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# Selection of floating photovoltaic system considering strong sustainability paradigm using SSP-COPRAS method

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*Abstract*—**This paper presents research involving the selection of floating photovoltaics (FPV) system constructions under Polish conditions using a multi-criteria method incorporating criteria compensation reduction following the strong sustainability paradigm. The applied method is called SSP-COPRAS (Strong Sustainability Paradigm based Complex Proportional Assessment). The selection was carried out among four FPV designs and one reference conventional ground-mounted PV (GMPV) system. Data were obtained from the reference research paper. The results proved that the FPV system has a noticeable potential for making it competitive with GMPV, especially when technical criteria and criteria compensation reduction play an important role. However, GMPV's higher ratings, especially in terms of economics, show that FPV would have to reach a higher product maturity to become realistically competitive.**

## I. Introduction

THE DEVELOPMENT of renewable energy sources (RES) has been an important element of energy and climate policy in European countries for many years. The objectives of the adopted policy oblige European Union member countries to increase the share of energy obtained from RES both in total energy consumption and in individual branches of the economy [1]. Poland's energy system is mainly based on coal [2]. However, the coal-based energy economy is one of the most important causes of climate change caused by carbon dioxide emissions into the atmosphere [3]. It implies that Poland is facing an urgent transition to energy systems using renewable energy sources [4]. Floating photovoltaics (FPV) can contribute to fulfilling this challenge [5]. Due to forecasts of rapid development of FPV in Europe [6], [7], it was decided to focus on applying this technology in Poland. FPV is currently a new and as yet immature technology [8]. However, factors such as the lack of available space for conventional photovoltaic systems, the increase in the number of producers, and financial encouragement in the form of fixed prices for FPV installations will stimulate the intensive development of this technology [9], [10].

This paper presents the assessment results concerning the technical and economic criteria of four different constructions for a designed FPV system. The data for the alternatives considered were derived from the reference paper, in which the analysis was carried out based on simulations performed on the PVsyst system [10]. The main objective of the analysis carried out in this article, which serves as a reference for this research work, was to investigate whether the application of FPV could be profitable in Polish conditions. The FPV under consideration has a capacity of 1 MWp. Such installed capacity was chosen because the auction mechanism provides the most cost-effective prices for PV systems under 1 MWp. The artificially created upper reservoir of the Porąbka-Żar pumped storage power plant was adopted as the target site for the considered structures. This reservoir has a limited usable area due to its rounded walls. In this article, the considered constructions were evaluated separately for each criterion with the performance values of each criterion. Simulations at PVsyst showed that FPV systems showed a slight advantage over ground-mounted PV (GMPV) for specific constructions.

Since FPV in Poland are new, this work provides a comprehensive source of knowledge on how such systems can work in Polish conditions, highlighting the novel character of the investigated topic. However, the manner of evaluation in the discussed article is complicated because it forces the analyst to consider the following criteria without considering them simultaneously. The present method also does not allow to assign of relevance to the evaluation criteria, which is essential from the decision-makers point of view. Finally, such a way of evaluation does not provide an opportunity to take into account the strong sustainability paradigm, which is important in terms of sustainable development of FPV systems [11]. Its consideration is justified by the fact that one system may have an extremely good value within one criterion that will compensate for less favorable values for other criteria. Preventing the phenomenon of criteria compensation is, therefore, one of the elements of the strong sustainability paradigm that should be considered in the field of RES. The limitations mentioned above in the discussed research became the motivation for presenting in this paper results of research using the new SSP-

COPRAS (Strong Sustainability Paradigm based Complex Proportional Assessment) multi-criteria method [12], [13], [14] for selecting the best construction of a floating solar farm from among four FPV variants and one reference system installed on the ground. MCDM methods have proven useful in FPV-related selection problems involving site selection [15], [16] and construction assessment [17].

