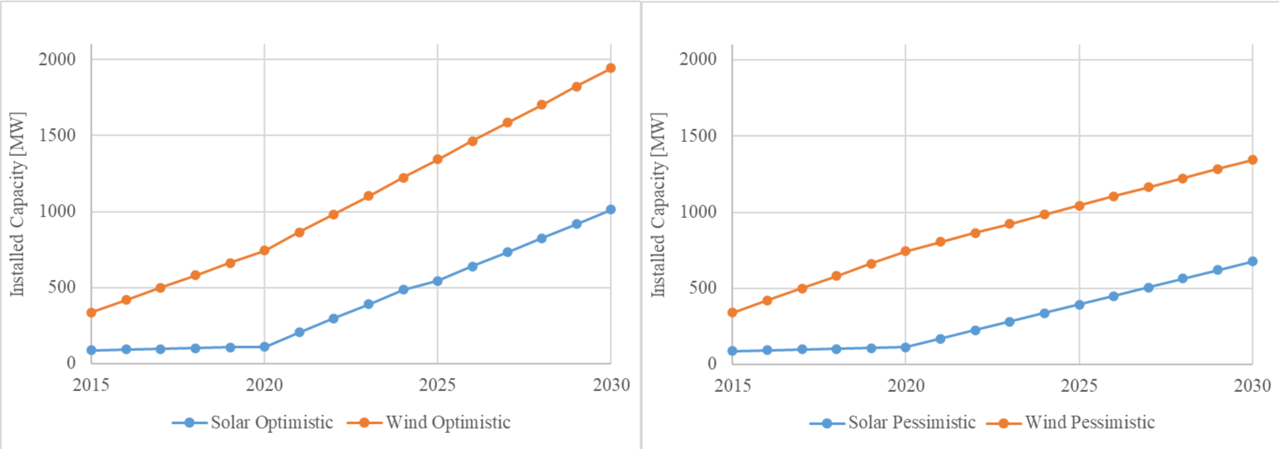

Figure 1: REPS installed capacity for different scenarios

As already stated, electric batteries are only type of energy storage technologies used in power system model. Optimization is performed in two main steps: long and short term. In long term optimization time horizon is 16 years (2015-2030) with time step of one year. In short term optimization time horizon is 10 years (2021-2030) with time step of two weeks and time interval of one hour.

Different sizes of battery system are investigated for both scenarios and each time levelized cost of energy (LCOE) [EUR/MWh] for battery system are calculated. For most cases ratio between battery power (P_B [MW]) and battery capacity (C_B [MWh]), P_B/C_B is equal to 1, but cases where it is higher and lower than 1 are also investigated.

Battery charge-discharge cycle efficiency is conservatively set to 90% and for LCOE only discharged energy is included. Namely it can be perceived that batteries will charge in scope of ancillary service provision and will get profit from that service. Conservatively, in this paper it is assumed that batteries are charging at price equal to 0 EUR/MWh. Battery build cost is in most scenarios set to already mentioned 500,000.00 EUR/MWh, but price-based sensitivity analysis is also performed. Battery life is conservatively set to only 10 years, equal to short term optimization time horizon.

5 Results and discussion

First LCOE was calculated for four different battery system sizes with P_B/C_B equal to 1: 100 MW – 100 MWh; 500 MW – 500 MWh; 1000 MW – 1000 MWh and 2000 MW – 2000 MWh. Optimization and calculation are performed for both 'Optimistic' and 'Pessimistic' scenarios. Results are shown in Fig. 2. and it can be observed that in both scenarios LCOE of battery system increases with its size. It can be concluded that battery utilization factor or capacity factor is also decreasing with increase in both power and capacity of battery. Additionally, it is obvious that LCOE is lower in

‘Pessimistic’ scenario than in ‘Optimistic’ scenario for all battery sizes. Battery build cost is equal to 500,000 EUR/MWh.

