1. Katarzyna DYNDAŁ[1], 2. Konstanty W. MARSZALEK[1], 3. Zbigniew KĄKOL[2]

Institute of Electronics, AGH University of Science and Technology, (1) Department of Solid State Physics, AGH University of Science and Technology (2)
ORCID: 1. 0000-0003-2874-5760; 2. 0000-0002-0564-5743; 3. 0000-0002-5978-8627

doi:10.15199/48.2022.09.57

Design of complex energy systems (thin film photovoltaics, collectors, heat pumps and energy storage)

***Abstract**. This paper presents a method for obtaining photovoltaic thin films and simulation results of complex power systems. Photovoltaic thin films were obtained using the magnetron sputtering method. Simulations of complex power systems consisting of thin photovoltaic modules, energy storage and a heat pump have been performed. The capabilities of one of the most powerful design software such as Vela Solaris Polysun software were presented by showing chosen the simulation results.*

***Streszczenie.** W pracy przedstawiono metodę otrzymywania cienkich fotowoltaicznych warstw oraz wyniki symulacji złożonych systemów elektroenergetycznych. Cienkie warstwy fotowoltaiczne otrzymano za pomocą metody rozpylania magnetronowego. Wykonano symulację złożonych systemów energetycznych składających się z cienkowarstwowych modułów fotowoltaicznych, akumulatorów i pompy ciepła. Przedstawiono możliwości jednego z najbardziej zaawansowanych programów projektowych, jakim jest oprogramowanie Polysun firmy Vela Solaris na przykładzie wybranych wyników symulacji. (**Projektowanie złożonych systemów energetycznych (fotowoltaika cienkowarstwowa, kolektory, pompy ciepła i magazyn energii)**).*

Keywords: thin film, magnetron sputtering, photovoltaics, electric power systems, energy analysis, Polysun
Słowa kluczowe: cienkie warstwy, rozpylanie magnetronowe, fotowoltaika, systemy elektroenergetyczne, analiza energetyczna, Polysun

Introduction

Last ten years is a period of extremely fast development of renewable energy sources, especially photovoltaics [1]. Perovskite and thin films technology are two fasted developed technology [2]. The sputtering method of deposition of thin photovoltaic system as well as designing of the photovoltaic power plant [3] are presented in this paper. Most popular method thin films photovoltaic system preparation are evaporation, DC sputtering and magnetron sputtering [4]. Current photovoltaic installation are monocrystal solar cells because of huge production Si monocrystalline in China. Nerveless, in March 2022 the number of photovoltaic installation in Poland exceed 1 million. It is reason production of solar cells as well as the designed program are extremely important.

The most popular programs to the designed photovoltaic system are TRNSYS [5], Archelios [6], Polysun [7-9], PVSyst, PV*SOL [10] and PVGIS [11].

The Photovoltaic Laboratory at the Department of Computer Science, Electronics and Telecommunications at AGH University of Science and Technology is equipped with two specialized programs for designing power and thermal systems. These programs are PV*SOL and Polysun [12,13] used by designers all over the world.

In this work, a method for obtaining thin films applied in thin-film photovoltaic cells is presented. Moreover, the results of simulation of complex energy systems consisting of thin-film photovoltaic modules, an energy storage and a heat pump using Polysun program are presented.

Materials and deposition methods

Thin copper oxide layers dotted with chromium have been obtained as absorber in thin-film photovoltaic cells. These films were obtained using magnetron sputtering by applying a system whose picture and schematic diagram are shown in Figure 1 and Figure 2, respectively.

carried out at the same time. In the present work, photovoltaic thin films were obtained in chamber B. Chamber A enables the deposition of layers using the GLAD technique, which requires changing both the substrate angle and the rotation rate during deposition. Whereas chamber B is equipped with a non-moving table.

The system is equipped with a pumping system consisting of an EDWARDS E2M18 rotary pump and an ELTRAVVA S450 turbomolecular pump, with the ability to pump the system to a pressure of $5 \cdot 10^{-4}$ Pa when pumping one chamber or $1 \cdot 10^{-3}$ Pa for two chambers. Chamber A is equipped with a WMK100 circular magnetron and chamber B with a JC70 circular magnetron. The gas flow into the system is controlled by MKS MFC mass flow controllers operated by MKS 647B controller.

