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Battery Energy Storage Management for Smart Residential Buildings

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***Abstract*—The environmental issues caused by conventional and centralized fossil-fuel based power generation has driven the decentralized structure of electricity grid. These grids are dominated by high penetration of variable Renewable Energy Sources (RES) such as a wind and solar photovoltaic (PV) units, which is challenging to the grid operation and control. In that connection, nowadays buildings are also becoming more technologically complex and intelligent due to increasing automation, integration of energy sizable flexible loads (heat pumps, electric vehicles etc.) and local RES units. The energy generated by private residential RES are generally intended for private use but it can also be sold back to the grid based on different operational and electricity market scenarios. To efficiently balance the local energy systems in the residential buildings, maximize the use of RES and financially benefit the prosumers, storage units like Battery Energy Storage Systems (BESS) plays an important role. This paper aims to analyse the management of such smart sustainable buildings subjected to variable generation and demand scenarios.**

Keywords—Energy management, Smart Buildings, Home Energy Management System (HEMS), Battery Energy Storage System (BESS), battery management system.

I. INTRODUCTION

Due to the rapid growth of global electricity consumption and climate change, the EU countries have established three main climate and energy targets to be reached before 2020: 20% reduction in greenhouse gas emissions, 20% of energy derived from renewables and a 20% increase in energy efficiency [1]. In synergy with the ambitious EU energy targets, the Danish government has established a national Energy Strategy 2050 with the main goal to make Denmark 100% independent of fossil fuels by 2050 [2], and the “Road map for Smart Grid research, development and demonstration up to 2020” [3]. The large-scale integration and penetration of more distributed and intermittent RES and flexible loads into the power grid in combination with more stringent environmental mandates can lead to significant social, environmental, economic and technical impacts. These impacts may lead to both positive consequences such as improving energy efficiency, reducing CO2 emission and preventing global warming, as well as negative effects, connected with issues of managing the large amount of unpredictable power generation that can result in voltage, frequency unbalance and reverse power flow. In order to develop a sustainable power system for the future, to derive maximum benefit from such changes and to prevent negative consequences these impacts should thoroughly be investigated and a sophisticated complex set of innovative activities have to be introduced.

According to [4] the buildings account for about 40% of total final energy consumption, and around 55% of electricity consumption in the EU-28 in 2012. The share of buildings’ energy consumption in Denmark is one of the highest in Europe and takes about 44%. Since the energy systems in buildings are considered not only from consumption point of view, but also from energy production, and, to some extent, as an energy storage, in this manner, the buildings are one of the most attractive platforms to implement smart energy technologies and integrated energy systems to increase renewable energy supply, and energy efficiency. However, in order to implement it, the intelligence schemes, data management, responsiveness and activation of energy assets of the existing buildings must be improved to optimally utilise the local energy supply and demand. The building management and operations, and further grid support can significantly be improved by:

- advancement of the level of automation within buildings by introducing Building/Home Energy Management System (BEMS/HEMS) providing thereby a proper control interface between these smart buildings and electric grid by enhancing bi-directional power flow and data exchange [5-8];
- exploiting demand respond [9-11] and flexibility in power supply by utilizing the flexible loads such us plugged in electric vehicles, heat pump, electric boilers, etc., and;
- utilizing the energy storage technologies such as BESS [12-15].

The main objective of this work is focussed on improving the energy and sustainable use of energy in buildings by increasing the utilisation of renewable generation and storage units. Thereby cost of energy may be reduced by flexibly utilising the energy storage unit and facilitate more opportunities for the prosumers to trade their energy flexibility services from buildings in energy markets.

