Energy Storage for Renewable Energy

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***Abstract*— The paper presents a dynamic modelling approach to optimise the capacity of Battery Energy Storage Systems (BESS) using hourly generation profiles of Renewable Energy Sources (RES) and electricity demand. The objective is to maximise the effective use of wind (onshore and offshore) and photovoltaic (PV) generation. The analysis is based on hourly data from the Polish power system covering the years 2021–2024.**

***Index Terms*—Energy storage, power system operation, renewable energy sources, energy policy targets, hourly profiles of RES generation.**

I. INTRODUCTION

Like all EU member states, Poland is required to develop and submit an Energy Policy covering the horizon to 2040 [1], [2]. A central objective of this policy is to reduce electricity generation from coal and other fossil fuels, replacing it with renewable energy sources.

Decarbonisation will require major investments in renewable technologies, mainly photovoltaic (PV) panels and onshore and offshore wind farms. These sources are weather-dependent and variable, leading to periods of surplus generation followed by periods of low output [3], [4].

To manage this variability, energy storage (ES) is needed both to absorb excess generation (otherwise subject to curtailment) and to supply power when RES production is insufficient.

The volume of energy that can be stored depends on two key parameters: (i) energy capacity (E), which defines the total amount of energy the system can store, and (ii) power capacity (P), which represents the rate at which energy can be charged into or discharged from the storage, typically measured over an hour.

Various storage technologies can be deployed [5]; however, practical experience with large-scale units that could support energy policy goals remains limited [6]. In particular, there is a need to analyse the time-based coincidence between RES production and electricity demand, as it directly affects the extent to which renewable generation can be utilised and policy targets met

Although energy storage is widely regarded as a key enabler of renewable energy integration—providing short-term flexibility and supporting system balancing—its actual contribution remains constrained by scale. The current capacities of storage systems are marginal compared to the overall electricity demand and the output of large-scale renewable sources. As the share of renewables in the generation mix increases, paradoxically, it becomes more difficult to find suitable conditions for discharging stored energy. This counterintuitive phenomenon may lead to lower utilisation rates and reduced economic viability of storage. Therefore, it is essential to understand not only whether energy storage is beneficial, but under what operational conditions and to what extent it can actively support the functioning of a decarbonised power system. This paper addresses these questions by applying detailed simulations based on hourly profiles of renewable generation and electricity load in the Polish power system [7], [8], [9], [10].

II. ENERGY MIX – DECARBONISATION

A. Energy System Context in Poland

The Polish energy mix is dominated by electricity production from fossil fuels, mostly hard coal and lignite, accounting for nearly 70% in 2023 [3], [4]. Renewable energy production is based on two main technologies: panels PV and onshore wind – Table 1. The first offshore wind farm is under construction and the first stage of the offshore wind construction is to be completed by the year 2030 with 5.9GW of power installed.

Table 1. Energy production in Poland in 2023.

Energy mix	Energy (TWh)	Share in (%)
Biogas, biomass, hydro	11	6%
Panels PV	11	7%
Wind Onshore	23	14%
Total RES	*45*	*27%*
Conventional	*120*	*72%*
including: Hard Coal	66.1	40%
Lignite	34.8	21%
Natural gas	16.6	10%
Others	2.4	2%
Total electric energy	166	100%

The Polish energy policy is aiming at the decarbonisation of electricity production which should provide the reduction of electric energy generation from coal from over 100TWh in the year 2023 to only 4TWh in the year 20240. At the same time, the electricity production from natural gas will remain relatively stable with a small drop towards 2040 [2].

Table 2 The Polish energy policy -decarbonization

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Energy (TWh)	**2023**	**2030**	**2 040**
Coal	101	43	4
Natural gas	17	31	28
RES	43	108	195
Nuclear	0	0	58
Energy storage	1	7	20
Others	5	0	0
Total	***166***	***189***	***305***

The main electricity production technology should be based on renewables reaching nearly 200TWh in the year 2040. In a new energy mix, the nuclear power station should provide about 60TWh before 2040. The energy policy will also require the implementation of ES with the rated ES capacity accounting for 7GWh in the year 2030 and its increase to 20GWh in 2040 [2]. The effective use of ES is the key element of the successful energy transformation.

B. Hourly RES generation profiles

The analysis of power system operation requires information about load and generation every hour as their coincidence is decisive for the amount of the RES energy used by loads online, the energy that could be stored and energy that has to be curtailed. Most researchers use monthly or yearly profiles which cannot adequately reflect the dynamic processes in power systems operating with bulk renewable energy.

