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Profitability of Photovoltaic and Energy Storage System in a Foundry Plant

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Abstract

The article presents a case study on the effectiveness of photovoltaic farm and battery energy storage in one of the Polish foundries. In the study, we consider two investment options: stand-alone PV farm of 1MWp and the farm together with battery energy storage with a maximum capacity of 4MWh. The Payback Period and Net Present Value were used as measures of investment profitability. The paper provides a detailed presentation of the assumptions made, as well as the PV electricity production model of the farm and the optimization model that determines the operation cycle of the energy storage. The case study presented in the article shows that the PV farm is economically sensible and profitable, but the battery energy storage is too costly to give a positive economic effect. Energy storage is an important element that provides flexibility in the energy supply system, so it is necessary to find a technical solution that gives this flexibility. Such a solution could be a virtual power plant, which could include a foundry energy system with a RES installation inside.

Keywords: Economics of foundry process, Energy management, Environmental protection

1. Introduction

Due to rising electricity prices and increasing environmental awareness and regulations, proper energy management has become an important factor of businesses' success and profit [1]. This is especially true for energy-intensive industries, which include, among others, the foundry industry. Manufacturing companies must take into account not only the cost of energy, but also its sustainable generation. In addition to the price of energy sourced from various sources, taxes and fees (e.g., environmental), investment expenditures and sustainability criteria should be considered. The best energy supply option should be chosen here, that is, the ratio between obtaining energy from external suppliers and self-generation from own renewable energy sources (RES) [2]. It should also be noted that the energy market offers spot contracts and forward contracts, which vary in terms of costs and delivery time, so a reasonable choice is to create an energy purchase basket that is a mix of contracts (e.g., in Poland, spot contracts in next-day market (NDM) are popular, as well as monthly, quarterly and annual contracts). In the case of self-supply, a significant problem is the fluctuating volume of energy produced, which is due to the nature of RES [2, 3].

In energy-intensive industries, energy is mainly consumed in production processes, consumption for infrastructure and for maintaining the operation capacity is not very important [2]. Many methods of energy management have been proposed in the literature [1], in this paper we focus not on describing the methods, but on examining whether, in general, production from RES and energy storage makes technical and economic sense for the foundry industry. For this purpose, a case study for one of the Polish foundries is presented.

After this introduction, a detailed description of the models and procedure used in our study are given. Section 3 presents results of the case study. Section 4 contains the conclusion and future work, followed by the references.

2. Assumptions and constraints

In energy-intensive enterprises, as a general rule, there is a process (equipment) that dominates energy consumption, and this process is necessary for either preceding or following processes to take place. This is the case of foundry plants, where such a process is the melting of metal in electric furnaces. This process in a typical foundry consumes 60-70% of the plant's electricity, and it is technically and organizationally impossible to stop (interrupt) it. Even for small foundries, it is not a simple task to replace the external power supply of the melting process with power from own RES and energy storage - this would require the construction of a huge installation. In the example foundry (for which calculations will be done), three melting pots with a capacity of 6 Mg and a power of 5 MW each are in operation. The construction of a 5 MWp photovoltaic plant would require an area of about 10 hectares [4], which is not available in the neighbourhood of the plant (a similar situation exists in other similar plants or energy-intensive industries, such as the steel industry). Therefore, in the case of foundry plants, the only reasonable assumption is to build a RES system that will not be designed to replace the traditional power system, but to support it. This is the basic assumption made in this case-study.

2.1. Costs and expenditures

In this study, we consider two investment options:

1. PV installation of 1MWp,
2. PV installation + battery energy storage with a maximum capacity of 4MWh.

Solutions with such parameters were proposed by the consulting company for the foundry under review. Capital expenditures were estimated at PLN 4 million for PV installation and PLN 8 million for energy storage.

The simple payback period (PP) and Net Present Value (NPV) were used as measures of profitability (effectiveness) of the investment. The only elements of cash flow on the income side will be energy cost savings and depreciation, while on the expense side will be maintenance and repair costs, which were assumed at 50% of the depreciation value. Since the depreciation rate for this type of project is 7%, the forecast of results was made for a period of 15 years, under the conditions of energy prices and energy consumption of the plant from 2022.

In addition, three variants of a purchase basket composed of four contracts (annual, quarterly, monthly, and NDM) in the following proportions were considered: a) 25%-25%-25%-25%; b) 0%-33%-33%-33%; c) 0%-25%-25%-50%. In this case, we want to examine whether the calculation results depend on the energy mix assumed.