There are many different approaches to BESS utilisation which has already been described in variety of scientific papers. The utilisation of BESS is far from being new today, however since the global price of batteries has the decreasing tendency, this topic becoming even more realistic. Y. Li at al. in [12] investigate the performance and payback period of grid-connected residential PV-battery system. In [13] the system-level approach to co-schedule the usage of battery storage (in addition to grid electricity) to reduce the total building energy

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cost, including the electricity consumption charge, the peak demand charge, and the battery cost is introduced. An optimal battery sizing of smart home, considering real time pricing Demand Respond (DR) scheme and the features of customer load profiles under off-grid condition with respect to achieved revenue is presented in [14]. R. Luthander at al. [15] is focused on enhancing self-consumption and peak shaving of residential photovoltaics using shared storage that can effectively relieve the pressure on the public grid.

The rest of the paper is organised as follows: in Section II, the modelling of components of smart sustainable building is presented. In Section III, the methodology of modelling of smart building, the energy management algorithm and the simulation scenarios are described. Results and analysis are presented in Section IV. Finally, the conclusion from the work is presented in Section V.

II. MODELLING OF COMPONENT OF SMART BUILDING

It is assumed that smart building consists of the following component: Wind Turbine (WT), PV modules, and the energy storage unit (BESS). For the creation of energy model of smart building the following power curves are needed:

- Load curve,
- WT's curve,
- PV panels curve and,
- Based on a previous three, the State of Charge (SOC) curve of the battery unit.

A. Load

A historical hourly load profile of a single-family house in Denmark is taken as a basis. The period of observability is one calendar year, however, since the off-season months are predominant in Denmark (short, medium-warm summer and the partly snowy/rainy winter), the period of one week in April is presented for the reason of better observability.

The total annual energy consumption of the considered building is 5201.3 kWh. A monthly consumption varies from 695.5 kWh in the coldest month to 315.7 kWh in the warmest month respectively. A predominant monthly consumption is in between 421.8 - 498.5 kWh, while an average one is 433.4 kWh; average weekly consumption is 99.2 kWh; average daily consumption is 14.2 kWh. Since the load profile is based on a time step of one hour, an average hourly energy consumption is equal to an average power – 0.59 kWh (kW) while the maximal (peak) power demand is 5.4 kW. The reference loads consumption profile is presented in Figure 2.

B. Wind turbine

The data required for modelling a power curve of a wind turbine are the wind speed and power output recorded at periodic intervals over a certain period of time. The historical wind speed data are obtained from the weather forecasting station based at Aalborg University laboratory.

In order to calculate the power output of WT certain parameters such as blade length and rated power of wind turbine should be set in initially. In Denmark, the local municipalities determine whether the WT can be placed in building premises. There are some rules and regulations that include planning, technical certification in terms of energy production, safety and the environment protection legislation. Also it has to comply with noise margins, and grid connection regulation before the WT can be erected in the projected landscape. According to [16] there are three options of choosing of WT for household use with respect to certification rules. Registration exception is subject to WTs with the rotor swept area from 1 to 5 sq. m., rotor diameter from 1.13 to 2.52 m. The wind turbines with the rotor swept area from 5 to 40 sq. m., rotor diameter from 2.52 to 7.14 m. have to meet the Danish certification rules, while wind turbines with rotor swept area from 40 to 200 sq. m. and rotor diameter from 7.14 to 15.96 m. have to be certified according to ISO 61400-2 or 22. The power limit in this regards is 25 kW, and the maximal high of wind turbine's pole is 25 m. In this paper, it is assumed that the wind turbine meets all Danish rules and regulations, and base on this, the parameters of WT were chosen as follows.

The rotor swept area of the wind turbine is 11.3 sq. m., rotor diameter is 3.8 m., cut-in wind speed is 1.8 m/s., cut-out wind speed is 60 m/s., rated wind speed is 11 m/s., high of the pole is 12 m., and the rated power is 3 kW.

For calculation of power output of wind turbine, the following fundamental equation of Wind Power Conversion have been used [17].

$$P = \frac{1}{2}\rho\pi R^2 v_\infty^3 C_P \tag{1}$$

where: P – power captured by the rotor of a wind turbine, ρ – air density, R – rotor radius (the length of the wind turbine blades), V - wind speed, C – power coefficient.