The new findings presented in this paper embrace in derivation of hourly generation and load profiles in per unit system. The data recorded by transmission system operators for several years allows for the determination of load profiles which can be implemented in simulations of various tasks such as load balancing, cable pooling or energy storage operations.

The examples of hourly profiles of system load, onshore wind generation (labelled as "Onshore") and photovoltaic (PV) generation are shown in Fig. 1. The profiles are normalised to the average monthly capacity and based on aggregated historical data from the Polish power system (PSE SA). While the profiles of PV and onshore wind may appear similar in some months due to averaging and weather patterns, this resemblance is not representative of typical seasonal variability. Further analysis of individual monthly profiles reveals notable differences in generation patterns between PV and wind. The profiles presented are based on the records of the Polish system operator (PSE SA) in four years between 2021 and 2024 [3], [4]. The standardised hourly profiles are computed in a per-unit (p.u.) system using the following formula:

$$P^{pu}_{profile}(t_i) = {P_{recorded}(t_i)}/{P_{Installed}} \tag{1}$$

where t_i – the time step of one hour, $P_{installed}$ - an average power in a given period (one month).

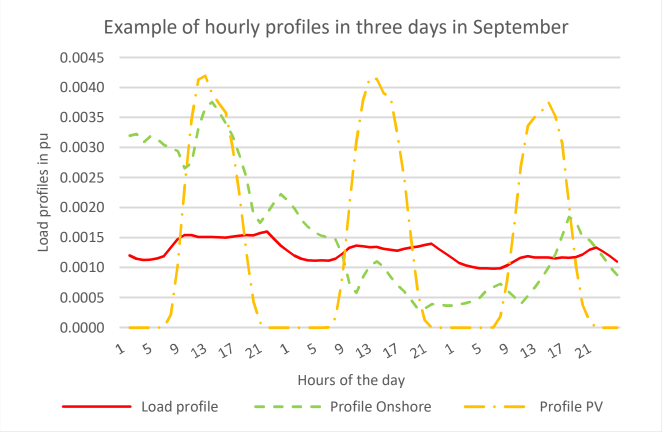

Fig. 1 Standardised hourly profiles of electricity load, onshore wind ("Onshore"), and photovoltaic ("PV") generation in the Polish power system based on data from 2021–2024.

The monthly averaging of installed power results from the accessible data and does not affect the final results. Thanks to the implementation of hourly profiles any real hourly profiles can be determined as a product of the standardized profiles and the power installed in a given system and technology.

III. SIMULATION OF SYSTEM BALANCING

A. Energy balance and RES integration

The energy balance analysis considers electricity production from the various energy sources in a given period assuming hourly granulation and compares such production with the electricity demand.

The technologies of electric energy production embrace the following sets of electricity generation assets: (i) Must-run generations which consist of two main groups: (a) large dispatchable generation power units to stratify the technical network constraints and security power balances and (b) cogeneration and industrial power production facilities which have priority of dispatch due to the constraints in system heat and industrial supply; (ii) partly dispatchable generation comprising mostly from small biogas, biomass and hydropower production units; (iii) onshore wind generation; offshore generation and (iv) energy produced by PV panels.

The example of the power balance for 10 days in January, with the technical conditions determined by Energy Policy as in 2030 and hourly generation profiles for January – Tab. 2 – is shown in Fig. 2. Simulations for 2030 take into the first stage offshore wind construction in the amount of 5.9GW of the installed power due to the Energy Policy.

It can be noticed that the implementation of the Energy Policy aiming at a significant increase of RES may lead to the total electricity production being larger than the entire power demand. It is in particular caused during good wind conditions allowing for the supply of bulk electricity from wind farms. Electric power delivered by PV panels is relatively small due to the winter season.

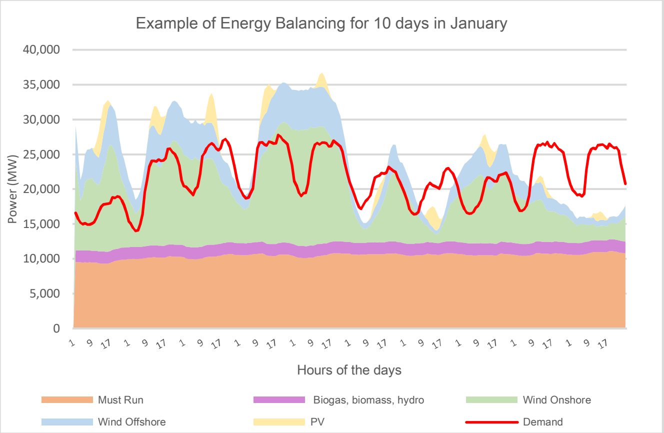

Fig. 2. Power balance for 10 days in January, showing system load and RES generation profiles. Colours representing PV, onshore wind, and load are used consistently with Fig. 3 to enhance interpretability.

