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ENERGY STORAGE AT AGGREGATOR ENTITY LEVEL

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Micro-grids (MG) which include PV and BESS are more common in many residential units, but also in the industrial sector. However, MG installations in residential buildings are a more complex problem, especially in the context of ownership and distribution of benefits resulting from the quantification of the produced and delivered electricity generation. A different way of aggregation for centralized management for residents and asset owners in residential buildings is proposed in this article. A model for invoicing, benefits distribution, and an algorithm for a predictive control model for optimizing MG operations is analyzed.

Keywords: Battery Energy Storage Systems (BESS), Photovoltaic System (PV), Aggregator Entity (AE), Aggregation Services (AS)

1. Introduction

In the recent years, in residential buildings, the number of MG which includes PV and BESS increased. Nevertheless, the installation of MG in residential buildings is not considered feasible due to the complexity of ownership in buildings with multiple owners. The importance of analyzing residential buildings for installing MG was taken into consideration due to the electricity consumption, including usage of electric vehicles (EV) which increased in the last decade. In Romania, electricity consumption for the residential sector increased 18% between 2012 and 2022 [1].

In a study of a German photovoltaic system, it was demonstrated how the charging system of EV could improve the profitability of an autonomous photovoltaic system [2]. In another study, an energy management system consisting of solar photovoltaic panels and wind turbines was installed on a five-house complex, where the energy surplus was stored using BESS [3]. In this article these problems are trying to be addressed by proposing the creation of a new aggregator system, as follows: an invoicing system based on internal trading is integrated with a platform for central management for MG managing, in order to increase the profitability of the service. With the purpose of encouraging the end customers to participate to the AS, a strategy is used to guarantee low prices and rewards for participation. A five-level block with thirty apartments, located in Bucharest is analyzed to endorse the performance of the AE in an analysis using three different invoicing prices.

2. Overview of the services provided by the AE

The services provided by the AE for the end customers from the building are taking into consideration, not only the benefits of the MG owners, but also of the residents from the building. In order to curtail the investments and also the operating costs of the AE, while increasing the benefits for the owners, a comprehensive solution is presented below.

There are several indications which demonstrate that AE could efficiently decrease invoices value, an example is presented in [4]. Generally, the AE services have two essential features: MG assets management, including BESS, PV, EV and the sale of electricity to the connected active users. The AE purchases electricity from the wholesale electricity market and sells it to the end customers at a lower price compared to electricity suppliers.

2.1. Diagram of the electrical circuit of the AE services

For AE services analysis and for understanding the services proposed in this article, in Fig. 1 is presented an electrical circuit diagram in which the PV and BESS systems are connected to a building. Also, the EV charging station is represented, as well as a building without PV.

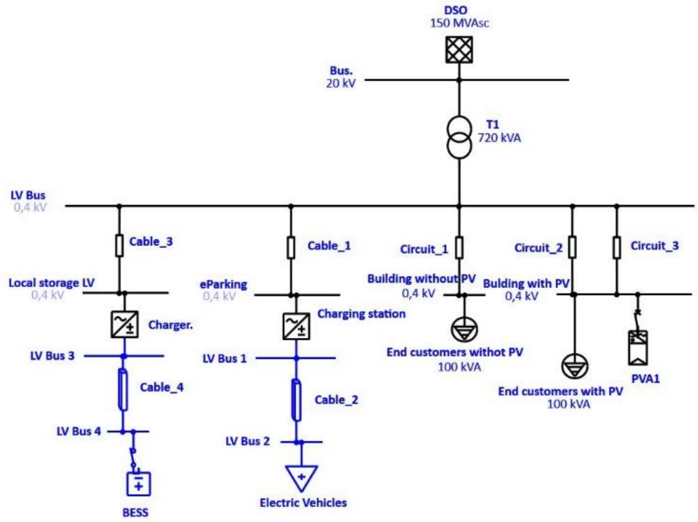

Fig. 1. Electrical circuit diagram with BESS and PV systems

As per fig. 1, the starting point is the distribution system operator (DSO). The connection of the low voltage bus to the DSO is established using the T1 transformer. Also, in fig. 1 both PV and BESS systems are connected.

