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The UNIPEDE method of assessing electric energy generation costs in photovoltaic systems

Summary: *The paper presents a methodology for calculating the cost of production of a unit of electric energy from photovoltaic systems, fixed and 2-axis tracking, according to the designed and constructed system working in the Institute of Electrical Engineering and Electronics of Poznan University of Technology. Assumptions and input data for the analysis, including the discount factor, are presented. A pseudorandom number generator for the assumed range of electric energy variations was created for the purpose of the calculations. The cost of electric energy production with the use of a photovoltaic system with the maximum power of 1,05 kWp was compared with other technologies.* ***(The UNIPEDE method of assessing electric energy generation costs in photovoltaic systems)***

Streszczenie: *W pracy przedstawiono metodykę oceny kosztów wytwarzania jednostkowej energii elektrycznej dla układów fotowoltaicznych stacjonarnych i nadążnych dwuosiowych na przykładzie zaprojektowanego i wykonanego układu pracującego w Instytucie Elektrotechniki i Elektroniki Przemysłowej Politechniki Poznańskiej. Przedstawiono założenia oraz dane wejściowe do analizy z uwzględnieniem rachunku dyskonta. Na potrzeby obliczeń przygotowano generator liczb pseudolosowych dla założonego przedziału zmienności produkowanej energii elektrycznej. Porównano koszt produkcji energii elektrycznej z wykorzystaniem układu fotowoltaicznego o mocy maksymalnej 1,05 kW$_p$ z uwzględnieniem innych technologii wytwórczych.* ***(Metoda UNIPEDE oceny kosztów wytwarzania energii elektrycznej w układach fotowoltaicznych)***

Słowa kluczowe: koszt wytworzenia, współczynnik dyskonta, układ fotowoltaiczny, energia elektryczna
Keywords: generation cost, discount factor, photovoltaic system, electricity

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Introduction

Strengthening of the economic policy of the country will result in lowering the discount factor, whose value influences the assessment of the validity of energy generation from selected production sources, including renewable sources.

A parameter used for comparing electric energy generation is the unit cost of its production in the assumed period of system operation. The comparative evaluation should incorporate both investment as well as operation costs, including disposal costs. In the case of a photovoltaic system, the analysis should also include environment factors, in particular – the geographic location, the spatial orientation of the receiver, as well as time factors (daily and yearly). Also the parameters of the system itself, including its maximum power, construction solution (a fixed system, a tracking system), the technology in which the PV panels are manufactured and their material parameters, potential cooperation with concentrators, are important. Also, the so-called external costs, that is – the environmental impact of the selected conversion, constitute an additional, especially important factor. All of the elements that contribute to the unit cost of energy production understood in this way should be verified for the same time period, including the discount factor.

Electric energy of solar origin is characterized by a number of advantages: its omnipresence and fewer problems connected with its transmission connected with that. The energy of the Sun is free and virtually inexhaustible. Its conversion is not associated with any harmful emissions to the atmosphere. Thus, using solar energy does not affect the energy balance of the Earth. However, the cyclicality of solar energy supply (daily and yearly), the varying concentration, low insolation values, and the necessity to store the electric energy obtained that results from that, as well as the need to allocate a large area for the installation pose a problem.

On the basis of the report of Ernst and Young, it is estimated that the current investment value per average power unit is 75,9 mln PLN [1].

Figure 1 presents a summary of electric energy production from renewable energy sources in 2012 [1]. The summary includes the parameters of new production sources.

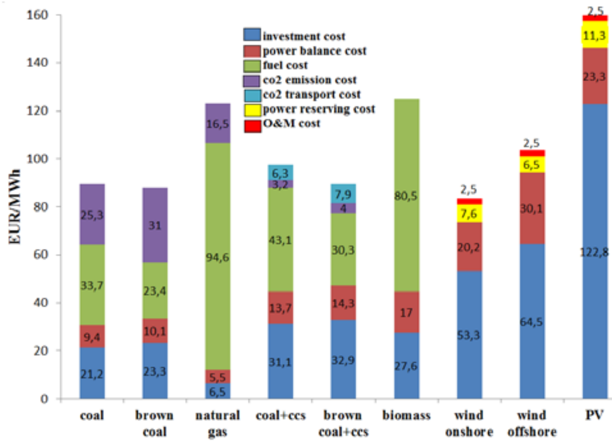

Fig.1. Summary of the costs of electric energy production from renewable energy sources (own work on the basis of [1])

As shown in Figure 1, the costs of producing electric energy by means of photovoltaic conversion are high. However, on the basis of [2], strong dynamic of changes occurring in the costs of electric energy generation from renewable energy sources is observed. In relation to photovoltaics, cost reduction at the range of 170 - 300 €/MWh till 2030 is estimated.

UNIPEDE method

The UNIPEDE method accepted by the EU was used to evaluate the discount unit cost of electric energy production including all the elements, that is – investment costs, maintenance costs, renovations, and fuel used, among others, of two photovoltaic systems (a fixed one and a tracking one). The method was approved by the International Union Producers Distributors of Electrical Energy) [3], where the value of expenses and the profits obtained from them are present at a lower grade in relation to the values for the years "ahead" [4]. The evaluation is performed with the use of the discount factor, while eliminating the influence of inflation. The investment value, the cost resulting from the failures that occur, the cost of obtaining a unit of electric energy, and the amount of electric energy generated throughout the years subject to the analysis constitute the elements of the formula.