Despite the oversupply in the first several days, there are also days and hours in which the power system can accommodate more electricity production than RES can generate – left section in Fig 2.

Taking electricity balance patterns as shown in Fig. 2 the power system operator has to reduce (curtailment) electricity production in the days of its excess over the demand, while it has to increase the production from conventional power units to cover imbalances between supply and demand in other days. It will lead to poor utilization of RES power production capabilities.

The solution can be the implementation of Energy Storage (ES) to charge the excess RES energy to the ES facilities and discharge them during periods when the power system can accommodate more RES energy than the production.

The patterns shown in Fig. 2 are typical for winter and late autumn seasons with the modest generation of PV panels; however, during late spring and summer, the RES generation patterns are different demonstrating large changes in electricity supply during days and nights – Fig. 3. In Fig. 3, the hourly profiles of PV, onshore wind, and system load are displayed using the same colour scheme as in Fig. 2 to ensure visual consistency and clarity.

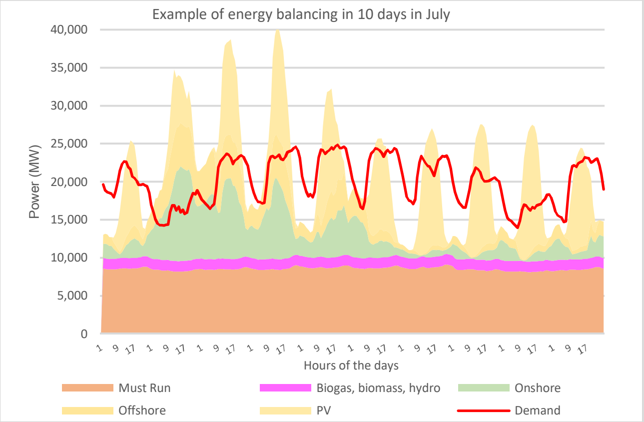

Fig. 3. Power balance for 10 days in July, illustrating RES generation and load profiles. PV and onshore wind generation are shown using distinct colours consistent with Fig. 2.

During springs and summers, there are opportunities to charge and discharge energy store facilities practically every day. It should lead to better utilization of ES capacities reducing the Capex component of ES operation costs.

B. Energy Storage operation

The research presented aims to investigate how the implementation of ES can reduce the excess of RES energy avoiding at least in some parts renewables curtailment. The energy stored after discharging will increase the share of renewables in the total energy consumption [11],[12].

The operation on ES for the same days of January which the energy balance is presented in Fig.2 is shown in Fig.4. The area (green) over the horizontal timeline denoted the excess of RES energy production that cannot be used by loads online. The area below this timeline means the space for perspective RES production which can be filled by energy discharge from ES.

The red bold line presents the state of ES expressing how much energy is stored in a given hour. Two other lines (green and blue) denote the charge (green line) and discharge (blue line) of ES.

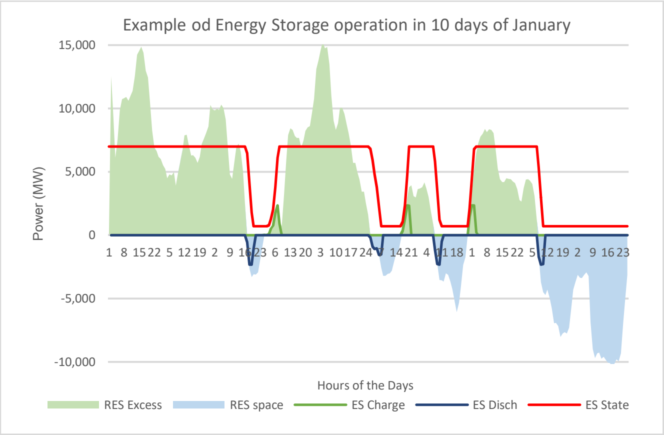

Fig. 4. Example of Energy Storage operation in January

At the beginning of the period analysed the ES is fully charged until the third day afternoon when the smaller RES generation creates the space for ES discharge. The technical constraints allow discharge only to 10% of the ES-rated energy. After discharge, ES is again charged to the rated value and it preserves in this stage for about another two days not having the space to discharge energy. The pattern charge/discharge is repeated several times during this month.

It is worth noting that ES is not charging every day as it is allowed for discharging only in periods when there is no access to renewable energy. If ES were allowed to discharge during the excess of RES energy, it would lead to the curtailment of another renewable source which can deliver RES energy to loads online.