Fig. 1 was created using the ETAP program and the data presented in table 1 are exported from the above-mentioned program after running the power circulation and checking the accuracy of the system.

Table 1

Technical specification for the presented electrical circuit

		BUS				Transformer
	U.M.	eParking	Local storage LV	Building w/o PV	Building w/ PV	2 W transformer 20/0,4 kV
Cable length	m	100	100	100	100	-
Type of cable	N/A	1 - 3/ C 150	1 - 3/ C 95	1 - 3/ C 120	1 - 3/ C 120	-

Allowable	-	345,5 A	258,9 A	258,9 A	299,8 A	720 kVA
Reactive power flow	kVAr	10,76	7,16	16,33	5	46,83
Active power flow	kW	43,72	46,46	99,40	23,5	231,30
The neutral power factor	-	0,97	0,99	0,99	0,98	0,98
kW losses	kW	0,188	0,323	1,48	0,067	-

According to the report exported from ETAP and presented in table 1, the neutral power factor is higher than 0,97 for all for all BUS-es and the losses for each BUS are at a minimum level, considering the load.

2.2. Physical structure of the building

In order to implement the AE service proposed with minimal costs, a large part of the cables and connections from the building will be reused. Only a couple of updates need to be performed, such as smart remote monitoring and installing control devices.

In fig. 2, the arrows represent the electricity injected/extract and exchanged with the system. For smart remote monitoring and control devices, bidirectional smart meters (BM) are installed at the building's main power supply. Also smart meters are installed to monitor the electricity flows for PV and BESS. In the end, compact controlling and monitoring devices are installed for each end customer for the main supply and for household appliances, which are convenient for direct control of the load.

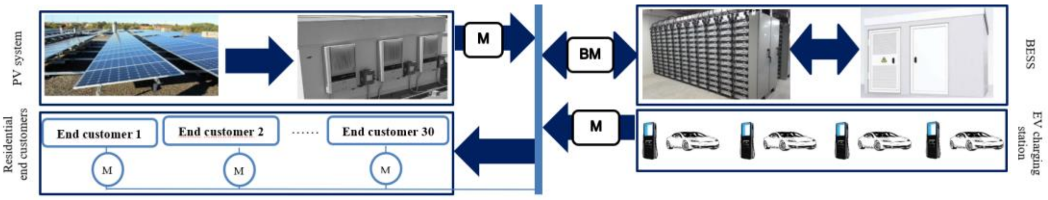

Fig. 2. The physical structure of the AE

With help from smart devices, the AE service can monitor the power flows, including any injection or extraction of electricity to or from the grid, the electricity consumption of each end customer, the electricity produced by the photovoltaic system and the operation of the BESS and electric vehicles charging stations. The integration management platform supports the optimization of the energy flows by controlling loads from household appliances, charging stations and BESS.

2.3. Telecommunications infrastructure

The control and monitoring system presented above is based on communication and information technology. Monitoring in real-time and data control will be quickly exchanged between the centralized AE service and distributed control and monitoring nodes.

For smart-home automation communication options include Wi-Fi, SmartThing, Google Home, Controller Area Network, Ethernet, Programmable Controller [5]. Nevertheless, the AE service proposed requires high security, high reliability, wide communication area and data exchange at high speed with an external network. Hence, a combination of fiber optic wireless network is selected.

The presented building will have six Wi-Fi sub-networks, each connected to a secondary server, which are coordinated by a main server via ethernet fiber optic. The secondary server will gather data from all control and monitoring nodes compress, encrypt, and then transfer them to the main server for central data processing, which essentially reduces communication traffic from and to the main server, as well as curtail the complexity of the calculation and data processing [6].

The main server is a powerful server which acts as the nucleus of the structure. Regarding data transmission, it not only collects data from the local smart devices but sends also control commands to the sub-networks. Additionally, to ensure network security and integrity, only the main server is capable to exchange data with numerous external platforms, using dedicated encrypted links, such as Virtual Private Network (VPN).