The paper adopts nine evaluation criteria from a reference research paper: five are technical, and four are economic. The use of the MCDA method is justified by the fact that the MCDA results allow considering multiple criteria simultaneously and analyzing various scenarios, which is important from the decision-makers point of view [18], [19]. In addition, SSP-COPRAS makes it possible to reduce the compensation of criteria according to a strong sustainability paradigm [20], [21].

## II. Methodology

This section presents the following steps of the SSP-COPRAS method, including basic assumptions and mathematical formulas. SSP-COPRAS implemented in Python is available at GitHub repository, along with a dataset of FPV constructions under consideration at link https://github.com/energyinpython/SSP-COPRAS-FPV.

**Step 1.** Create the decision matrix $X = [x_{ij}]_{m \times n}$ as Equation (1) shows. This matrix includes performance values $x_{ij}$ collected for $m$ alternatives, where $i = 1, 2, \ldots, m$ regarding $n$ evaluation criteria, where $j = 1, 2, \ldots, n$.

$$X = [x_{ij}]_{m \times n} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

**Step 2.** Calculate the Mean Deviation $MD$ for each performance value $x_{ij}$ by subtracting the mean value of each alternative's performance $\overline{x_j}$ for each criterion $C_j$. Multiply the resulting value by the sustainability coefficient $s_j$ defined for each criterion as a real number in the range between 0 and 1. Equation (2) presents the complete procedure performed in this step.

$$MD_{ij} = (x_{ij} - \overline{x_j})s_j \quad (2)$$

**Step 3.** Assign 0 value to these $MD$ values that for profit criteria $C_j$ are lower than 0 (when $x_{ij}$ is less than $\overline{x_j}$) and to these $MD$ values that for cost criteria $C_j$ are higher than 0 (when $x_{ij}$ is higher than $\overline{x_j}$), as Equation (3) shows,

$$MD_{ij} = 0 \, \forall \, MD_{+ij} < 0 \, \vee \, MD_{-ij} > 0 \quad (3)$$

where $MD_{+ij}$ represent $MD$ values for profit criteria and $MD_{-ij}$ define $MD$ values for cost criteria. This step prevents unintended enhancement of performance values that are outliers from the average toward the worse.

The rest of the steps are the same as the classic COPRAS method.

**Step 4.** Normalize the decision matrix $X$ using sum normalization method presented in Equation (4)

$$R = [r_{ij}]_{m \times n} = \frac{x_{ij} - MD_{ij}}{\sum_{i=1}^{m}(x_{ij} - MD_{ij})} \quad (4)$$

where $i = 1, 2, \ldots, m$ denotes $i$th alternative and $j = 1, 2, \ldots, n$ represents $j$th criterion

**Step 5.** This step involves calculating the weighted normalized decision matrix by multiplying values $r_{ij}$ in normalized decision matrix $R$ by the weights $w_j$ determined for particular criteria, as Equation (5) demonstrates.

$$V = v_{ij} = r_{ij}w_j \quad (5)$$

**Step 6.** Calculate the sums of weighted normalized outcomes individual for profit criteria which have to be maximized ($S_{+i}$) and for cost criteria which have to be minimized ($S_{-i}$) as Equation (6) demonstrates,

$$S_{+i} = \sum_{j=1}^{n} v_{+ij}, \; S_{-i} = \sum_{j=1}^{n} v_{-ij} \quad (6)$$

where $v_{+ij}$ are related to profit criteria which have to be maximized, and $v_{-ij}$ are related to cost criteria which have to be minimized.

**Step 7.** Calculate the relative priority $Q_i$ of evaluated options using Equation (7),

$$Q_i = S_{+i} + \frac{\sum_{i=1}^{m} S_{-i}}{S_{-i} \sum_{i=1}^{m} \frac{1}{S_{-i}}} \quad (7)$$

where an alternative with the highest value of $Q_i$ is considered as the best option.

**Step 8.** Calculate the quantitative utility value $U_i$ for each alternative,

$$U_i = \frac{Q_i}{Q_{max}} \quad (8)$$

where $Q_{max}$ defines the highest relative importance score. The alternative with the highest $U_i$ value is the best scored option.