The amount of energy preserved in ES depends on the number of charge/discharge cycles. The smaller the number of cycles the smaller the amount of energy recovered from ES and the more expensive ES operation as the ES fixed cost is distributed on a smaller amount of the energy stored [13], [15].

The different energy production patterns can be observed during late spring and summer when the Sun operation allows for large energy generated by PV panels – Fig. 3. In this period, ES can practically operate every day due to the differences in day and night RES energy production.

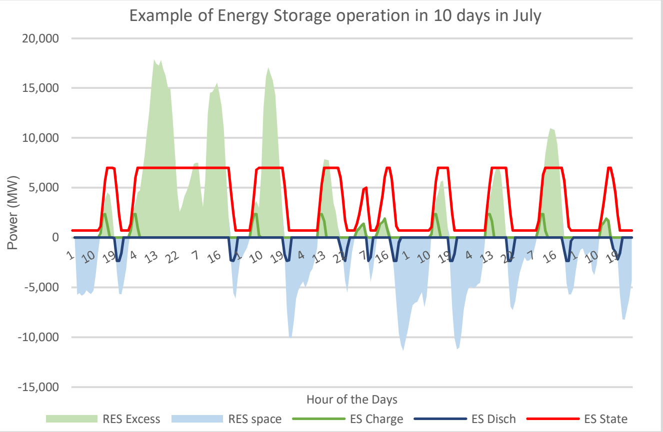

Fig. 5 Example of Energy Storage Operation in July

The number of ES cycles in a summer month can be similar to the number of days in the period analysed – Fig. 5. It leads to large amounts of stored energy, better utilization of ES facilities and lower cost of ES operation calculated per a unit (MWh) of discharged energy – Fig. 5.

C. *Use of rated storage capacity*

The basic element impacting the cost-effectiveness of ES is Capex reflecting the investment costs of ES facialities. It is calculated as the overnight cost (Engineering and Services) with the financial cost of investment. Usually, Capex costs are computed for a discharge energy unit (MWh), which strictly depends on the number of ES discharges in the calculated period, usually a year. So the question arises of how to tie up ES discharges, in terms of numbers with the energy discharged expressed in units of electrical energy (MWh).

The examination of ES operation presented in Fig. 4 and Fig.5 indicates that some discharges can be classified as "full discharge" in which the amount of energy stored drops from the maximum value to the minimum; however, there are also "partial" discharges relating to the changes of energy stored levels not reaching the extreme values. It is necessary to recalculate "partial" discharges to the "full" discharges to find a single and universal measure of ES operation.

Such universal measures can be defined as the Number of Full Discharge of ES facilities in a given period and it can be calculated as follows:

$$NFD = \sum_{i=1}^{N} E_{discharge}(i) \Big/ E_{rated}^{ES} \qquad (2)$$

where NFD – Number of Full Discharge in a year; $E_{discharge}(i)$ – energy in "i" discharge; E_{rated}^{ES} – rated energy of ES facilities.

The coefficient NFD allows for the simple calculation of the total energy discharged in a given period as such energy can be computed as:

$$E_{discharge}^{annual} = NFD * E_{rated}^{ES} \qquad (3)$$

Despite NFD being a simple and convenient way of the energy discharged calculation, what is particularly important in the evaluation of ES investment return; the precise determination of this coefficient requires the information on hourly operation of ES plants as shown in sections IV and V.

Another important problem is the evaluation of the impact of external factors such as values of RES generation or the development of energy storage facilities in the entire power systems.

VII. SYSTEM-LEVEL IMPACTS OF ENERGY STORAGE

A. *Impact of RES generation*

The European Energy transformation implemented by the Energy Policies of member states will lead to an increase in RES generation to fulfil the Energy Policy targets measured by the share of renewable energy in the total energy consumption. Moreover, there are proposals to increase RES shares to make the Energy Policy more ambitious in achieving energy transformation targets. The increase of RES generation will impact the operation of the entire power system including the operation of ES facilities.

The impact of Energy Policy targets on ES operations in particular on the number of annual discharges are presented in Table 3. Three RES generation options have been analysed: (i) RES production as defined by Energy Policy, (ii) increase of RES generation by 50% and (iii) rise of renewables production by 100% in the period between 2030-2050.

Table 3. Number of Full Discharges (NFD) for three variants of energy policy and resulting increase of RES generation.

Number of full discharges per year (NFD)	**2030**	**2040**	**2050e**
RES as in Energy Policy (EP)	193	153	113
Plus 50% more RES than in EP	193	143	89
Plus 100% more RES than in EP	193	104	69

As it can be seen in Tab. 3 the number of full discharges (NFD) decreases with the increase of renewable energy production. It happens in two directions: (i) time when the RES amount goes up due to the increasing targets of RES shares in the total electricity consumption and (ii) with the options considering the increase of renewable energy as the steps to more ambitious decarbonization policies.