2.4. The stimulation mechanism

The development of a stimulation mechanism can be essential for promoting AE services in residential buildings. End customers will not participate to any AS, unless they receive rewards or benefits which can attract them. Per se, a set of stimulation mechanisms for AS is analyzed as follows:

- **Minimum price guarantee (MPG)**: This stimulation mechanism enforced in the AS can be classified into three categories: lower price for off-peak intervals, direct reduction in electricity invoices and specific rewards for participating in the "demand-response" program or any other similar program [7], [8].
- **Participation rewards**: The photovoltaic system mounted on the roof and BESS system will occupy a considerable common space; therefore, the end consumers must be rewarded for participating in AS. The reward will be divided into two types: payment exemption from "daily fixed component", which usually is the interval 1 - 3 RON/day, depending on the electricity supplier [9] and dividends from the profit.
- **Smart Charging of EV**: The AS that manages controllable assets will provide for free to all end consumers smart charging services for electric vehicles.

2.5. The AE profit approach

1. Centralized Electricity Management System for Micro-Grid and Internal Trading - Centralized systems for managing the energy injected into the system by the AE will control and manage the assets which are controllable. Thus, electricity can be managed, traded internally, and balanced within the building to minimize the amount of electricity extracted from the grid. This trading system allows end consumers to purchase electricity from the AE rather than from electricity suppliers at a relatively lower price. The AE can even bid on the wholesale electricity market if it has a large enough capacity to achieve a more competitive electricity price, which in essence reduces the margin of operating costs.

2. Programming the charging of electric vehicles - Even though electric vehicles owners benefit from the EV smart charging service, they must pay for the electricity used, even at a lower price. Considering that the AE will program the electric vehicles to be charged during off-peak intervals, the AE will benefit from the low energy price of the electricity extracted from the grid. Additionally, since electric vehicles are an important user in the MG, the aggregator can earn additional profits by participating to reserve markets, in order to respond to demand for decreasing/ increasing consumption as a fast tertiary reserve [10].

2.6. The invoicing mechanism

The invoicing systems are expected to have an impact over the attractiveness and profitability of the AS. Based on the current prices, the AS usually offers tree types of contractual prices: The fixed price (P_F), the time-of-use differentiated price (for peak and off-peak) ($P_{P\text{-}OP}$) and price based on the market price (or spot price) (P_{SPOT}). It is worth mentioning that all price information for Romania are collected from OPCOM website [101 and ANRE platform [12].

1) The fixed price (P_F) applied on the Romanian market consists of the daily fixed component and the electricity price expressed in RON/kWh. Fixed prices presented below are from three suppliers from the electricity market, and the fixed price will be considered the lowest price in order to achieve the “MPG” strategy. Additionally, end customers are not paying the daily fixed component as part of the reward for participation in the program.

2) *Differentiated price based on time of use (peak price- P_P, off-peak price - P_{OP})* ($P_{P\text{-}OP}$). Since the installation of remote-controlled smart meters increased, the time-differentiated price has become increasingly contracted. Also referred to it the as the economic price, it offers end customers different prices for peak load hours and off-peak load hours. The off-peak period is usually considered for 8 hours, between 22 and 6. The differentiated price of the aggregator is considered at least among the three offers in the energy market. In table 2 are presented the fixed prices, the daily fixed component also the differentiated prices of three electricity supplies.

Table 2

Prices of the main suppliers from Romania [9]

Supplier	P_F	P_P	P_{OP}	Daily fixed component
U.M.	RON/kWh	RON/kWh	RON/kWh	RON/day
Supplier 1	0,76	0,85	0,31	1,05
Supplier 2	0,74	0,94	0,38	2,30
Supplier 3	0,72	0,87	0,40	1,62
AE	0,72	0,85	0,31	0,00

3) Price based on sport market (P_{SPOT}) is based on the market price and is a dynamic price every hour. The offer is based on Day Ahead Market price plus a tariff for each kWh used.