C. PV panels

The data required for modelling a power curve of a PV panels are the solar irradiance data and power output recorded at periodic intervals over a certain period of time respectively. The same as the data for a WT curve, the historical solar irradiance data are obtained from the weather forecasting station based on the laboratory of Aalborg University.

Following the wind turbines, a PV panels also have to meet specific rules and regulations. The restrictions for households are mainly related to the inverter power and the amount of energy generated to the grid. For the time being, the limitation should not be over the 6 kWh. In this paper, it is assumed that the PV panels array meets all Danish rules and regulations, and base on this, the parameters were chosen as follows.

The peak power – 0.315 kW, rated voltage – 54.7 V, rated current – 5.76 A, efficiency – 19.3 %, open circuit voltage – 64.6 V, short circuit current – 6.14 A, dimensions – 1559 x 1046 x 262 mm., quantity – 18 pcs, inverter losses – 8 %, temperature losses 8%, DC cables losses 2%, AC cables losses – 2 % , shadings – 3%, losses at weak irradiation – 3%, losses due to dust, snow – 2%, other losses – 0%.

The power output of a PV array is calculated using the following equation:

$$P = A \cdot r \cdot H \cdot PR \tag{2}$$

where: P – power output, A – total solar panel area, r – solar panel efficiency, H – annual average solar irradiation on tilted panels, PR – performance ratio, the coefficient for losses.

Figure 1 represents power curves for both wind turbine and PV panels array. Since the wind activity is not high enough during the certain period (the maximal wind speed is 9.8 m/s in the 1st of April at 15:00), and due to the rated wind speed of the wind turbine is 11 m/s, the low power output is observed in the most of time. However, the power output from the solar PV panels can be observed in the most of daytime periods. The sum of the power outputs of the wind turbine and PV panels array with respect to the household's consumption can be found look at the Fig. 2.

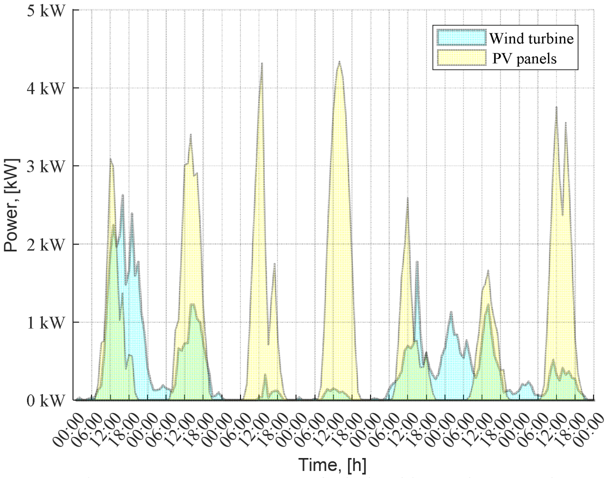

Fig. 1 Power output curves of wind turbine and PV panels.

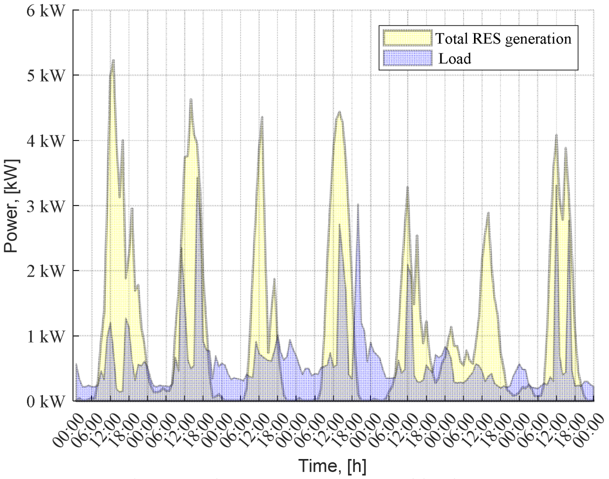

Fig. 2 Total RES power output and load curves.

D. Energy storage unit

The parameters of BESS should be chosen when the all values of the power outputs of WT and PV panels and the load has already calculated and known.