The system has two deposition chambers, marked as A and B in Figure 2, which allows two independent processes to be

Fig. 1. Picture of the magnetron deposition equipment with two vacuum chamber

Simulation Tool

A complex power system consisting of thin-film photovoltaic modules, an energy storage and a heat pump was designed by using Polysun software (Vela Solaris) and the system operation was simulated.

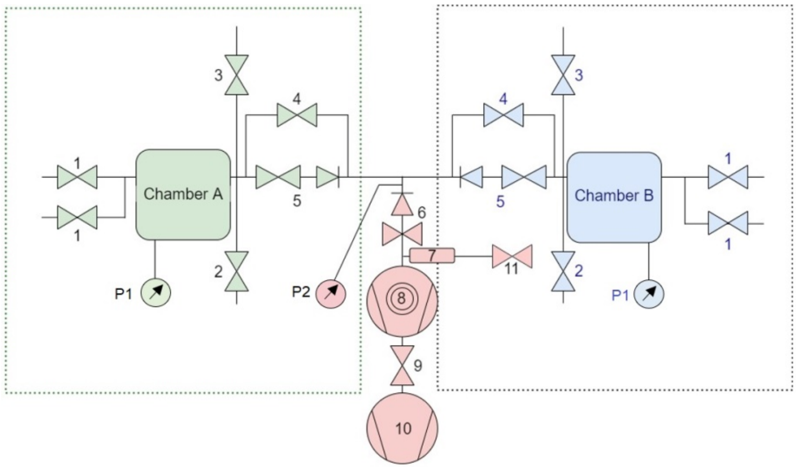

Fig. 2. Schematic of a two-chamber vacuum system for cathodic magnetron sputtering. Designations in the figure: P1 - high vacuum sensor (PKR251); P2 - pressure sensor at the turbomolecular pump output (TPR280); 1 - electromagnetic valve for dosing of gases; 2 - electromagnetic valve for pumping out the chamber; 3 - electromagnetic valve for ventilation of the chamber; 4 - manual valves BY-PASS; 5 - electromagnetic valve (230 VAC); 6 - electropneumatic flap valve cutting off vacuum and technological part; 7 - filter; 8 - turbomolecular pump (ELEKTRORAVA S450); 9 - electromagnetic valve shutting off rotary pump (230 VAC); 10 - rotary pump (EDWARDS E2M18); 11 - electromagnetic valve for venting the turbomolecular pump

Simulation

The Polysun software makes it possible to perform annual dynamic simulations of a building's demand for heating, cooling, domestic hot water and electricity. It allows the design and optimization of different energy and thermal systems consisting for example of photovoltaic modules, solar collectors, heat pumps and energy storage [14]. The program contains data sheets of system components from manufacturers from all over the world, which are constantly updated. By using the software it is possible to calculate the most important parameters of the systems for electricity and heat production and amortization of the systems [15]. In the next part of the paper, example simulation results of a chosen power system are presented, demonstrating the capabilities of the program.

Statistical meteorological data

Calculation of energy produced by photovoltaic modules, heat and hot water demand, among other things, depends on the availability of real data on solar irradiation, temperature etc. The simulation of weather conditions in Polysun is carried out thanks to an integral part of this program, which is the meteorological database Meteonorm [16], contains information from over 8 000 weather stations worldwide and 5 geostationary satellites. Annual weather data are obtained using stochastic models [17]. These models store monthly averages and Markov matrices to obtain hourly meteorological data. By defining the location of the energy system, Meteonorm automatically assigns statistical weather data so that a weather profile is generated.

Power system definition

In this paper, a complex electrical system consisting of thin-film photovoltaic modules, an energy storage and a pump was designed for a family consisting of working parents and one child. For this purpose, the consumer's electricity and heat demand profile was designed by knowing the power of the appliances used by the household members and their operating time, as well as the size of the house (200 m^2) and the desired indoor temperature (19 °C). Based on the data, an energy demand of 4200 kWh/year was estimated.

A photovoltaic system was constructed with 18 thin-film photovoltaic modules, an inverter of SK-L 5500, an energy storage of Hoppecke 24 OpzS 3000, and a heat pump of WPL 47/-A SR to meet the electricity and heat demand. The photovoltaic installation was oriented southward at an angle of 30° to the ground surface and located in Krakow (Poland). A schematic of the complex energy system made in Polysun is shown in Figure 3.