3. Methodology of control

The optimization technique and the mathematical model for platform for central management of the AS are presented below.

3.1. Objective optimization function

The AE intention is to minimize the costs of electricity extracted from the grid. The intention can be expressed by the following formulas:

$$Min \sum_{k=1}^{T} C_{ag} = \sum_{t=1}^{T} \left(B_{ag} - C_{ag}^{i}\right) \quad (1)$$

$$B_{ag} = q_{e/i}^{ag} \cdot p_{i}^{ag} \cdot \Delta t \ \left(if\ q_{\frac{e}{i}}^{ag} < 0\right) \quad (2)$$

$$C_{ag}^{i} = q_{e/i}^{ag} \cdot p_{e}^{ag} \cdot \Delta t \ \left(if\ q_{\frac{e}{i}}^{ag} < 0\right) \quad (3)$$

Where: T – the total number of intervals; C_{ag} – the cost of the aggregator in interval t; B_{ag} – the benefits of the aggregator for the electricity sold; C_{ag}^{i} – the cost of the aggregator for the injected electricity; $q_{e/i}^{ag}$ - the amount of electricity extracted or injected from/into the network; p_{i}^{ag} – the price at which the aggregator injects electricity into the grid; p_{e}^{ag} – the price at which the aggregator extracts electricity into the grid; Δt – duration of the interval t (considered 1).

3.2. BESS and EV constrains

According to the energy balance, the power of PV, BESS and the quantity extracted from the grid should be equal to the energy consumption, including residential consumption and consumption for charging electric vehicles. The energy balance is express in formula (4). When $p_{i/d}^{BESS}$ is positive, BESS is loading and when $p_{i/d}^{BESS}$ is negative, BESS discharges.

$$\sum_{m=1}^{N_{ap}} c_{ap,t}^{m} + \sum_{n=1}^{N_{EV}} c_{i,t}^{EV,n} + q_{c/d,t}^{BESS} - q_{b/s,t}^{ag} - q_{t}^{PV} = 0 \quad (4)$$

Where: N_{ap} represents the number of apartments; $c_{ap,t}^{m}$ – the consumption of the apartment m in interval t; N_{EV} – the number of electric vehicles; $c_{i,t}^{EV,n}$ – consumption of electric vehicle charging stations in interval t; $q_{c/d,t}^{BESS}$ – the quantity used for charging/discharging by BESS in interval t; $q_{b/s,t}^{ag}$ – the quantity that the aggregator buys or sells in interval t; q_{t}^{PV} – the amount of electricity produced by PV in interval t.

It is assumed that the BESS installed in the residential building is composed of recycled batteries. BESS operation should comply with the following constrains:

$$p_{min,c}^{Bat} \le q_{c/d,t}^{Batt} \le p_{max,c}^{Batt} \ \text{ when } \ q_{c/d,t}^{Batt} > 0 \quad (5)$$

$$p_{min,d}^{Bat} \le q_{c/d,t}^{Batt} \le p_{max,d}^{Bat} \ \text{ when } q_{c/d,t}^{Batt} > 0 \quad (6)$$

$$E_{t+\Delta t}^{Bat} = \begin{cases} E_{t}^{Bat} + q_{c/d,t}^{Batt} \cdot \eta_{c}^{Batt} \cdot \Delta t \ \text{ when } \ q_{c/d,t}^{Batt} \ge 0 \\ E_{t}^{Bat} + q_{c/d,t}^{Batt} \cdot \eta_{d}^{Batt} \cdot \Delta t \ \text{ when } \ q_{c/d,t}^{Batt} < 0 \end{cases} \quad (7)$$

Where: $p_{min,c}^{Batt}$ – Minimum power (kW) for battery charging; $p_{max,c}^{Batt}$ – Maximum power (kW) for battery charging; $p_{min,d}^{Batt}$ – Minimum power (kW) for battery discharging; $p_{max,d}^{Batt}$ – Maximum power (kW) for battery discharging; $E_{t+\Delta t}^{Batt}$ –

Battery capacity; E_t^{Batt} – Capacity of the battery in interval t; η_c^{Batt} – battery efficiency when charging; Δt – time frame; η_d^{Batt} – battery efficiency at discharge.