The battery power (P_{Bat_rated}) and the converter power ($P_{Bat\_converter}$) is chosen with respect to the maximal household's load during an hour. There are two batteries with the different energy capacity (E_{Bat_rated}) are taken into consideration during the simulation process. It is assumed that initial, maximal and minimal State of Charge (SOC) of the battery is similar to both batteries (see below). Since the SOC is an indicator of the energy level of the battery in percentage, the parameters for two batteries are as follow.

Battery №1. Lithium-ion. $P_{Bat\_rated} = P_{Bat\_converter} = 5.4$ kW, $E_{Bat\_rated} = 5.4$ kWh (that is the capacity that assumed to cover a maximal household's load during an hour), $SOC_{Init} = 50\%$, $SOC_{Max} = 90\%$, $SOC_{Min} = 10\%$, $E_{Bat\_init} = 2.7$ kWh, $E_{Bat\_max} = 4.86$ kWh, $E_{Bat\_min} = 0.54$ kWh.

Battery №2. Lithium-ion. $P_{Bat\_rated} = P_{Bat\_converter} = 5.4$ kW, $E_{Bat\_rated} = 13.5$ kWh (that is the capacity that assumed to cover a maximal household's load during the period of 2.5 hours), $SOC_{Init} = 50\%$, $SOC_{Max} = 90\%$, $SOC_{Min} = 10\%$, $E_{Bat\_init} = 6.75$ kWh, $E_{Bat\_max} = 12.15$ kWh, $E_{Bat\_min} = 1.35$ kWh.

The detailed explanation of SOC calculation and the energy flow is presented in the following section.

III. METHODOLOGY AND SIMULATION SCENARIOS

In order to proceed the simulation, all listed above values including the power outputs of WT and PV panels, the load, and the battery parameters have to be calculated, known and assigned. The period of simulation is 7 days (t_{start} is 00:00 1st April, t_{end} is 00:00 8th April) with a time step t_{step} of one hour.

The state of charge of the batteries at any time from t_{start} to t_{end} depends on the energy level of battery in the previous moment of time (E_{Bat_init}), the current value of generated energy (E_{Excess} or $E_{Shortage}$, see below), the battery rated power (P_{Bat_rated}), the throughput of the battery converter ($P_{Bat\_converter}$), energy, passed through the battery converter ($E_{Bat\_converter} = P_{Bat\_converter} * t_{step}$), and the maximal and minimal charging level of the battery (E_{Bat_max}, E_{Bat_min}). These are decision-making parameters to control the overcharging and the deep discharging of the battery storages. The case of overcharge may occur when high power is generated by the RES, when low load demand exists (as shown in many daytime periods in Fig. 2), or when the volume of energy storage is very limited. In such a case when the state of charge of the batteries reaches the maximal or minimal limit, SOC_{Max}, SOC_{Min}, the battery control system will stop the charging process and disconnect the load. This is important to prevent batteries from shortening their life or even their destruction.

The SOC of the batteries is calculated as follows [1] (the flowchart is presented in Fig.3).

1) When the power generated by the RES is greater than the load (as see in many periods of week in Fig. 2), the delta power (i.e. $P_\Delta = P_{RES} - P_{Load}$) is greater than zero ($P_\Delta > 0$), the excess of power can be observed. P_Δ is called P_{Excess}, in this case, and the energy (i.e. $E_{Excess} = P_{Excess} * t_{step}$) either stored in batteries (charged), either sold back to the grid. There are few sub-conditions in relation to this are described below.