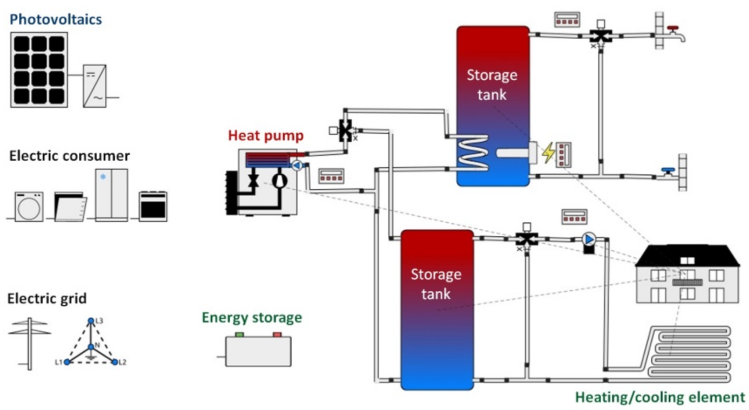

Fig. 3 Model of energy system consisting of photovoltaic modules, energy storage and heat pump applied to simulation by using the Vela Solaris Polysun

Results

Thermal and electrical energy demand was calculated for the selected energy consumption profile for each month by using Polysun software. The effect of ambient temperature on the temperature of the photovoltaic modules was also taken into account due to its effect on the performance of the modules. The ambient and photovoltaic module temperature profile in Krakow for each month of the year is shown in Figure 4. The maximum solar irradiance was obtained in the month of September and was equal to 1028 W/m^2, while the lowest value was in December 239 W/m^2.

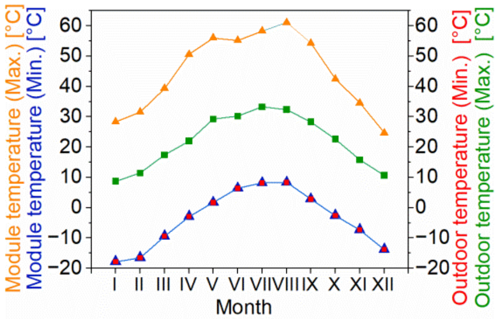

Fig. 4 Monthly meteorological data for Kraków, Poland output from Polysun software

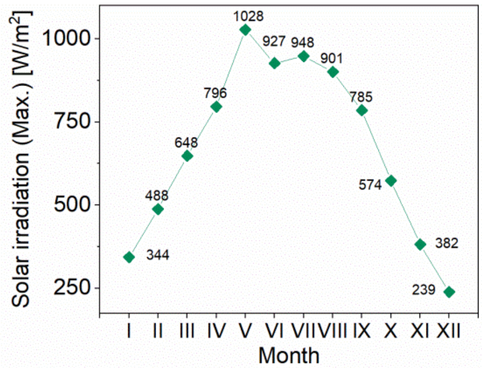

Fig. 5 Maximum solar irradiance by month of the year for Krakow (Poland) output from Polysun software

A simulation of the solar irradiance during the whole year was also performed. The results are shown in Figure 5. The monthly electricity consumption, that is sum of the electricity consumption from profiles and components included in the system (e.g. heat pump, energy storage) was shown in the Figure 6.

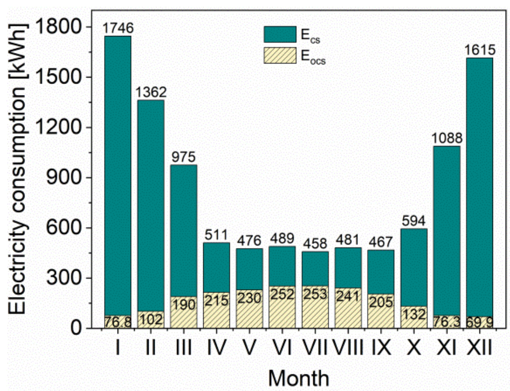

Fig. 6 Self-consumption (E_{OCS}) and total electricity consumption (E_{CS}) by month

The highest demand for electricity is in the winter months, the lowest in the summer. The total electricity consumption (E_{CS}) is 10262 kWh per year. The self-consumption (E_{OCS}), which is the share of the own electricity production that is used to cover consumption was also calculated. The simulation results are shown in Figure 6. The annual sum of E_{OCS} is 3396 kWh.