For reused batteries in BESS, it is assumed that every single battery has the same state of health (SoH) and that their capacity is initially the same. The battery modules of the BESS should comply with the following:

$$E_{BESS} = N \cdot E_{Bat}^{original} \cdot SoH \quad (8)$$

$$0 < Cs_t = \frac{E_t^{Bat}}{E_{BESS}} \leq 100 \quad (9)$$

Where: E_{BESS} – modules capacity in BESS; N – number of batteries installed; $E_{Bat}^{original}$ – initial battery capacity; Cs_t – charging status in interval t.

With regards to EV charging stations, current EV models are compatible with various charging stations and can offer a wide range of custom interface functions. For example, the owners of EVs can schedule ahead their preferred charging period once they connect the EV to the charging station.

Can be assumed that the charging stations in the parking lot of the building analyzed are charging at a constant speed and that the owners can schedule the departure time. The operation of charging stations should comply with the following:

$$\sum_{t=T_{EV}^{start,n}}^{t=T_{EV}^{final,n}} S_t^{EV,n} \cdot p^{VE} \cdot \Delta t = E_{EV}^n \quad (10)$$

$$T_{EV}^{start,n} \leq t \leq T_{EV}^{final,n} \quad (11)$$

$$S_t^{EV,n} = 0 \ or \ 1 \quad (12)$$

Where: $T_{EV}^{start,n}$ - the time of arrival for electric vehicle n; $T_{VE}^{final,n}$ – the time of departure for electric vehicle n; $S_t^{VE,n}$ – binary variable indicating the state of charge of the electric vehicle n in interval t; p^{VE} – constant charging power of the electric vehicle; E_{VE}^n – total charge demand for electric vehicle n.

3.3. The approach for optimization

From the mathematical models presented above, it can be deducted that the EV variables are integer values, and the rest of the variables are continuous. Hence, this model is a linear programing problem with mixed integers. Nevertheless, the higher the number of EV, the more computationally difficult the problem becomes. An analogy between continuous approximation models, control using fuzzy logic and the linear programming method with mixed integer numbers to optimize the power management issue is analyzed in [13]. The conclusion of the analysis is that the method of continuous approximation offers encouraging performance in electricity management and can be faster compared to the problem of linear programming with mixed integers. Therefore, to address this problem, applying an optimization approach based on continuous approximation is the solution. The approach of optimization is split into two steps as presented below:

In the first step, integer variable is considered as continuous variable, with values in the range [0 to 1]. The problem can be solved as a classical linear problem.

The first step of the optimization approach contains the following operation: Collection of information on market prices, consumption and production forecast → Continuous approximation of the amount needed to charge the EV and solve the linear problem → Value of the decision to charge the EVs (1 for charging, 0 for stand-by) → Comparison with the maximum quantity and decision to charge the EVs. When the first step is finished, the algorithm continues to step 2 which contain the following operation: Solving the linear problem, determining the power of BESS, and exchanging electricity with the grid.

Considering that the value for integral variables were determined in the first step, the other values must be determined in the second step, which means to find a solution for the linear problem.

The encoding of the proposed optimization process approach in two steps is accomplished with a modeling and optimization tool from GNU Octave and solved using the mathematical problem-solving software from IBM. The optimization process will be applied every 30 minutes with real time and forecastable quantities and/or prices and optimize the EVs and BESS operation for 24 hours. Because of the errors generated by the forecast, the control range is established at 30 minutes, which indicate that BESS and EVs will only respond to optimization commands for half-hour intervals, not for 24 hours.

4. Case study

The model and mechanism of the AS in residential buildings were presented above to validate the performance of the proposed AS, the application parameters at the aggregator level are first entered. Afterwards, the aggregator test is applied using the parameters proposed using the GNU Octave application. Lastly, the profitability is analyzed with the above presented contractual prices.