Energy prices (for basic a) purchase basket) and energy consumption of the plant in 2022 are presented in Tables 1 and 2. These data were the inputs to the forecasts. As can be seen from these data, energy prices and the plant's energy consumption show a high degree of volatility, due to the nature of the energy market and the characteristics of production processes. This is confirmed in Figures 1 and 2, which show detailed values from selected weeks of 2022.

Table 1.
Basic statistics of energy prices by month [PLN/MWh]

month	min	max	mean	median
11.2021	442.64	695.43	534.59	530.09
12.2021	437.38	998.30	600.80	570.77
01.2022	525.38	914.96	664.41	638.47
02.2022	572.25	807.41	668.39	664.38
03.2022	549.95	954.18	644.83	639.20
04.2022	591.46	901.48	701.29	695.57
05.2022	574.25	855.42	684.86	675.63
06.2022	580.10	1104.02	757.46	749.51
07.2022	688.70	1381.01	886.54	865.66
08.2022	830.17	1676.43	1055.55	1026.82
09.2022	896.09	1395.32	1011.76	1005.26
10.2022	1111.67	1452.12	1202.67	1203.01

Table 2.
Hourly energy consumption at the plant by month [MWh]

month	min	max	mean	median
11.2021	0.26	7.62	3.54	4.01
12.2021	0.26	8.23	3.58	4.03
01.2022	0.31	8.33	3.61	4.13
02.2022	0.31	8.06	4.00	4.47
03.2022	0.29	8.35	4.05	4.55
04.2022	0.20	8.00	3.67	4.25
05.2022	0.19	7.41	3.36	3.93
06.2022	0.13	7.40	3.43	4.00
07.2022	0.17	7.14	3.31	3.79
08.2022	0.16	7.25	3.18	3.62
09.2022	0.16	7.76	3.51	3.94
10.2022	0.16	7.72	3.30	3.81

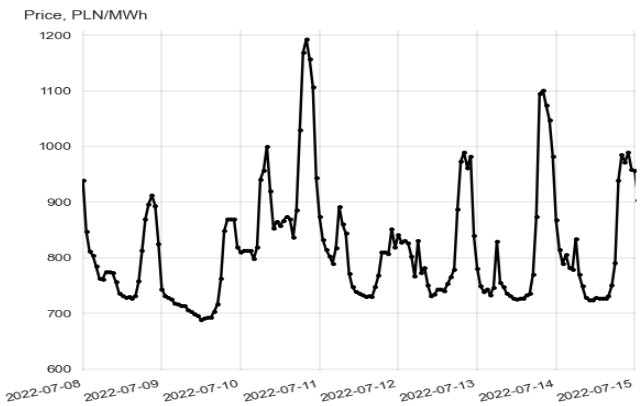

Fig. 1. Detailed energy prices for the selected week

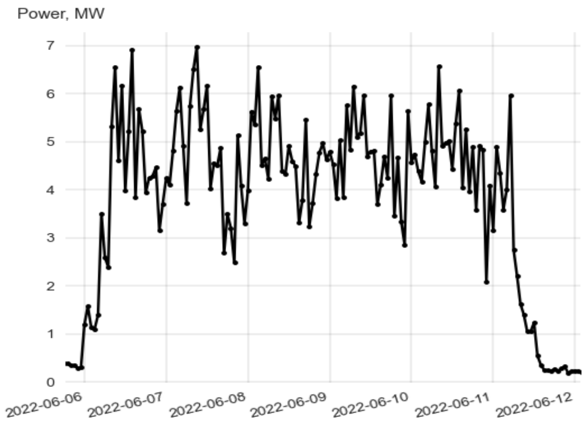

Fig. 2. Detailed energy consumption for the selected week

2.2. Procedure and models

In order to perform a reliable study, two methodological problems had to be solved:

1. how to model the operation (energy production) of a farm that does not exist on or near the company's site,
2. how to model the operation of an energy storage.

The first is a relatively straightforward problem to solve, while the second is an optimization problem that involves determining the storage cycle to maximize energy savings.

In the first case, we used a benchmark approach: the average generation from three 1 MWp farms located in Lublin Province was used as the reference unit - for these farms we had full information on the amount of energy produced and weather conditions on consecutive days of the year (with a grain of 1 hour). Weather data collected for the location of the analyzed foundry was used to build the model, taking into account the parameters: temperature, cloud cover, wind speed, UV index. The model also takes into account the technical solution assumed: the farm consists of 3448 single LG290N1C-G3 panels of 290 Wp each. A simulation model of the photovoltaic farm was made using the Pvlib library of the Python language, presented by the Holmgren et al. [5].The results of the approach used are shown in Figure 3, which illustrates the electricity production of the modeled farm compared to a reference unit.