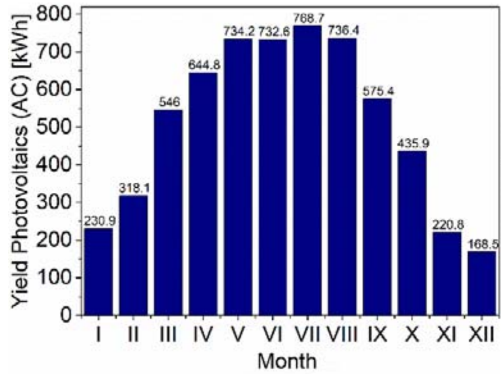

Fig. 7 The monthly electricity production AC by the PV solar system

The total amount of electric energy from the photovoltaic system that has not been consumed on a daily basis and has been fed into the power grid is 2722 kWh/year. The annual amount of electricity produced by the photovoltaic system is 6118 kWh that shown in the Figure 7.

If the photovoltaic system does not cover the electricity demand, the energy is withdrawn from the grid. For the selected demand profile, this value was 7781 kWh/year. The amount of energy given to and taken from the grid for each month is shown in Figure 8.

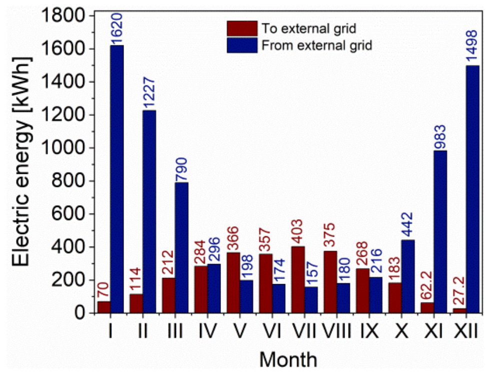

Fig. 8 Electric energy withdrawn to and from the external power grid

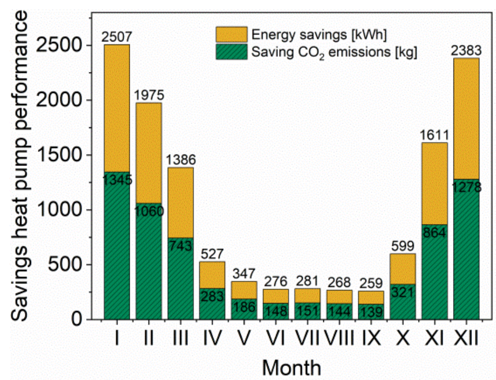

Fig. 9 The energy and CO_2 savings due to the heat pump performance factor, compared to electric resistance heating system

The fraction of direct consumption equal to the percentage of energy produced that is then directly consumed was 27.6 %/year. The degree of self-sufficiency was calculated, which was 26.5%/year. This value corresponds to the relationship between self-sufficiency and total consumption. The energy and CO_2 savings due to the coefficient of performance of the heat pump compared to electric resistance heating was calculated to be 12419 kWh/year and 6662 kg/year, respectively. The values of these parameters for each month are presented in Figure 9.

Conclusions

In this paper the capabilities of the Polysun program are presented on the basis of a realized complex energy system consisting of thin-film modules, an energy storage and a heat pump. However, only chosen parameters characterizing the energy system and energy yield are presented. The advanced interpolation models in Meteonorm allow results for solar radiation, temperature, and additional parameters to be obtained anywhere on earth. Polysun enables the prediction of energy and thermal yields for different types of energy systems, as well as a comparison between them.

Acknowledgments

The paper was financially supported by Institute of Electronic AGH project no 16.16.230.434.

***Authors**: dr inż. Katarzyna Dyndał, AGH University of Science and Technology, Institute of Electronics, Al. Mickiewicza 30, Kraków, Poland, E-mail: kkoper@agh.edu.pl; dr hab. inż., prof AGH Konstanty W. Marszałek, AGH University of Science and Technology, Institute of Electronics, Al. Mickiewicza 30, Kraków, Poland, E-mail: marszale@agh.edu.pl; prof. dr hab. inż. Zbigniew Kąkol, AGH University of Science and Technology, Department of Solid State Physics, Al. Mickiewicza 30, Kraków, Poland, E-mail: kakol@agh.edu.pl*

REFERENCES

[1] Fraunhofer Institute for Solar Energy Systems and PSE Projects GmbH, "Photovoltaics Report -2022- Fraunhofer ISE," no. February, pp. 1–52, 2022.