## III. Results

In this paper, a multi-criteria evaluation was performed using the SSP-COPRAS method considering the criteria compensation reduction for the four variants of FPV constructions and one corresponding ground-mounted PV system (GMPV) equivalent considered as a reference point for the FPV project assessment. Four FPV variants include two systems produced by Ciel&Terre: C&T S12 and C&T EW12 and two by Solaris Synergy: SolSyn S12 and SolSyn S25. Five technical parameters and four economic indexes serving as evaluation criteria are provided in Table I, together with units and objectives. Cost type represents criteria with the aim of minimizing performance values. On the other hand, Profit type defines criteria with the aim of maximizing performance values. The performance values of each FPV and reference GMPV construction collected for evaluation criteria are provided in Table II.

The investigation was conducted in two stages. Stage one involves an evaluation using SSP-COPRAS for the different relevance of the two criteria groups considered: technical parameters and economic indexes. When the significance of the technical criteria group was incremented from 0.25 to 0.75 with a step of 0.05, the significance of the economic group was reduced accordingly. Obtained values were then divided by 5 for the technical criteria and 4 for the economic criteria, and the resulting values were assigned to each criterion. Thus, an equal distribution of weights within the two criteria groups was applied. Sustainability coefficient $s$ values were set as standard deviation values calculated from the normalized decision matrix for each criterion.

TABLE I
TECHNICAL PARAMETERS AND ECONOMIC INDICATORS OF DIFFERENT FPV SCENARIOS AND REFERENCE GMPV SYSTEM.

| Criteria | | Unit | Type |
|---|---|---|---|
| Technical parameters | | | |
| $C_1$ | Area | [m$^2$] | Cost |
| $C_2$ | $Y_f$ (Final PV system yield) | [kWh/kWp] | Profit |
| $C_3$ | PR (Performance ratio) | [%] | Profit |
| $C_4$ | AED (Annual Energy Density) | [kWh/m$^2$] | Profit |
| $C_5$ | $T_{IWA}$ (Irradiance-weighted average temperature) | [$^\circ C$] | Cost |
| Economic indicators | | | |
| $C_6$ | NPV (Net Present Value) | [€] | Profit |
| $C_7$ | IRR (Internal Rate of Return) | [%] | Profit |
| $C_8$ | LCOE (Levelized Cost of Energy) | [€/MWh] | Cost |
| $C_9$ | Minimum Auction price for which NPV = 0 | [€/MWh] | Cost |

TABLE II
DECISION MATRIX WITH PERFORMANCE VALUES OF TECHNICAL PARAMETERS AND ECONOMIC INDICATORS OF DIFFERENT FPV SCENARIOS AND REFERENCE GMPV SYSTEM.

| Technology | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ |
|---|---|---|---|---|---|---|---|---|---|
| GMPV S25 | 10982 | 1079 | 86.92 | 96.5 | 25.5 | 82645 | 13.3 | 73.2 | 46.7 |
| SolSyn S25 | 15220 | 1104 | 89.52 | 71.3 | 19.1 | 82426 | 12.9 | 74.5 | 46.9 |
| SolSyn S12 | 9901 | 1046 | 89.26 | 103.8 | 19 | 44062 | 10.63 | 79 | 51.1 |
| C&T S12 | 9901 | 1027 | 87.67 | 102 | 22.2 | -26787 | 8 | 88.8 | 57.2 |
| C&T EW12 | 8514 | 936 | 87.99 | 108 | 21.4 | -83161 | 3.3 | 96 | 63.5 |

The SSP-COPRAS evaluation was then conducted sequentially for different scenarios of criteria relevance. SSP-COPRAS preference values obtained for this part of the study are contained in Table III.