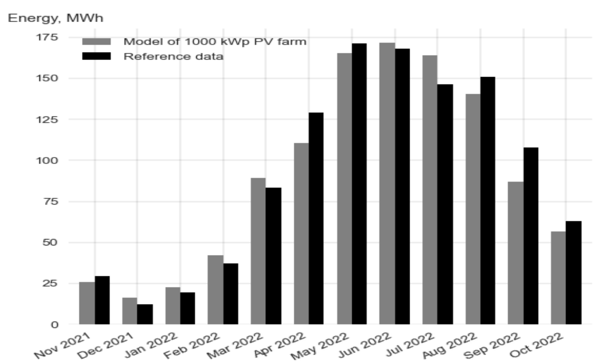

Fig.3. Electricity production in the modeled farm compared to the reference unit

In turn, Figure 4 shows the details of the operation of the modeled PV farm during the selected week. The lower power generated by the farm on 24.05.2022 is the result of significant cloud cover in the area where the farm is to be located.

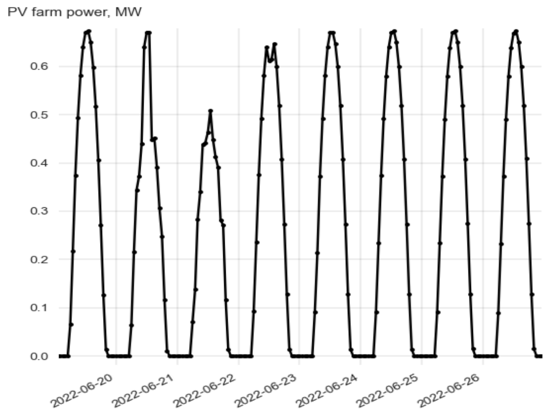

Fig. 4. Power generated by a 1 MWp PV farm over a sample week

In case of modeling the operation of an energy storage, we used a model of virtual power plant (VPP) presented in Chapter 2 of the book by Baringo and Rahimiyan [6]. The authors provide model for the most common components of VPP which include demands, conventional power plants, renewable generating units (solar- and wind-power), and energy storage facilities. These demands are generally flexible so that they can shift part of their energy consumption due to both technical and economic reasons. The available production level of renewable generating units depends on the availability of a weather resource such as the wind speed or the solar irradiation, which are generally subject to uncertainty. At last, energy storage units (batteries) can store energy to be used in the subsequent period.

The MIP (Mixed-Integer Problem) model presented herein takes into account the assumption that all the energy produced in the assumed time interval (here - 1 hour) by the RES installation is consumed to cover the demand for plant production or charging of energy storage. We use the following notation:

Indices

$t = 1,\ldots, T$ – simulation horizon [hours].

Parameters

c_t – cost of external energy in period t,

Pc_t^{min}, Pc_t^{max} – minimum and maximum power consumption of the plant in period t (here - 0.00 MW, 8.62 MW),

Ppv_t^{min}, Ppv_t^{max} – minimum and maximum power generated by the PV farm in period t (0.0 MWp, 1.0 MWp),

Es_t^{min}, Es_t^{max} – minimum and maximum charge level (capacity) of the energy storage in period t (0.2 MWh, 4.0 MWh),

$Psch_t^{min}, Psch_t^{max}$ – minimum and maximum charging power of the energy storage in period t (0.0 MW, 1.0 MW),

$Psrch_t^{min}, Psrch_t^{max}$ – minimum and maximum recharging power of the energy storage in period t (0.0 MW, 1.0 MW),

ech– charging efficiency (0.926),

erech – recharging efficiency (0.926).

Variables
u_{it}= 1, if the energy storage is charged/recharged, otherwise 0,
pc_t – electrical power consumed by the plant in period t,
ppv_t – electrical power generated by the PV farm in period t,
es_t – charging level of energy storage in period t,
$psch_t$, $psrch_t$ – charging and discharging power of energy storage in period t.