1.1) When the value of exceeded power is greater or equal to the rated power of the battery converter $P_{Excess} \geq P_{Bat\_converter}$, there are two options of the energy redistribution can be observed in this case:

a) if the sum of values of battery energy in a previous moment of time E_{Bat_init} plus the energy passed through the battery converter $E_{Bat\_converter}$ is lower or equal to the maximal battery energy level E_{Bat_max}, the amount of charging energy E_{To_Bat} will be equal to the value of $E_{Bat\_converter}$. The rest of energy goes to the grid and equal $E_{To\_Grid} = E_{Excess} - E_{Bat\_converter}$. The partial charging and partial generation to the grid is observed in this case;

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[1] The calculation is made without taking into account the storage round-trip (charge/discharge) efficiency, aging (capacity degradation) and other coefficients, that means no any energy losses for the battery and converter taken into account. However, in the real life, the round-trip coefficient typically is about 0.8 (that means that only 80% of energy put into the storage can be retrieved).

b) if $E_{Bat\_init} + E_{Bat\_converter} > E_{Bat\_max}$. In this case, the partial charging and partial generation to the grid can also be observed. The amount of energy passed to the grid and the amount of battery charging energy are calculated as shown in block 1.1.b., Fig. 3.

1.2) When the value of exceeded power is lower than the rated power of the battery converter $P_{Excess} < P_{Bat\_converter}$, and:

a) if $E_{Bat\_init} + E_{Excess} \leq E_{Bat\_max}$, the only charging process is observed in this case. $E_{To\_Grid} = 0$, $E_{To\_Bat} = E_{Excess}$;

b) if $E_{Bat\_init} + E_{Excess} > E_{Bat\_max}$, this case is also shows partial charging and partial generation to the grid. The calculations of E_{To_Grid} and E_{To_Bat} are presented in Fig. 3, block 1.2.b.

2) When the power generated by the RES is less than the load, the delta power is less than zero ($P_{\Delta}<0$), the shortage of power can observed. P_{Δ} is called $P_{Shortage}$, in this case, and the energy (that is $E_{Shortage} = P_{Shortage} * t_{step}$), either taken from the batteries (discharged) or from the grid. There are also few sub-conditions in relation to this are described below.

2.1) When the value of missing power is greater or equal to the negative value of the rated power of battery converter $P_{Shortage} \geq - P_{Bat\_converter}$, and:

a) if the sum of values of battery energy in a previous moment of time E_{Bat_init} plus the value of energy shortage $E_{Shortage}$ is greater or equal to the minimal battery energy level E_{Bat_min}, the amount of discharged energy E_{From_Bat} will be equal to the value of $E_{Shortage}$. The amount of energy taken from the grid is equal $E_{From\_Grid} = 0$, that means, there is no any power supplying from the grid;

b) if $E_{Bat\_init} + E_{Shortage} < E_{Bat\_min}$, the partial discharging of the battery and partial power supplying from the grid is observed in this case. The discharging energy E_{From_Bat} and the energy taken from the grid E_{From_Grid} are calculated as shown in Fig. 3, block 2.1.b.

2.2) When the value of missing power is less than the negative value of rated power of the battery converter $P_{Shortage} < - P_{Bat\_converter}$, there are also two possible directions of energy flow is provided in this case:

c) if $E_{Bat\_init} - E_{Bat\_converter} \geq E_{Bat\_min}$, the partial discharging and partial power supplying from the grid is observed in this case. The calculation of E_{From_Bat} and E_{From_Grid} is presented in Fig. 3, block 2.2.a.

d) if $E_{Bat\_init} - E_{Bat\_converter} < E_{Bat\_min}$, this case is also directed on partial charging and partial power supplying from the grid. The calculation of E_{From_Bat} and E_{From_Grid} is described in Fig. 3, block 2.2.b.