In turn, rankings of the evaluated systems were built by sorting the preference values in descending order, as in the SSP-COPRAS evaluation, the alternative that received the highest preference value is considered the best scored. Rankings obtained for different weighting of technical and economic criteria groups are visualized in Figure 1. It can be observed that when economic criteria are more important and account for up to 60% of relevance, the leader of the ranking of evaluated systems is the reference system, namely the GMPV S25. This result coincides with the analysis of the authors of the reference article. However, when the relevance of the technical criteria group begins to dominate (from 65%), the ranking leader becomes SolSyn S12. This system receives the most significant promotion of all the alternatives when increasing the relevance of the technical criteria group.

SolSyn S12 has favorable performances in Annual Energy Density, $T_{IWA}$, performance ratio, and area. The C&T S12 and C&T EW 12 systems remain at the bottom of the ranking regardless of the change in the significance of the criteria groups. It is worth noting the two FPV systems, which are SolSyn S12 and SolSyn S25. SolSyn S25 has an advantage over SolSyn S12 when economic criteria are more relevant. When their relevance is aligned, SolSyn S12 gains an advantage over SolSyn S25. It is justified by the fact that SolSyn S25 has superiority over SolSyn S12 in terms of all economic criteria: NPV, IRR, LCOE, and minimum auction price. However, considering technical criteria, SolSyn S12 has an advantage over SolSyn S25 in terms of area, Annual Energy Density (significant advantage), and $T_{IWA}$.

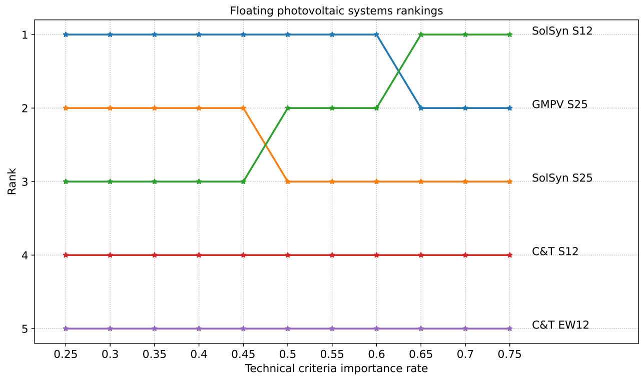


Fig. 1. SSP-COPRAS ranks of evaluated FPV and GMPV systems for different criteria weights.

In the case of FPV design, the desire for the smallest possible area is justified because the area of the power plant tank for which the study was conducted is limited, reducing the usable area for the floating system. In addition, a sufficient distance from the edge of the reservoir is required. Besides, a larger surface area requires more photovoltaic modules, which increases the cost of purchasing, installing, and maintaining the system. Annual Energy Density is an important profit criterion, as its high value increases the amount of electricity produced by the system during the year, which raises profits from system performance. Low irradiance-weighted average temperature ($T_{IWA}$) values increase the water cooling effect. The advantage of FPV systems over GMPV is partly due to the water-cooling effect, which enhances the efficiency of the solar farm.

In the following research stage, an analogous analysis was performed for modified values of the sustainability coefficient. Criteria weights were set as equal. Table IV provides performance values obtained for this analysis. Rankings of evaluated systems are displayed in Figure 2. In the case of sustainability coefficient modification, which was the subject of the second stage of the study, it turned out that all studied alternatives are stable in terms of the phenomenon of criteria compensation.

TABLE III
SSP-COPRAS PREFERENCE VALUES OF EVALUATED FPV AND GMPV SYSTEMS FOR DIFFERENT CRITERIA WEIGHTS.