All of the elements of the quotient listed above must be subject to discounting considering the risk factor for the given power generation technology S_r and the factor that is equal to the interest rate of long-term treasury bonds S_a dependent on the economic and financial situation [5][6]. The discount rate is described in the work [6]:

$$d = (1 + S_a) \cdot (1 + S_r) - 1 \approx S_a + S_r \quad (1)$$

The discount factor is expressed as [5]:

$$a_t = \frac{1}{(1 + d)^t} \quad (2)$$

The discount unit cost of electric energy production is expressed by means of the following dependency [5]:

$$k_j = \frac{\sum (I_t + KU_t + F_t)(1 + d)^{-t}}{\sum A_t (1 + d)^{-t}} \quad (3)$$

$$k_j = \frac{\sum_{t=-b+1}^{0} \frac{I_t}{(1 + d)^t} + \sum_{t=1}^{N} \frac{KU_t + A_t \cdot k_{pt}}{(1 + d)^t}}{\sum_{t=1}^{N} \frac{P_t T_t}{(1 + d)^t}} \quad (4)$$

If the time needed to construct the object does not exceed one year, the dependency (4) takes the following form:

$$k_j = \frac{I_0 + \sum_{t=1}^{N} \frac{KU_t + A_t \cdot k_{pt}}{(1 + d)^t}}{\sum_{t=1}^{N} \frac{P_t T_t}{(1 + d)^t}} \quad (5)$$

where: I_0 – investment costs during the construction of the PV power plant, KU_t – cost of maintenance and renovations in a given year, k_{pt} – cost of fuel used for the generation of a unit of electric energy, $P_t T_t$ (A_t) – amount of electric energy generated in a given year

Preliminary assumptions for the analysis

In order to determine the unit cost of electric energy generation, a photovoltaic installation with the maximum power of 1,05 kW_p was analyzed. The yearly amount of electric energy generated by the PV system under analysis comprised of a fixed system and of a 2-axis tracking system with the same maximum power, described in [7], was rescaled for the analyzed power. A view of the measurement stand is presented on Figure 2. The object operation time of 25 years, the construction time of less than a year were assumed in the calculation. The discount rate of 7 % was established on the basis of the actual interest rate of treasury bonds and the rate risk [8][9].

The investment costs I specified for the "past" years, including the construction time, and the maintenance cost KU were established on the basis of the following dependencies (6) and (7) [10]:

$$I = \frac{\sum_{t=-b+1}^{0} I_t}{(1 + d)^t} \quad (6)$$

$$KU = \frac{\sum_{t=1}^{N=25} KU_t}{(1 + d)^t} \quad (7)$$

The discount investment cost is equal to the yearly expense value. The maintenance cost connected with servicing, module cleaning, construction and electrical connection checks is established at the level of 1748 PLN/kWp.

Fig.2. A view of the measurement stand consisting of a 2-axis tracking system and a fixed system located on the roof of the Institute of Electrical Engineering of Poznan University of Technology

In order to determine the yearly generation of electricity by the systems under analysis and its volume for the assumed period of operation, a dependency modified by the author was introduced based on the total insolation value for the horizontal plane for a typical meteorological year [11]. In view of the system operation in the tracking mode, median correction factors were developed for this system on the basis of the measurements as well as the average yearly value for the fixed system with the set inclination angle.

Table 1. Insolation values on the planes with different spatial orientation on the basis of 30-year measurement cycles for the city of Poznań (on the basis of [11])

M	I_TH	I_E__30	I_S__30	I_W__30	I_E__45	I_S__45	I_W__45
-	Wh/m²/month						
1	26123	25177	36561	25231	24187	40173	24150
2	35757	35953	44727	33303	35380	47455	32188
3	71678	69852	88066	67562	67912	91863	65115
4	104355	104070	115121	97525	102041	116073	93905
5	143561	137225	150049	137742	132359	147000	132648
6	149279	146947	150239	141546	143587	145844	136913
7	141631	141998	142918	132791	139799	139242	128522
8	116520	114980	122480	110624	112480	121483	106900
9	81621	79370	90529	78729	77220	91864	76342
10	45552	43407	53441	45489	42300	55734	44822
11	26381	24474	35283	26640	23475	38287	26261
12	18375	18126	21235	18187	17855	22252	17940

Insolation values on the basis of 30-year measurement cycles for the city of Poznań were used in the consideration.

Table 1 presents insolation values for different inclination angles of the receiver in relation to the surface and for different azimuth angles in comparison with the values for a receiver set horizontally for particular months of the year.