There are three different scenarios is taken into the consideration during the simulation process:

Scenario 1. Without BESS;

Scenario 2. With battery unit №1 (see the parameters of the battery in section II D);

Scenario 3. With battery unit №2 (see the section II D);

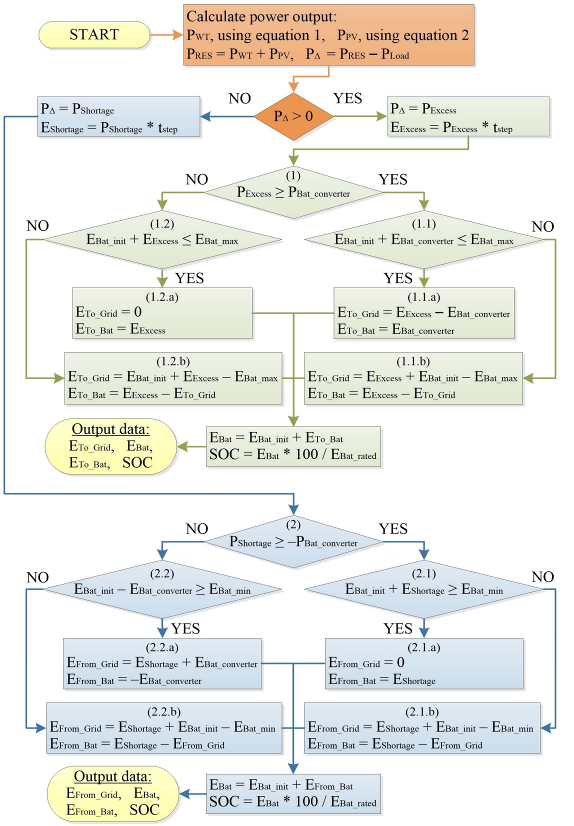

Fig. 3 Flowchart of creating (RES-Battery-Grid) building model.

IV. RESULT AND DISCUSSION

The results of simulation process are presented in the following figures and the tables. Fig. 4 represents the delta power curve. The delta power in this sense means the difference between the power generated from RES and the household's load, where the positive value is Excess of power that could either be generated to the grid or accumulated in the BESS (if there is one exist), and the negative value is Shortage of power, that means that power is supplied either from the grid or battery respectively. Since the RES generation prevails over the load at that period of time, the big excess of power during the whole period can be observed and the small shortage of power in the middle of the week is exist.

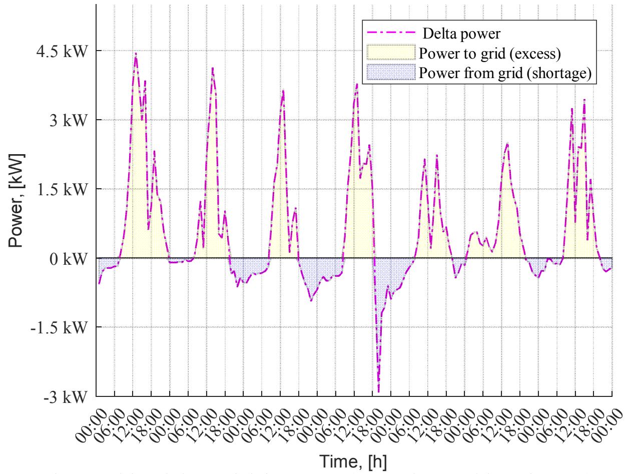

Fig. 4 Grid activity and delta power (Scenario 1. Without battery).

The charging and discharging curves of the battery unit №1 is presented in Fig. 5 (see the battery №1 parameters in section IID). The figure shows the part of power with respect to the delta power (shown in Fig. 4) that is accumulated to the battery unit in an hours of high activity of RES and low consumption (see the 3rd midday period in Fig. 2), and from the other side the part of power that is taken from the battery in an hours of peak consumption or low RES generation (see evening-time periods in Fig. 2).

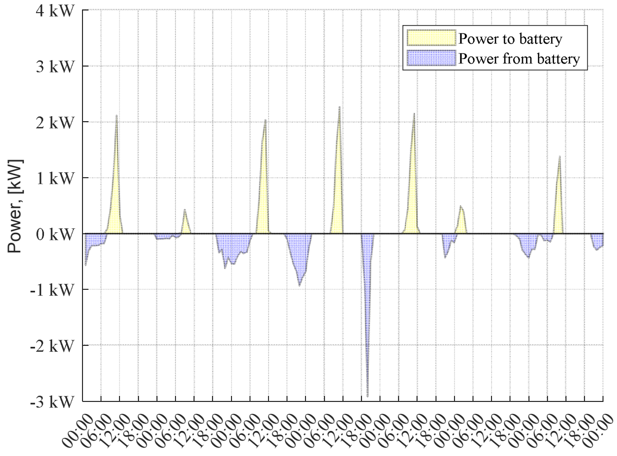

Fig. 5 Battery activity (Scenario 2. Battery N1).