Using above notation the problem of minimizing energy cost of a plant using VPP approach can be defined as follows:

Minimize
$$\sum_{t=1}^{T} p_t c_t \tag{1}$$

subject to:

$$Pc_t^{min} \leq pc_t \leq Pc_t^{max} \tag{2}$$

$$Ppv_t^{min} \leq ppv_t \leq Ppv_t^{max} \tag{3}$$

$$Es_t^{min} \leq es_t \leq Es_t^{max} \tag{4}$$

$$Psch_t^{min} \leq psch_t \leq u_t Psch_t^{max} \tag{5}$$

$$Psrch_t^{min} \leq psrch_t \leq (1-u_t) Psrch_t^{max} \tag{6}$$

$$es_t = es_{t-1} + ech \times psch_t - {}^{psrch_t}/_{erech} \tag{7}$$

$$p_t = pz_t - ppv_t + psch_t - psrch_t \tag{8}$$

The objective function (1) minimizes the costs of energy used by plant. Inequalities (2-6) limit the values of the power variables for the VPP components to the accepted min-max ranges. Equation (7) determines the charging level of the energy storage at the end of period t. Finally, equation (8) balances supply, generation and consumption of power in period t.

The presented MIP model was solved using OR-Tools, which is an open source software for combinatorial optimization developed by Google [7]. OR-Tools includes powerful GLOP linear optimizer solver for Linear and Mixed-Integer Programming problems, which finds the optimal value of a linear objective function.

The result of the solver is to determine the charging and discharging cycle of the energy storage for known energy demand and known energy production by the RES farm on consecutive days of the year. The result is also the determination of what part of the total energy demand must be covered by purchases in the market (with a given purchase basket). Since presenting the optimization results in graph form would be unreadable for longer time periods, Figure 5 shows detailed results for a sample day (here – 14.07.2022).

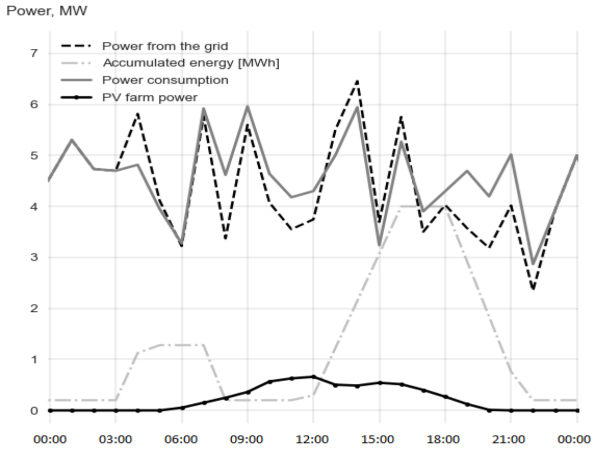

Fig. 5. The optimization results over a sample day (14.07.2022)

These results must be examined in the context of the hourly energy prices in the assumed purchase basket, which - for the day under consideration - are shown in Figure 6.

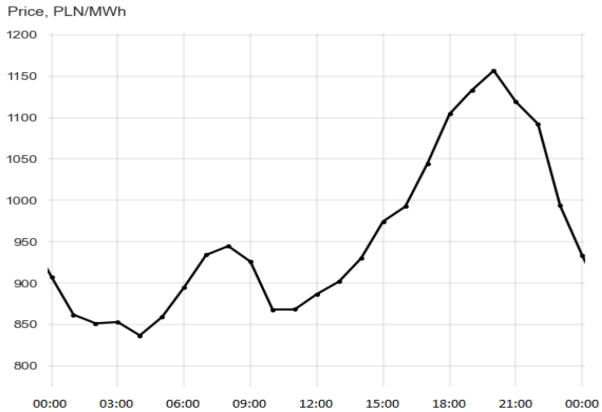

Fig. 6. Market energy prices over a sample day (14.07.2022)

In this context, we see the usefulness of charging energy storage during midday hours, when market energy prices are low and PV production is high, and of using the stored energy during evening hours, when market energy prices are high and PV production is negligibly low.

3. Results of the case study

This chapter presents the results of an efficiency study of the proposed energy solutions. The calculation is based on the annual ex-post forecast of the plant's savings in electricity consumption resulting from the PV farm and energy storage application. Based on the annual forecast, a 15-year forecast is made to determine PP and NPV of the considered solutions. We present several variants of calculations for discount rates (dr) in the 14-25% range, reflecting the difficult and unpredictable business environment in the forthcoming years.

3.1. PV farm

Table 3 shows the annual energy costs and savings from the operation of a 1MWp PV farm for the assumed purchase baskets.