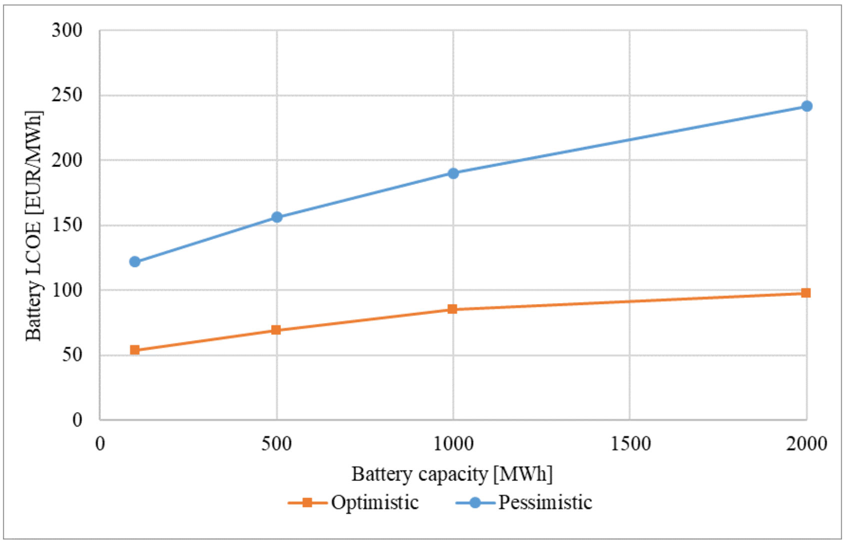

Figure 2: LCOE of batteries for different scenario and size

It can be concluded that in case of ‘Optimistic’ scenario battery systems are quite competitive on market, especially with capacities lower than 1000 MWh, therefore there is opportunity for private investors in this niche. On the other hand, in ‘Pessimistic’ scenario battery LCOE is too high (from around 120 to around 250 EUR/MWh) for all sizes and can be only part of system service due to low attractiveness to private investors.

For the rest of analysis only ‘Optimistic’ scenario will be considered. Let’s first look how increase in battery capacity, while not changing battery power, affects LCOE. Now LCOE was calculated for four different battery system sizes with P_B/C_B equal to 0.2: 100 MW – 500 MWh; 500 MW – 2500 MWh; 1000 MW – 5000 MWh and 2000 MW – 10000 MWh. Battery build cost is this time equal to 400,000 EUR/MWh. Results are shown on Fig. 3. (left part).

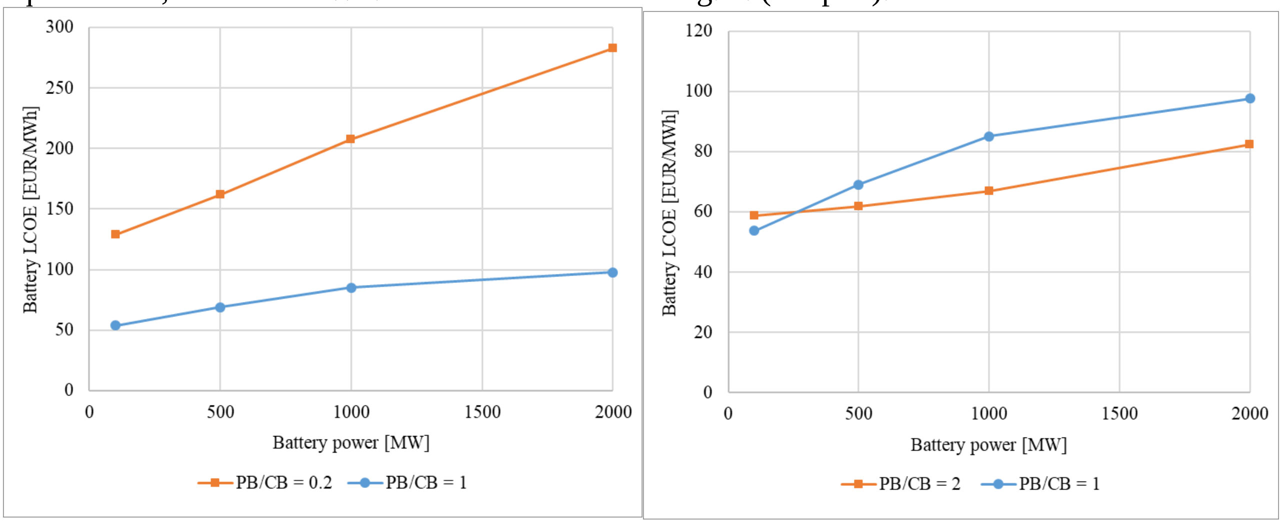

Figure 3: LCOE of batteries for different P_B/C_B ratios

Now we can see how decrease in battery capacity while not changing battery power affects LCOE. Now LCOE was calculated for four different battery system sizes with P_B/C_B equal to 2: 100 MW – 50 MWh; 500 MW – 250 MWh; 1000 MW – 500 MWh and 2000 MW – 1000 MWh. Battery build cost is this time equal to 625,000 EUR/MWh. Results are shown on Fig. 3. (right part).