The figures shown in Tab. 3 show the expected values of NFD and indicate that the investment in ES facilities before 2030 can expect about 200 NFD per year in the first period of operation. However, the NFDs per year decrease in both cases: increase of RES energy in time and more ambitious options of Energy Policy.

The effect of decreasing NFDs concerning the increasing RES energy amount can be explained by examining energy balances as shown in Fig. 2 and 3. The larger the RES production the less space for discharging ES as most of the demand can be supplied online by the larger RES energy. The increase in RES production allows for better (easier) conditions to charge ES but at the same time, it reduces the opportunities to discharge ES installations. It causes the ES to remain in longer periods in fully charged modes reducing the NDFs and leading to the reduction in ES facilities as the investment return strictly depends on NFDs.

B. *Impact of ES facilities*

The second important factor which may have an impact on NFDs is the investment in ES installations and the increase of

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total ES capacity. Despite the different reason the effect relating to NFDs is the same, as NDFs drop with the increasing amount of ES capacities. The more ES installations the more competition in the allocation of stored energy and the reduction of an expected NFD for a single ES – Tab. 4.

Table 4. Number of Full Discharges (NFD) for three variants of ES facilities and resulting increase of energy to discharge.

Energy storage variants	**2030**	**2040**	**2050e**
ES as Energy Policy	193	153	113
Plus 50% more ES than in Energy Policy	182	145	111
Plus 100% more ES than in Energy Policy	163	133	104

The figures shown in Tab 4 illustrate the typical behaviour in any competitive market where a higher level of competition leads to smaller market participation.

C. *Curtailment and role of energy storage*

The results of the Energy Policy simulation are shown in Tabl. 5. The input values for the year 2023-2040 are adopted directly from the Energy Policy data, while the parameters for 2050 have been estimated using the Energy Policy data.

The increasing amount of RES production observed between 2023 and 2050 cannot be entirely used by online energy consumption as renewable energy production is larger than its generation taking into account the time coincidence in RES production and consumption. The energy not used online can be curtailed; however, it leads to the inefficient use of RES production resources or the energy excess can be stored for later use when the RES generation is smaller than demand.

Table 5. RES energy production in Energy Policy

Energy and Shares	**2023**	**2030**	**2040**	**2050e**
Potential RES	45.1	108.0	187.5	263.4
RES use online	44.4	82.3	142.0	198.1
RES stored in BESS	0.0	1.3	2.6	4.5
Total RES used	44.4	83.6	144.6	202.6
RES curtailment	0.7	24.4	42.9	60.8
RES curtailed as % of potential RES	2%	23%	23%	23%
RES used as % of potential RES	98%	77%	77%	77%
RES Potential as % of load	27%	56%	72%	79%
Real RES as % of load	27%	43%	56%	61%

The capacity of the energy storage system is determined by Energy Policy as 7GW in the year 2030 and 17GW in the year 2040. The estimated ES capacity in the year 2050 is assumed to reach 40GW.

The energy stored (BESS) is equal to 1.3TWh in 2030 and it increases to 2.6TWh in the year 2040 and to 4.5TWh in the year 2050, respectively. It allows to increase in the total use of RES energy in comparison to the use online.

However, despite the use of energy storage, there is still a need for the RES energy curtailment which reaches 23% of the entire RES production in 2050, when RES energy counts for 61% of the total demand. It is expected that the further increase in RES production will lead to larger renewable energy curtailment and ES capacity should increase to accommodate at least a part of RES energy access [14].

CONCLUSIONS

The paper presents the first stage of research aiming at the determination of energy storage operation conditions and investigates the possible amount of energy stored to increase the RES consumption and facilitate the Energy Policy implementation leading to the increasing shares of renewables in the total energy consumption.

The key element in the evaluation of the economic effectiveness of energy storage is the amount of energy that can be charged and discharged to the storage facility. The research proposes using a new coefficient defined as the Number of Full Discharges (NFD) which can facilitate the calculation of the efficient energy storage size installations.

Moreover, the results highlight a strategic dilemma: as the installed capacity of RES and ES grows, the number of full discharges (NFD) may decrease, reducing the utilisation of storage systems. This indicates a competitive dynamic in which increasing RES output or ES capacity can limit the operating space of other storage units within the system.

The simulations of power system operations with large amounts of renewable energy production require the implementation of hourly profiles of loads, renewable and energy storage to embrace the time coincidence energy production, consumption and storage.

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