4.1. AS input parameters

The roof area of the analyzed building is approx. 900-1200 m^2, and the basement area is about 1200 m^2. There are forty parking spots in the building.

On the Romanian electricity market, ANRE reported that electricity prices for small, medium, and large consumers are 32,6%, 37,8% and respectively 46,2% lower compared to the household users in the period 2020-2022 [14]. In the calculation it is assumed that the AE is a medium/small sized electricity user, and that the price is reduced by 36% compared to the contractual prices presented above.

The installed power of the PV power plant is assumed to be 110 kWp, estimated based on the roof surface. An example for the daily production data of the PV system is presented in Fig. 3 based on real-time nebulosity data from a weather forecast website [15]. Also, a BESS of 160 kWh is installed in the building based on photovoltaic production capacity and users' demand. The maximum limit for charge/discharge of the BESS it is assumed at 30 kW. Efficiency for charging and discharging are defined at 96% as described in [16].

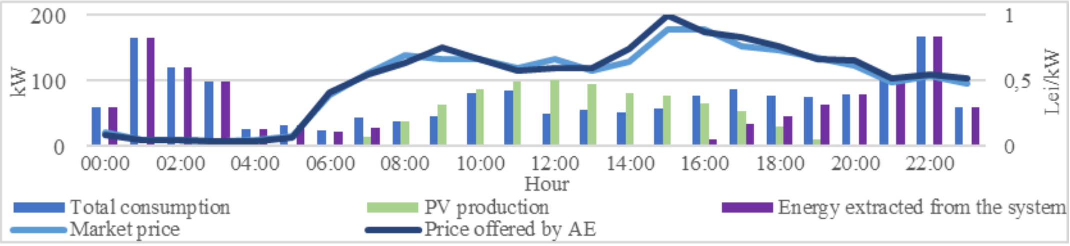

Fig. 3. AS performance for a residential building with thirty apartments

The daily energy consumption for the thirty residential users analyzed is estimated based on [17]. EV and BESS require forecasting data. It is assumed that the forecast data is provided by electricity suppliers, meteorological services companies, and other related companies. In the simulation, a random error of ±16%, applicable to the metered data are applied to simulate the forecasted values.

4.2. AS operational results

1) Overall performance: Results of day-to-day operations of the analyzed building are presented in fig. 3. The total consumption is represented with blue including the consumption of the apartments and the charging power of the EV.

Energy prices from the market are higher during day-time between 07:00 and 20:00 and lower between 00:00-07:00 and 21:00-00:00. Therefore, the electricity extracted from the system is considerably higher in off-peak hours and in peak hours reaches the minimum and in some interval is even zero. The AE stores electricity when the price is low and uses it in the intervals when the price is higher.

In fig. 4 are compared the results of programming the EV before and after the application of AS. Blue represents the initial charging status of the EV. Can be observed from fig. 8 that about 28% of the unmanaged charging of the EV occurs between 16:00 and 20:00, intervals in which the price of electricity is still at a higher level. The optimized charging program changes most of the charging activity from 21:00 to 03:00, intervals when the price of electricity is at a lower level.

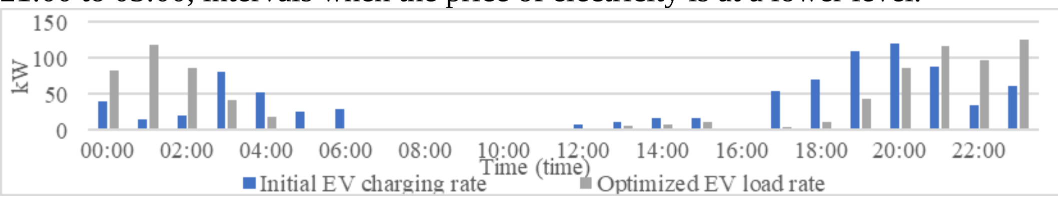

Fig. 4. EV load planning results

In fig. 5 is presented the status for charge and discharge of the BESS for 24 hours. Total energy used during peak hours is 122,7 kWh, which means 82,6% of the energy stored in the battery system has been used. By comparing the discharge power in the peak price intervals and the charge power in the off-peak price intervals, it can be established that the AE will derive profits from the price differences of the changed loads.