It is obvious that regarding LCOE Croatian power system with high REPS penetration favors higher P_B/C_B ratio, or in other words battery power over battery capacity.

Last part of analysis is price-based comparison of LCOE for referent case: battery power 100 MW, battery capacity 100 MWh for five different build prices: 100,000 EUR/MWh; 200,000

EUR/MWh; 300,000 EUR/MWh; 400,000 EUR/MWh, 500,000 EUR/MWh, 600,000 EUR/MWh and 700,000 EUR/MWh.

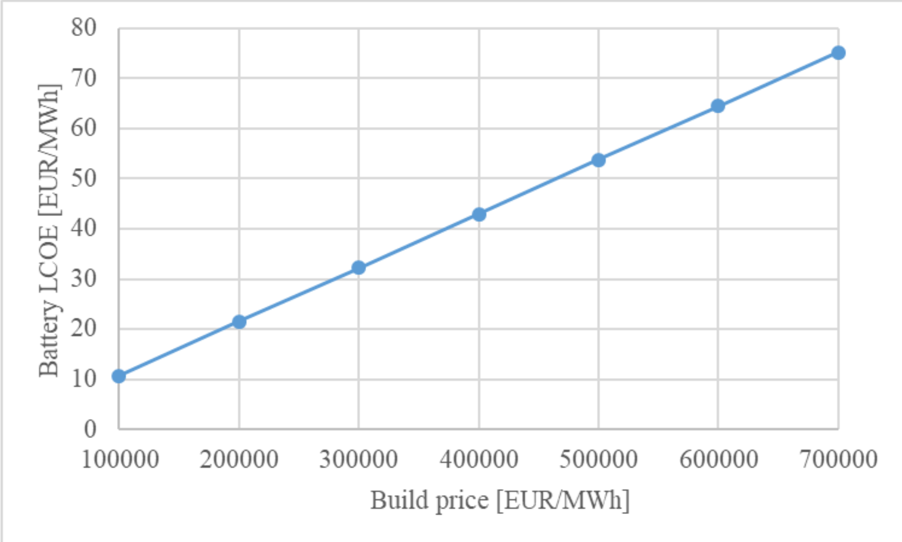

Figure 4: LCOE of 100 MW, 100 MWh battery for different build price

From Fig. 4 it is obvious how volatile LCOE of battery is regarding battery build price, where it ranges from around 11 to around 75 EUR/MWh for battery 100 MW, 100 MWh and for build prices from 100,000 EUR/MWh to 700,000 EUR/MWh. Therefore, if predictions of future significant battery price drop come true, battery systems will be more than competitive in Croatian power system.

6 Conclusion and future work

With increased level of penetration of renewable electrical power sources (REPS) worldwide there is a growing need for additional system flexibility support. This paper provides analysis of potential role of battery systems in Croatian power system in case of high penetration of REPS with two basic scenarios: 'Optimistic' and 'Pessimistic', where in 'Pessimistic' scenario REPS penetration is slower than in 'Optimistic' scenario. Analyzed period is from 2021 to 2030. It considers different REPS penetration levels and different sizes of battery systems. Batteries are used only for electric energy arbitration between periods of high availability of REPS to period of high availability of REPS. Analysis is based on model of Croatian power system made in PLEXOS software. Results points to stronger need for battery support in scenario with higher REPS penetration where levelized cost of energy (LCOE) for batteries falls well under 100 EUR/MWh. LCOE of battery system increases with size of battery system. Results also show that Croatian power system favors battery systems with higher power and lower capacity. In other words, Croatian power system seeks for short term arbitrage of volatile REPS energy. It can also be concluded that if predictions of future significant battery price drop come true batteries can become very attractive even for private investors. But, even with current level of battery build price there is niche for private investors to support volatile REPS by energy storage in terms of battery systems.

In future work battery system degradation, minimum state of charge (SoC) and other technical constraints will be included to refine current results. Future work can also point to amount of 'saved' REPS energy by battery systems that would be otherwise curtailed or thrown away.

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