| Technical criteria group total weight<br>Economic criteria group total weight | 0.25<br>0.75 | 0.3<br>0.7 | 0.35<br>0.65 | 0.4<br>0.6 | 0.45<br>0.55 | 0.5<br>0.5 | 0.55<br>0.45 | 0.6<br>0.4 | 0.65<br>0.35 | 0.7<br>0.3 | 0.75<br>0.25 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technology | | | | | | | | | | | |
| GMPV S25 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.9964 | 0.9867 | 0.9770 |
| SolSyn S25 | 0.9782 | 0.9754 | 0.9726 | 0.9698 | 0.9670 | 0.9641 | 0.9612 | 0.9583 | 0.9519 | 0.9396 | 0.9274 |
| SolSyn S12 | 0.9312 | 0.9397 | 0.9483 | 0.9570 | 0.9660 | 0.9751 | 0.9844 | 0.9939 | 1.0000 | 1.0000 | 1.0000 |
| C&T S12 | 0.7478 | 0.7644 | 0.7815 | 0.7989 | 0.8168 | 0.8351 | 0.8538 | 0.8729 | 0.8893 | 0.9005 | 0.9117 |
| C&T EW12 | 0.5433 | 0.5717 | 0.6008 | 0.6306 | 0.6613 | 0.6928 | 0.7251 | 0.7584 | 0.7897 | 0.8167 | 0.8441 |

TABLE IV
SSP-COPRAS PREFERENCE VALUES OF EVALUATED FPV AND GMPV SYSTEMS FOR DIFFERENT SUSTAINABILITY COEFFICIENTS.

| Technology / Sustainability coeff. | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GMPV S25 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 0.9983 | 0.9921 | 0.9854 | 0.9783 |
| SolSyn S25 | 0.9641 | 0.9632 | 0.9624 | 0.9615 | 0.9606 | 0.9597 | 0.9589 | 0.9564 | 0.9496 | 0.9424 | 0.9348 |
| SolSyn S12 | 0.9690 | 0.9727 | 0.9767 | 0.9810 | 0.9856 | 0.9906 | 0.9959 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| C&T S12 | 0.8278 | 0.8346 | 0.8417 | 0.8492 | 0.8569 | 0.8651 | 0.8737 | 0.8813 | 0.8854 | 0.8895 | 0.8938 |
| C&T EW12 | 0.7187 | 0.7209 | 0.7232 | 0.7257 | 0.7284 | 0.7312 | 0.7342 | 0.7362 | 0.7350 | 0.7337 | 0.7323 |

In the case of a significant degree of compensation reduction, we observe an advancement to the leading position of SolSyn S12, which, with a sustainability coefficient value of 0.7, outperforms the reference system GMPV S25.

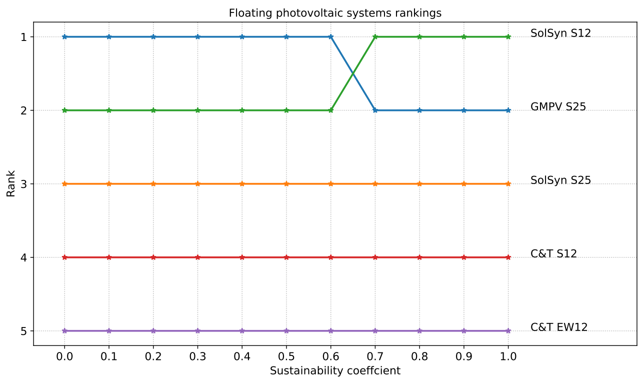


Fig. 2. SSP-COPRAS ranks of evaluated FPV and GMPV systems for different sustainability coefficients.

## IV. Conclusion

Research results proved that the alternative that is robust in terms of technical criteria and sustainability and has the most potential to be a real competitor to the reference GMPV S25 design is the SolSyn S12. The potential of FPV systems in technical terms was also noted in the background paper [10] referenced in this research work, where a slight advantage of FPV systems over GMPV in terms of power generation capability was found. On the other hand, if economic factors play the most important role, the conventional reference PV design called GMPV S25 is the unquestionable leader. This result confirms the conclusions of the analysis carried out by the authors of the article [10], who found that FPV systems are currently less favorable from an economic point of view, especially in the auction system. It is because of the need for high capital expenditures, which currently cannot be compensated for even by a floating system with the best performance. FPV would have to reach a higher product maturity to become realistically competitive, especially from an economic point of view. In contrast, the results show promising potential in technical terms.

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