Table 3.
Annual energy costs and savings from the operation of a 1MWp PV farm

Item/basket	25%-25%-25%-25%	0%-33%-33%-33%;	0%-25%-25%-50%.
The cost of energy without a PV farm [PLN]	26 835 508	27 245 696	27 251 374
The cost of energy with PV installation [PLN]	25 971 170	26 364 739	26 386 732
Annual savings [PLN]	864 338	880 956	864 642
Annual savings [%]	3.22	3.23	3.17

As can be seen from the above data, the structure of purchase basket does not have a significant impact on the total cost of energy consumed and its savings. This is most likely because there is little price differentiation between the different elements of the basket. In addition, the data presented shows that PP is about 4.5 years, i.e. after this time the savings from the production of energy from the PV farm will cover the expenses for its installation. This is a very satisfactory value for Payback Period indicator.

NPV values, calculated according to the assumptions presented in Section 2.1 and for different discount rates, are shown in Table 4.

Table 4.
NPV of PV farm investment

No.	Discount rate [%]	NPV [PLN]
1	14	2 189 580
2	15	1 893 554
3	16	1 620 418
4	17	1 367 940
5	18	1 134 142
6	19	917 263
7	20	715 737
8	25	-105 663

The results in Table 4 indicate satisfactory efficiency of investment in the PV farm. For the accepted discount rates NPV has a positive value, only for *dr*=25% the NPV is negative. Thus, based on the obtained PP and NPV values, it can be concluded that the installation and operation of a 1MWp PV farm is cost-effective and profitable for the foundry under study.

3.2. PV farm and battery energy storage

Table 5 shows the annual energy costs and savings from the operation of an installation consisting of a 1MWp PV farm and a 4MWh energy storage for the assumed purchase baskets.

Table 5.
Annual energy costs and savings from the operation of a 1MWp PV and a 4MWh energy storage

Item/basket	25%-25%-25%-25%	0%-33%-33%-33%;	0%-25%-25%-50%.
The cost of energy without installation [PLN]	26 835 508	27 245 696	27 251 374
The cost of energy with installation [PLN]	25 899 396	26 240 847	26 138 065
Annual savings [PLN]	936 111	1 004 848	1 113 309
Annual savings [%]	3.49	3.69	4.09
Number of energy storage cycles	169	224	292

As can be seen from the above data, the purchase basket does not have a significant impact on the total cost of energy consumed and its savings, although the impact is greater than that of a stand-alone PV farm installation. This greater impact is due to the greater flexibility of the operation of the entire system - energy storage can respond to dynamic changes in the prices of externally sourced energy, while a stand-alone PV farm does not have such capabilities. This is also reflected in the number of cycles (charging and discharging) of energy storage - the more fluctuating the price of external energy, the greater the number of cycles and the greater the energy savings. Nevertheless, these savings compared to a stand-alone PV farm are small, indicating the lack of synergies and the low efficiency of the energy storage installation. This is confirmed by the high PP value of 12 years and the results of NPV calculations for the assumed discount rates (Table 6).

Table 6.
NPV of PV farm and energy storage system

No.	Discount rate [%]	NPV [PLN]
1	14	-3 228 018
2	15	-3 645 892
3	16	-4 031 599
4	17	-4 388 258
5	18	-4 718 641
6	19	-5 025 213
7	20	-5 310 168
8	25	-6 472 514

The results in Table 6 indicate unsatisfactory efficiency of investment in the energy storage - NPV has a negative value for all accepted discount rates. Thus, based on the obtained PP and NPV values, it can be concluded that the operation of an installation consisting of a 1MWp PV farm and a 4MWh energy storage is not profitable for the considered foundry.

4. Conclusions

The case study presented in the article shows that not all elements of the RES system are economically efficient for foundry plants in Poland. Although the results of the case study for the analysed company cannot be directly transferred to other plants in the industry, we believe that the results - for similar installations - will be similar: the PV farm is economically sensible and profitable, the battery energy storage is too costly to give a positive economic effect.

The RES installation is a major technical and organizational challenge, mainly related to the uncertain forecast of electricity production from RES installations. The quality of this forecast depends on a number of factors [8, 9, 10], primarily the short-term weather forecast, which is a very difficult research and scientific task. More recently, market energy prices (from third-party suppliers) have also become such a factor, with unpredictable trends that make decisions about the cycle of storage and use of stored energy very difficult. This factor may also be one of the reasons for the economic inefficiency of battery energy storage, but the primary one is certainly the high capital expenditure. This is a great problem, since energy storage gives flexibility to the energy supply system of the plant, of which the RES installation is a part.

A promising solution here seems to be the concept of a Virtual Power Plant [6, 11], which is a flexible combination of decentralized units producing, storing or consuming electricity that are coordinated through a common (IT) control system. Such solutions operate already in the Polish energy market [12].

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