The other part of power, based on the SOC of the battery №1 and the delta power, either goes to the grid (excess) or taken from the grid (shortage). These power curves are presented in Fig. 6.

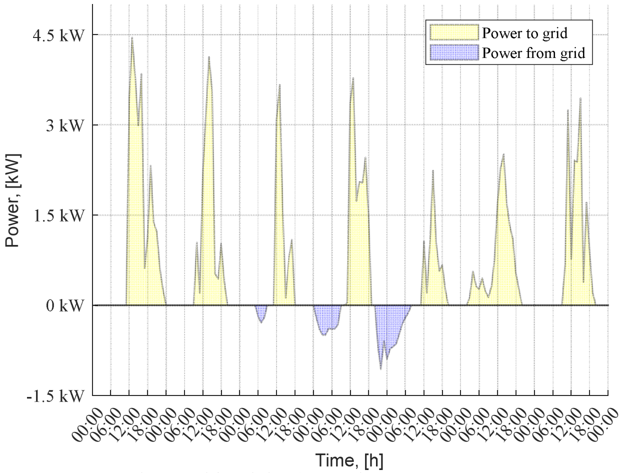

Fig. 6 Grid activity (Scenario 2. Battery N1).

In the figure 7, the charging and discharging power curves of the battery unit №2 are presented. The parameters of the battery №2 are given in section IID. Fig. 8 represent the excess and shortage of power based on the delta power and the SOC of the battery unit №2.

State of charge for both battery №1 and battery №2 is presented in Fig. 9.

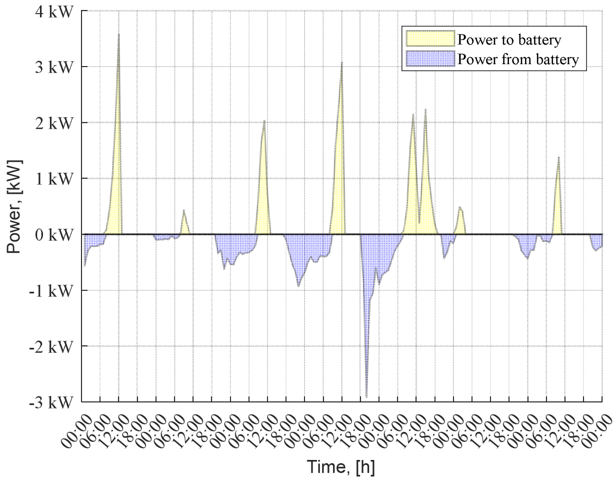

Fig. 7 Battery activity (Scenario 3. Battery N2).

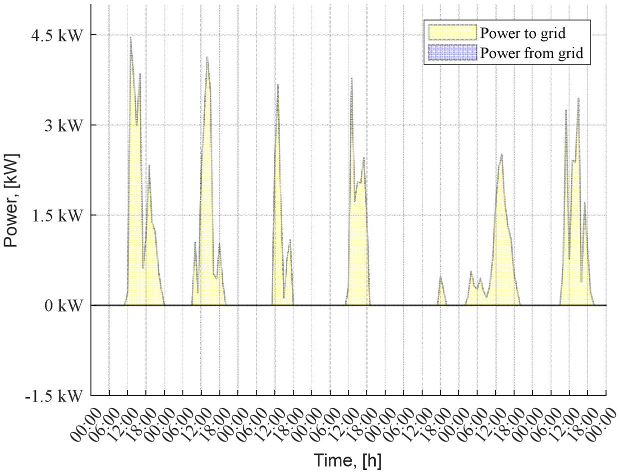

Fig. 8 Grid activity (Scenario 3. Battery N2).