Fig. 5. BESS charge/discharge status

2) AE performance at different prices: Based on the simulation date, the invoicing information are calculated and presented in table 3. Should be taken into consideration that the invoices calculated based with on the prices for grid import are identical for an entire day, which indicated that the proposed mechanism is correct for all users. The invoice calculated using the fixed price have a higher value compared to the invoices calculated using the other two prices. The other two prices are higher because owners of electric vehicles with fixed price are not able to benefit from the charging program of electric vehicles, as they have a predetermined purchase price. Additionally, the photovoltaic system brings an electricity contribution of more than 310 kWh to satisfy the electricity use.

Table 3

Values of the invoices

Cost \ Calculated with	P_F [RON]	$P_{P\text{-}OP}$ [RON]	P_{SPOT} [RON]
Extraction from the system	374,81	374,81	374,81
PV	259,40	274,18	342,80
BESS	69,26	64,60	104,76
Internal trading	265,86	187,99	73,04
Total	**969,32**	**901,58**	**895,41**

Photovoltaic and battery system costs when applying the market price are substantially higher compared with the fixed price and price depending on the market price. This happens since the price of electricity is higher in peak consumption intervals and contributes to higher differences in the prices offered by AE.

4.3. Comparison of the reimbursement period (RP)

The cost estimation for the photovoltaic and BESS system is calculated based on [18], [19]. The data used for the calculation of the RP must include the electricity produced by the PV system, the prices for electricity and the charging information of electric vehicles. The PV generation data for year 2022 are obtained from [15]. The calculation equations for the RP are presented below [20].

$$Reimbursement\ period\ (years) = \frac{I_{BESS}+I_{PV}}{P_{AE}^{yearly}} \qquad (13)$$

$$P_{AE}^{yearly} = \sum_{k=1}^{n} P_x \qquad (14)$$

Where: I_{BESS} – represents the investment in the BESS system; I_{PV} – represents the investment in the PV system; P_{AE}^{yearly} – the yearly profit of the AE; n=365 – number of days in one year; P_x – represents the profit of the AE in day x.

The initial investment, the RP and optimized RP are presented in table 4.

Table 4

Reimbursement period of PV and BESS

	P_F	$P_{P\text{-}OP}$	P_{SPOT}
Cost of PV system [RON]	1.134.900,00		
Cost of the BESS system [RON]	104.760,00		
Normal reimbursement period [years] [**Error! Bookmark not defined.**]	12-20		
Reimbursement period after using the aggregator service [years]	7,12	6,91	5,63

The general RP for BESS and photovoltaic system are estimated based on a Ministry of Environment study. The cost of maintenance and efficiency reduction caused by the state of health of the PV and BESS system are not taken into consideration. Comparing it with the general RP, all three types of prices can considerably diminish the period. Specifically, companies specialized in property management or investors will be more interested in installing systems in residential buildings, similar to the one analyzed.

5. Conclusions

Within the presented article, a new AS for residential buildings with PV and BESS is proposed based on three differentiated prices, internal trading, and LPG system. Both communication and physical structures of the AS are developed to support the AS implementation in the building. The business model, along with the invoicing system and mechanisms for incentive introduced by AE are also analyzed. The guarantee of the reduced price and the rewards for the participation promised by the AE can efficaciously attract new customers to participate in the service proposed.

In order to validate the efficiency of the aggregator, three prices – fixed price, differentiated price (peak, off-peak) and based on the market price – that can be offered to the end customers. The result demonstrate that the proposed AS can achieve substantial profits while providing low-priced electricity to end customers. Photovoltaic system and BESS play a significant role in the AS, because they contribute up to 77,9% to the profit margin when end customers choose the Market Price. According to the general RP, the AE can reduce the RP up to 5,63 years, which is curtailed with 64.82% compared with the normal reimbursement period.

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