[2] G. M. Wilson *et al.*, "The 2020 photovoltaic technologies roadmap," *J. Phys. D. Appl. Phys.*, vol. 53, pp. 1–47, 2020, doi: 10.1088/1361-6463/ab9c6a.

[3] K. Dyndał, J. Sanetra, and K. W. Marszalek, "Study of the second-generation of CdTe and CIGS thin film PV modules under natural sunlight conditions," *Renew. Energy Power Qual. J.*, vol. 19, no. 19, pp. 379–384, 2021, doi: 10.24084/repqj19.298.

[4] K. Ungeheuer *et al.*, "Influence of Cr Ion Implantation on Physical Properties of CuO Thin Films," *Int. J. Mol. Sci.*, vol. 23, pp. 1–14, 2022, doi: 10.3390/ijms23094541.

[5] F. Galizia, M. Gallina, and E. Garzone, "Simulation of solar domestic hot water (DHW) instalation - Polysun," 2016. doi: 10.13140/RG.2.2.19151.48809.

[6] D. Gonz, I. Garc, and M. I. Dieste-velasco, "Photovoltaic Prediction Software: Evaluation with Real Data from Northern Spain," *Appl. Sci.*, vol. 11, pp. 1–14, 2021, doi: https://doi.org/10.3390/ app11115025.

[7] D. Gonz, I. Garc, and M. I. Dieste-velasco, "Photovoltaic Prediction Software: Evaluation with Real Data from Northern Spain," *Appl. Sci.*, vol. 11, pp. 1–14, 2021.

[8] J. Koke, A. Schippmann, J. Shen, X. Zhang, P. Kaufmann, and S. Krause, "Strategies of design concepts and energy systems for nearly zero-energy container buildings (NZECBs) in different climates," *Buildings*, vol. 11, no. 8, 2021, doi: 10.3390/buildings11080364.

[9] M. Berger, B. Schroeteler, H. Sperle, P. Püntener, T. Felder, and J. Worlitschek, "Assessment of residential scale renewable heating solutions with thermal energy storages," *Energy*, vol. 244, pp. 1–14, 2022, doi: 10.1016/j.energy.2021.122618.

[10] R. Sharma and L. Gidwani, "Grid connected solar PV system design and calculation by using PV∗SOL premium simulation tool for campus hostels of RTU Kota," in *2017 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, 2017, pp. 1–5, doi: 10.1109/ICCPCT.2017.8074315.

[11] P. J. Axaopoulos, E. D. Fylladitakis, and K. Gkarakis, "Accuracy analysis of software for the estimation and planning of photovoltaic installations," *Int. J. Energy Environ. Eng.*, vol. 5, pp. 1–7, 2014, doi: 10.1186/2251-6832-5-1.

[12] P. Jelínek, J. Sedlák, and B. Lišková, "Comparison of polysun simulation with direct measurements of solar thermal system in rapotice," *Adv. Mater. Res.*, vol. 1041, pp. 158–161, 2014, doi: 10.4028/www.scientific.net/AMR.1041.158.

[13] A. A. R. Abdel-Aty, A. R. Nassief, M. Mikhail, H. M. Elsharkawy, R. Ghannam, and A. S. G. Khalil, "Solar Thermal Collector Education using Polysun Simulations Software," *Transnatl. Eng. Educ. using Technol. (TREET 2020)*, no. August, pp. 1–4, 2020, doi: 10.1109/TREET50959.2020.9189749.

[14] Vela Solaris, *User Manual. Polysun Software*. Vela Solaris AG, 2020.

[15] R. Bornatico, M. Pfeiffer, A. Witzig, and L. Guzzella, "Optimal sizing of a solar thermal building installation using particle swarm optimization," *Energy*, vol. 41, pp. 31–37, 2012, doi: 10.1016/j.energy.2011.05.026.

[16] R. Džiugaitė-Tumėnienė and G. Streckienė, "Solar hot water heating system analysis using different software in single family house," *9th Int. Conf. Environ. Eng. ICEE 2014*, vol. enviro.201, pp. 1–9, 2014, doi: 10.3846/enviro.2014.258.

[17] Meteonorm, *Meteonorm, Global Meteorrological Database. Software and Data for Engineers, Planners and Education*, 7th ed. 2012.