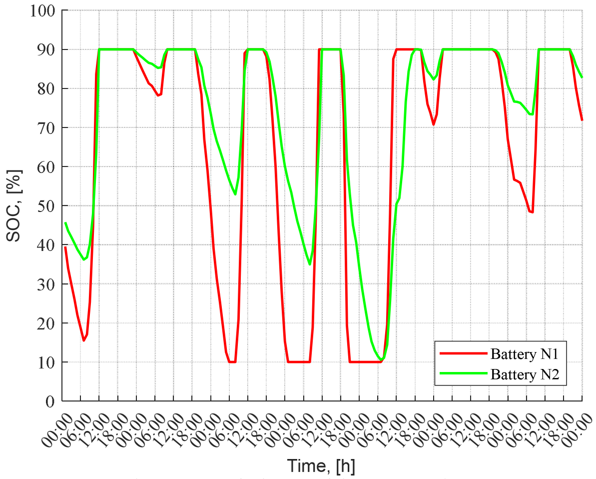

Fig. 9 State of Charge of the BESS unit.

Comparing three different scenarios it is observed that in the first case (scenario 1) even utilising the RES, there are still quite a lot of hours, when the energy is taken from the traditional grid to cover the household's consumption.

In the second case (scenario 2), the battery №1 in combination with RES partially covers the household's power supply needs and accumulate some amount of energy (see Table II) that can be either used in hours with low RES generation or sold back to the grid based on the variety of incentive programs offered by utilities.

Finally, in the third case (scenario 3), the battery №2 in combination with RES provides much more opportunity to a self-sufficient power supply of the household during periods with high energy generation from RES and has the capacity to accumulate enough energy to provide flexibility in the power supply and sustainable use of energy for household owners. The accumulated energy can also be either used in hours with low RES generation or sold back to the grid based on the variety of incentive programs offered by utilities. However, it is highly not recommended to cut off the traditional power supply due to a variety of the weather condition.

The numerical results are presented in Tables 1 and 2.

TABLE I. PERFORMANCE IN DIFFERENT PERIOD OF TIME

Time period	***Wind Turbine***	***PV panels***	***Total RES***	***Load***	P_{Δ}	E_{Excess}	$E_{Shortage}$
	kWh	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*	*kWh*
7 days	65.1	139.3	204.4	105.6	98.8	128.7	-29.9
1 month	201.0	496.6	697.5	487.7	209.9	426.5	-216.6
1 year	2,827.9	4833.3	7711.3	5,201.3	2510.0	4889.1	-2379.1

TABLE II. PERFORMANCE IN DIFFERENT SCENARIOS (7 DAYS)

Scenarios	E_{To_Grid}	E_{From_Grid}	E_{To_Bat}	E_{From_Bat}
	kWh	*kWh*	*kWh*	*kWh*
Scenario 1	128.7	-29.9	–	–
Scenario 2	107.8	-10.2	20.9	-19.7
Scenario 3	94.4	–	34.4	-29.9

V. CONCLUSION

Different countries in connection with climate change differently promote and stimulate the use of sustainable energy. In some countries, encouraging methods are based on the net metering, while others on a variety of "green tariffs". Since the growth of small distributed and interrupted energy generations over time leads to difficulties in regulating and balancing the network (over-saturation, voltage, frequency control etc.), in order to hold the balance, these incentive tariffs become more stringent and more complex.

The result, based on the data obtained from the simulation of the three different scenarios, shows that the utilisation of a BESS in combination with RES and grid may lead to techno-economic benefits for both building systems, in terms of reducing the cost of energy, as well as the overall energy networks in terms of facilitating the grid balance, energy efficiency and sustainable use of energy.

However, for the final assessment of the profitability of using different types of BESS, more accurate technical and economic analysis that include the dynamics of the Lithium-ion element's price, the market dynamics of tariffs, losses, optimization techniques and probable ways of development should be taken into account in calculations.

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