The yearly electricity generation value, including the installed power value [kW_p] for STC conditions [$1kW/m^2$], was established on the basis of the dependency developed:

$$E_{rz,track} = \left(\sum_{i=1}^{i=12} E_{TH} \cdot k_i\right) \cdot P_S \cdot n \cdot P_p \cdot FF \cdot \left|1 - \frac{1}{P_S}\right| \quad (8)$$

where: E_{TH} – insolation on the horizontal plane, k_i – monthly insolation correction factors, P_S – power loss in the system, n – number of installed unit powers, P_p – unit installed power, FF – filling factor

Electricity production estimation

The electricity value for the period under analysis was obtained as a result of the generation of a non-zero sequence of number values, preceded by an analysis of the generators described in literature, e.g. Fibonacci, congruent, LCG, Park – Miller, PRNG. Their applicability to the problem under consideration was investigated. It was concluded that incorrect selection of the parameters of the linear congruential generator LCG results in its fast repeatability, which forces the use of strictly specified values of the modulo m factor and the value of the constant “a” which multiplies the value of the previous element of the generated sequence [12][13]; on the other hand, in the case of the Park – Miller generator, the values of the dependency describing its consecutive elements must be selected empirically so that zero would not occur in the sequence in order to avoid zeroing of sequence elements. Zeroing of sequence elements makes the sequence deterministic and, thus, it becomes useless [14].

Using the properties of the selected generators, such as the congruential LCG generator and the Park – Miller generator, regarding the way in which the range of variability of consecutive elements and the randomness of the values obtained are determined, the pseudo-random number generator PRNG, which was modified by introducing the remainder of the modulo division in order to determine the range of variability of sequence elements, was used.

The generator initiated with the “grit” produces a sequence which is in certain ways indistinguishable from an actually random sequence, and its theoretical length limit is specified as 2^n, where n is the number of bits intended for storing the internal state [15].

Estimation of the amount of electricity generated in particular years of system operation was performed on the basis of measurements results obtained by the authors in the period of time under analysis and as a result of the generation of its values by means of the modified pseudo-random number generator PRNG. Such a procedure is justified by the stochastic character of the power density distribution of solar radiation in particular measurement years [16].

The task to be performed by the program developed by the authors was to generate a theoretically endless sequence of values. The sequence generated should be consistent with the “grit” value established on the basis of own yearly measurements. Its limited randomness should be considered in the process. By means of the program developed, consecutive sequence elements were determined for the 25-year period of system operation.

A fragment of the source code of the generator implemented in the Microsoft C++ environment is presented below:

```
#include<iostream>
#include<fstream>
#include<cstdlib>
#include<time.h>
using namespace std;
int tab[x];
int main()
{
   cout<<” pseudorandom_distrib”<<endl;
   srand(time(NULL));
for (int x=0;x<24;x++)
{
      int liczba=rand()%251+1120;
      cout<<liczba<<endl;
}
cout<<”input data_numb”;
for (int x=0;x<24;x++)
{
      cin>>tab[x];
}
ofstream file;
file.open(“list.txt”,ios::out | ios::app);
for (int x=0;x<24;x++)
{
      file<<tab[x]<<endl;
}
file.close();
system (“pause”);
return 0;
}
```

The discount unit cost of electricity generation resulting from the operation of the 2-axis tracking system, including the results of own insolation measurements performed between 06.2013 - 06.2014 and the values of the generated sequence, was determined on the basis of the following dependency:

$$k_j = \frac{I + KU}{E_{rz,track} \cdot (1+d)^{-t} + \sum_{t=2}^{N=25} \frac{P_t \cdot T_t}{(1+d)^t}} \qquad (9)$$

where: $E_{rz,track}$ – amount of electricity produced on the basis of calculations and own measurements, other symbols as above

The experiment results obtained were compared with the results for power generation sources in a different technology. The corresponding values are provided in table 2.

Table 2. The influence of generation technology on the unit cost of electricity generation (own work on the basis of Fraunhofer ISE, May 2012)

Generation type	Unit cost of generation
-	[PLN/kWh]
Micro photovoltaic installations	0,59-0,67
Small and large photovoltaic installations	0,55-0,59
Onshore wind power plants	0,25-0,34
Offshore wind power plants	0,46-0,67
Conventional power plants	0,17-0,29
2-axis tracking system analyzed	0,69
Fixed system analyzed	0,71

As it can be seen from the summary presented, the results obtained correlate with the results for a micro PV installation.

Conclusions

1.Using the UNIPEDE method for estimating the cost of electricity generation makes it possible to observe slightly lower cost of its generation with the use of 2-axis tracking system in relation to fixed systems.

2. In the photovoltaic systems – fixed and tracking – under analysis, the electricity generation cost determined on the basis of own study and the UNIPEDE method is comparable with the results provided in the work [1], presented during the CASE Center for Social and Economic Research Energy Seminar in Warsaw in January 2014.

3. While performing the assessment, it should be considered that fixed PV systems with the spatial orientation of the receivers that is optimal with respect to

the energy gain are characterized by the investment cost that is about 18 % lower.
4. At the same time, the value of electricity generated in the fixed systems mentioned above in one year is lower by about 25 % ("net" state) and even by 39 % ("gross" state) in comparison to the analogous tracking system (with the same installed power value).
5. In order to minimize the reduction in electricity generation by a PV system resulting from maintenance and service works, the works should be performed during the night, or, alternatively, during times of low solar activity.

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